The Project Physics Course

Supplemental Unit **B**

Discoveries in Physics

Supplemental Unit B

Discoveries in Physics

by

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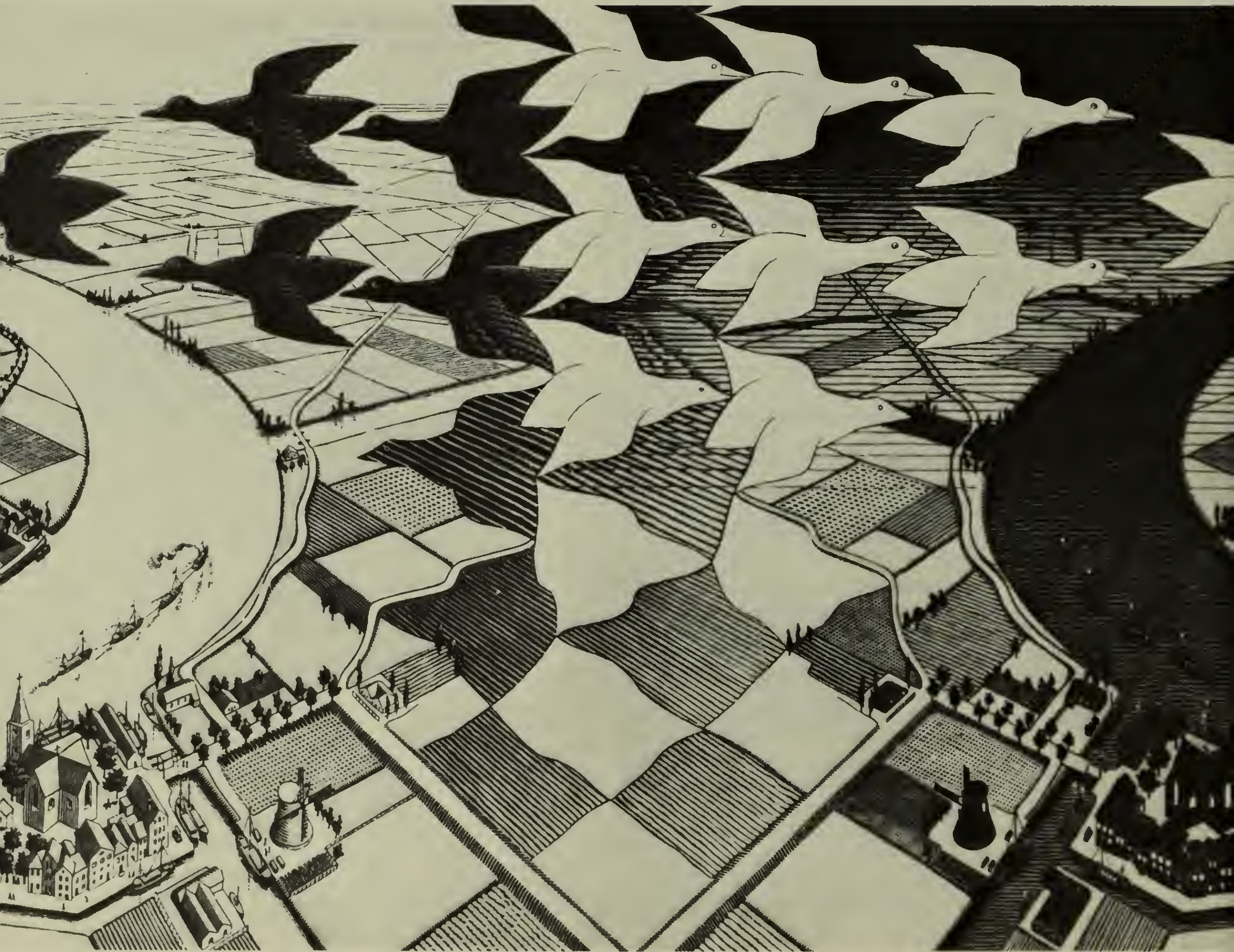

Day and Night, by M. C. Escher.

Discoveries in Physics

Prologue Some Models for Scientific Discovery

In this unit we shall examine in some detail four scientific discoveries: the finding of the planets Uranus, Neptune, and Pluto, the discovery and identification of cathode rays, the discovery and understanding of nuclear fission, and the experimental verification of the existence and the properties of the neutrino. Each of these discoveries is interesting in itself and is worth studying for that reason. But the four of them, taken together, can also provide us with good examples for thinking about the *processes* of scientific discovery. How do scientific discoveries happen? How do scientists go about solving problems?

Of course, one question we should raise at the outset is whether it is possible to make any useful generalizations about the processes of scientific discovery. Do the histories of individual discoveries fit into some sort of general pattern? This is the sort of basic question scientists themselves ask about phenomena they study; they look at some group of objects—the stars, for example—and try to fit them into categories according to their various characteristics. They ask how stars differ from each other and how they resemble each other. They make models of stars—not in the model railroad sense, but in terms of diagrams, equations, and graphs. They try to see whether their models of stars exhibit the properties real stars are observed to have. The better a model accounts for observable properties in terms of known physical principles, the more reliable and useful the model is.

In an analogous way, then, we ask whether there is any model that would describe what goes on in actual scientific discoveries—a model using concepts or pictures from real life. Several such models of the scientific process have been suggested. Some scientific discoveries are, for example, very much like voyages of discovery. The explorer sets out on an uncharted sea, and if he is lucky he finds new lands and perhaps civilizations. But the work of the scientist has also been compared to an army campaign, with interesting problems of strategy and tactics, with hard-won victories and occasional setbacks. Another way to look at great scientific discoveries is to compare them to the completion of a jigsaw puzzle, in which pieces have been slowly fitted together to reveal a previously hidden picture. But scientific work has also been described as being like the work of a detective in a "whodunit," in which all sorts of clues are sought, and in which much ingenuity is needed both to find the clues and to fit them together.

So at least four models for the processes of science have been suggested, and there could undoubtedly be others. In scientific work itself, when we find that many models present themselves, we can be fairly sure that *either* (a) one of the models, or a modification of it, will turn out to be by far the best, after more data are found, or (b) the phenomena are too complex to be explained adequately by any single model. In the second situation, each of several models says something true about the phenomena, but no one of them is adequate to give a complete picture. (In physics, for example, neither the simple particle model nor the simple wave model is adequate to describe the observable behavior of beams of light, but both models provide us with useful insights when we are experimenting with or thinking about light.) As you read about the four discoveries described in this unit, think about the models of discovery suggested above—and other models you may think up. Ask yourself which of them are adequate to describe the events of the particular discoveries and to help us think about scientific discovery in general.

In addition to thinking about models to describe the nature of scientific discoveries, we can also look at particular discoveries in a variety of other ways. We can ask some rather specific questions. Why, for instance, are some new ideas accepted quickly and eagerly, while others are rejected? And why are some discoveries made in duplicate—that is, by different men in different places, but at almost the same time? Consider also the importance of engineering and technological developments which often spring from some new scientific discovery. But sometimes an important scientific discovery can be made only after an engineering development.

More generally, we might ask whether there are any particular circumstances in which discoveries are especially likely to be made. In what political, economic, philosophical, and theological systems or climates have great discoveries been made? What are the roles of industrial or academic or governmental laboratories? The chapters which follow will not answer all the questions raised here, but they will provide you with some case histories which may be helpful in thinking about the conditions surrounding scientific discoveries.

We hope particularly that you will see that the word "science" has two meanings, and that both are necessary. On the one hand there is the scientist as a seeker of harmonies and constancies in the jungle of experience. He aims at knowledge and prediction, particularly through discovery of laws. This aspect of science is the speculative, creative, even subjective contribution of an individual, working on his own task by his own usually unexamined methods, motivated in his own way, and not always attending to the long-range philosophical problems of science. The other aspect of science comes to the fore when an individual's work is written up, published, and assimilated into the whole stream of such individual contributions. This is science as a public, shared activity, science as a growing network synthesized from these individual contributions. Here, science has become "objective" by the acceptance of those ideas—or even those parts of ideas—which do indeed prove meaningful and useful to generation after generation of scientists. The cold tables of physical and chemical constants, the bare equations in textbooks, are only the hard core, the residue distilled from individual triumphs of insight, checked and cross-checked by the multiple testimony of general experience.

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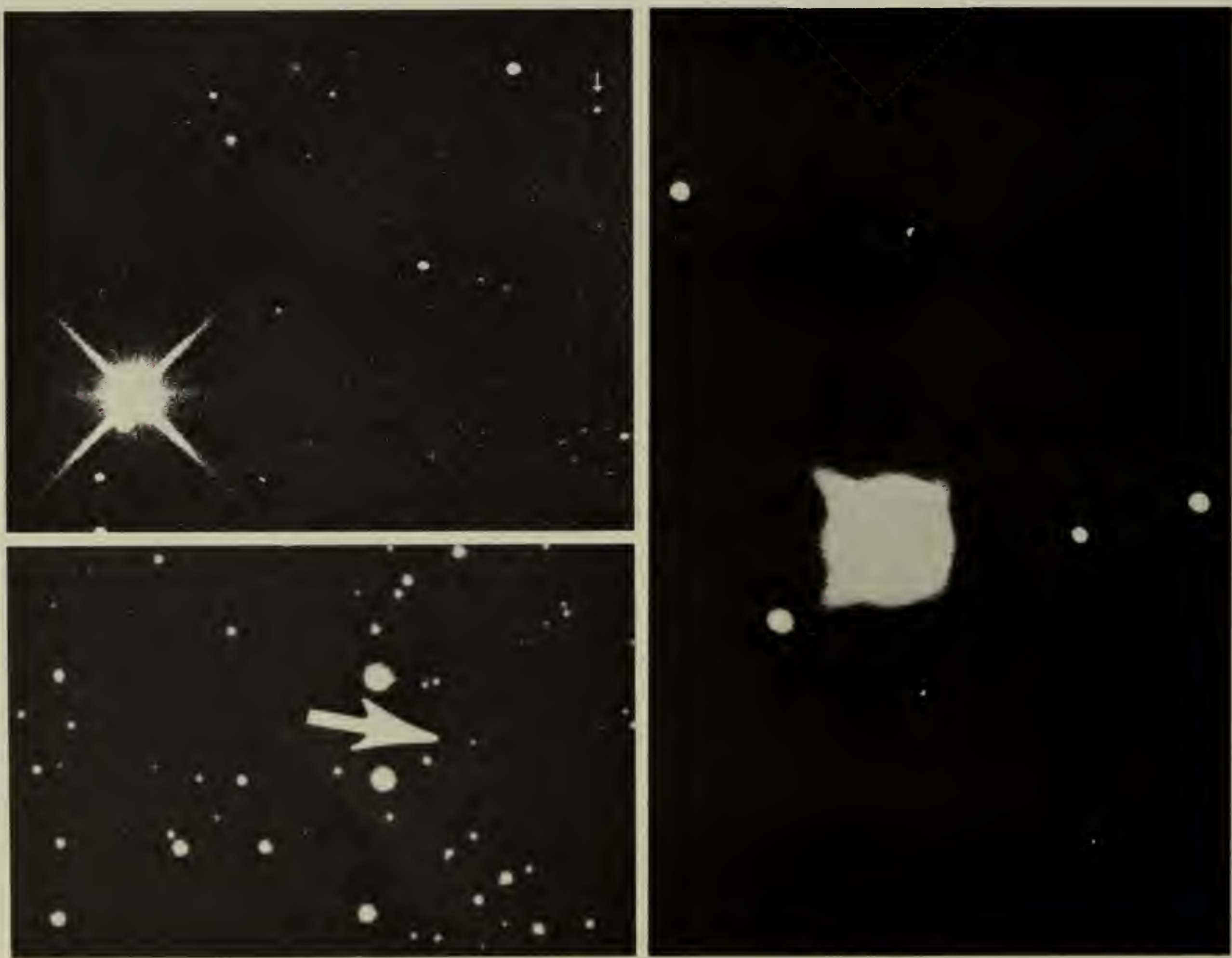


Recent discoveries: upper left, the second satellite of Neptune; lower left, Pluto; right, satellites of Uranus – the faint fifth satellite is overwhelmed by the over-exposed image of the planet.

CHAPTER ONE

New Findings in the Heavens—Uranus, Neptune, and Pluto

1.1 Introduction

For a review, see Chapter 8 of the Project Physics *Text.*

Great scientific theories are comprehensive. They explain a large number of phenomena that previously had seemed to be unrelated. Newton's theory of universal gravitation is such a theory. Although the theory was originally developed to account for the major motions of the moon and of the planets, Newton showed in the *Principia* that he could go on to use it to explain the variation in g (the acceleration of a freely falling object) from place to place, the behavior of the tides, the slow wobble of the earth's axis, and a variety of small peculiarities in the motion of the moon.

A great theory may also suggest to us where or how to look for new, previously unsuspected phenomena. If later observation shows the prediction to be correct, it is strong evidence that the theory is sound; it fits with observed phenomena. Here again the theory of universal gravitation provides a good example. Newton predicted from the theory that the rotating earth should bulge slightly at the equator, and indeed the earth was found to be oblate rather than perfectly spherical. He also predicted that projectiles shot horizontally at high speed could travel around the earth in circular or elliptical orbits or, if their speed were high enough, could escape from the earth along parabolic or hyperbolic paths. Today, almost 300 years later, many artificial earth satellites move as Newton's theory said they would.

When Newton formulated his theory of universal gravitation, he was unaware of the existence of any planets other than those known since ancient times: Mercury, Venus, Earth, Mars, Jupiter, and Saturn. We shall see, however, that his theory was instrumental in the discovery, about 120 years after his death, of another planet, Neptune. The story of the discovery of Neptune will involve us in the related discoveries of Uranus and Pluto. All three of these planets are too dim to be seen without a telescope. The existence and position of Neptune were predicted by means of the theory of gravitation. The subsequent observation of Neptune in the predicted position was one of the crowning triumphs of Newton's theory.

Fig. 1-2 William Herschel (1738–1822) with diagram showing Uranus and its two brightest satellites, Oberon and Titania, discovered by him on January 11, 1787.

1.2 The discovery of Uranus

Before we can discuss the discovery of Neptune, we must first consider the discovery of Uranus, an event which owed much to chance. Uranus was found in 1781 by William Herschel (1738–1822), who was not looking for any new planet at all.

Herschel, who was originally a musician, immigrated to England from Germany when he was nineteen years old. In his spare time he took up the study of languages, then mathematics, and then astronomy. He began building his own telescopes and within a few years was making better telescopes than were then available to professional astronomers.

When he was in his early forties Herschel embarked on the tremendous task of counting the number of stars visible in various parts of the sky through his best telescope. His primary object was to determine how the stars are distributed in the three-dimensional space around us. In other words, he was trying to find the size and shape of what we now call our galaxy.

As he was carrying out his observations, he happened to notice, on the night of March 13, 1781, an unusual object among the stars of the constellation Gemini. The object, just a bit too faint to be seen without a telescope, appeared as a disc rather than as a point of light. Herschel knew that stars are too far away to show up in telescopes as anything but points of light, whereas planets and comets, being much closer, can be seen as discs. The observation that in the course of several days the object moved relative to the stars confirmed his suspicion that it was not a star.

In spite of the fact that the object lacked any hint of a tail or of any fuzziness, Herschel assumed that the newly discovered object was a comet, not a planet. This was not surprising; most of the astronomers to whom Herschel communicated the news of his discovery agreed with him. New comets were being discovered fairly frequently, whereas no one since the dawn of recorded history had ever found a new planet.

Fig. 1-3 Uranus (overexposed) and its five satellites.

The only problem, then, was to determine the shape, size, and orientation of the orbit of the "comet," the so-called *elements* of the orbit, from its observed positions at various times. The process of determining elements from observational data is tedious, particularly if one does not have data from observations over a long period of time. (A "long period of time" here means about the length of time it takes for the object to make a circuit around the sun.) In addition, there was in Herschel's time no way to calculate elements from observational data without depending on unreliable guesses as to the shape of the orbit. Not until 1809 was a method developed for calculating elements without having to guess at the shape of the orbit; the inventor of this method was the brilliant mathematician Karl Friedrich Gauss (1777–1835). Gauss' method did assume that the orbit was a conic section (that is, an ellipse, a parabola, or a hyperbola), an assumption that was justified by Newtonian physics. Unfortunately, Herschel, working in 1781, was obliged to base his calculations on uncertain hypotheses about the type of orbit he was studying. His attempts to find the elements of the orbit of his supposed comet were unsuccessful. Some comets have parabolic or very eccentric elliptical orbits which bring them quite close to the sun at perihelion. The data for Herschel's object did not fit into any such orbit.

In May of 1781 a French astronomer calculated an orbit in which the perihelion distance would be more than twelve times the distance from the earth to the sun. This is an astonishingly large perihelion distance for a comet. Perhaps the object was not a comet after all; perhaps it was a distant planet. Shortly thereafter, Lexell, a Russian astronomer visiting in London, computed the elements on the assumption that the orbit was circular. This orbit had a radius nineteen times that of the earth's orbit, and was more than twice the radius of the orbit of Saturn. Lexell's results made generally acceptable the idea that the new object was a planet far beyond the orbit of Saturn. Within two years of Herschel's original observation, the French mathematician Laplace and others used the accumulated data to compute the elements of an elliptical orbit. Since Uranus (as the new planet eventually came to be called) takes 84 years to make one revolution around the sun, it is obvious that a two-year span of observations does not give one very much to go on. (See Fig. 1.6 for a scale drawing indicating the path of Uranus in a two-year period.) It is a tribute to the precision with which the observations were made that tolerably useful calculations of the elements of the orbit could be made at all.

A German astronomer, Johann Bode (1747–1826), soon thought of a possible way around this difficulty of having observations covering only a short span of time. It occurred to him that astronomers in earlier years might have observed Uranus while compiling catalogs of stars and, assuming it to be a star, included it in their catalogs. He used the orbit to calculate where Uranus had been in the sky at earlier times. Then he looked to see whether any stars situated near the expected path of Uranus had been recorded in one catalog but not in

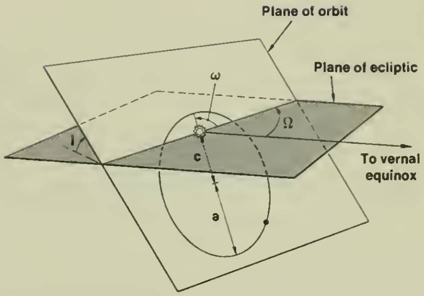


Fig. 1-4 An orbit in its plane compared to the plane of the earth's orbit (the ecliptic plane).

To specify the size, shape, and orientation of an elliptical orbit in the solar system, we need to know six quantities or *elements*. Five of these quantities are indicated in Fig. 1-1 by the symbols, i, Ω, ω, a and c. The angles i, Ω, and ω specify the tilt of the plane of the orbit and the direction of the major axis of the ellipse. The distances a and c define the shape and size of the ellipse. The angle i is the inclination of the object's orbit relative to the plane of the earth's orbit. The angle Ω is the angle between the line of intersection of these two planes (called the lines of nodes) and a line drawn from the sun toward the vernal equinox. (The vernal equinox is the point at which the sun crosses the celestial equator from south to north about March 21. See Unit 2 Section 5.1 of the Project Physics *Text*.) The angle ω is the angle between the major axis of the ellipse and the line of nodes. The distance a is half the major axis of the ellipse; c is the distance from the sun at a focus of the ellipse to the center of the ellipse. The shape of an elliptical orbit is often specified as the eccentricity, $e = c/a$. (See Unit 2 Section 7.3 of the Project Physics *Text*.) The sixth orbital element, a date when the object passed its perihelion point, is needed for the computation of a timetable of past and future positions.

others compiled at different times. He found that such a "star" had been observed on December 23, 1690, and another on September 25, 1756. Later, observations recorded in 1764 and in 1769 were found. Using these positions observed in the past, together with the contemporary ones, the French astronomer Delambre in 1790 derived new elements for the orbit of Uranus.

Thus, within a decade of its accidental discovery by Herschel, Uranus seemed to be a perfectly well-behaved member of the sun's family of planets, with accurately known elements.

1.3 The strange motion of Uranus

There was no doubt, then, that Uranus was one of the sun's planets; but by 1820 there were hints that it was not so well-behaved after all. The French scientist Alexis Bouvard (1767–1843) found that an orbit computed from observations made during the four decades since Herschel's discovery in 1781 could not be made to fit the old data that had been found in star catalogs by Bode and others. Bouvard assumed that the old observations had been less precise than had generally been believed. As time went on, however, it became clear that Bouvard's orbit (1820) and his explanation of the discrepancies were inadequate. As new observations of the positions of Uranus were made they disagreed more and more with the positions predicted by Bouvard's elements—the elements that had been based on the 1781–1820 observations. In other words, unlike all other planets, Uranus was not moving "properly" along a reasonable orbit on a predicted timetable, even if the old, pre-1781 observations were discounted. The differences between observed and predicted positions increased to more than one minute of arc—considered a scandalous amount!

Several hypotheses were put forward to explain the strange behavior of Uranus. One suggestion was that space might be filled with a very subtle fluid which could interact with planets. However, no known frictional or other force between such a fluid and Uranus could account for the observed oddities in the motion of Uranus. Besides, one would have to ask why the effects of such a fluid had not been noticed with other planets.

Another suggestion was that Uranus might have a massive but undiscovered satellite. If so, the motion of Uranus and its satellite around each other would account for the irregular speeding up and slowing down of the visible planet which differed from its predicted orbital motion. However, it was difficult to imagine that such a massive satellite would be invisible; in any event, its period would be too short to account for the observed slow variation in the motion of Uranus.

Yet another suggestion was that shortly before Herschel's discov-

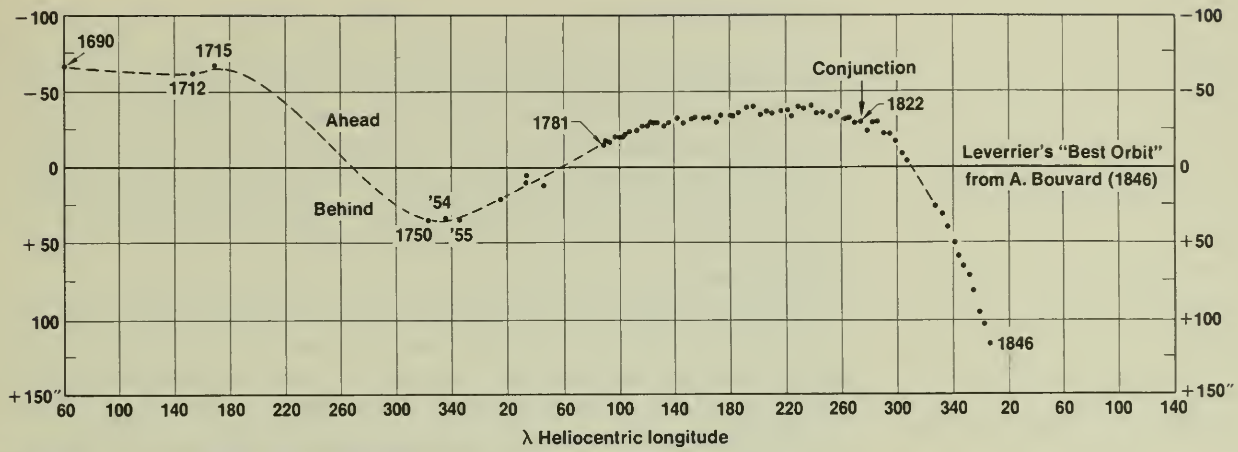


Fig. 1-5 Differences between observed positions of Uranus (heliocentric longitudes) and those predicted by Leverrier from the "best orbit."

ery in 1781 Uranus might have changed its orbit by a collision with a comet. Such a change of path would give one set of elements for the pre-1781 orbit and another set for the later orbit. Such a collision, although possible, would have been a remarkable coincidence. It seemed less and less plausible because even the revised observations began to disagree more and more with the calculations based on recent observation.

A fourth proposal was that perhaps Newton's law of gravitation was not quite correct at that distance from the sun. Maybe in the equation $F_{\text{grav}} = G\,\frac{m_1 m_2}{R^2}$ the exponent of the distance in the denominator was slightly different from 2, or maybe there were some additional terms which were functions of the distance and which were negligible except for very large distances. However, because of the success of the simple inverse-square law for gravitation in dealing with a large number of phenomena, most astronomers and physicists did not take very seriously this idea that the force might not vary exactly with the inverse square of the distance ($F \sim 1/R^2$).

From about 1835 onward, a growing number of scientists wondered whether the peculiar motion of Uranus might possibly be due to attraction by some undiscovered planet in an orbit beyond that of Uranus. Such a planet would be faint and visible only through a telescope because of its great distance. Finding it among the myriad of stars along the ecliptic would be a virtually hopeless task. Some attempts were made to search for it, but without success. What was needed was a prediction of the planet's position, so that astronomers would know where to look for it.

1.4 Perturbations

Newton deduced that a planet acted on by an inverse-square gravitational force directed toward the sun will move in an elliptical orbit with the sun at one focus. Furthermore, the speed of the planet will vary in the way described by Kepler's Law of Areas. If we observe the motion of any planet in precise detail, we will find, however, that it does not follow exactly an elliptical orbit; or a time-table based on the law of areas.

Is there something wrong with the Law of Gravitation? Not at all; there is something wrong with the way we used it. We forgot that gravitation is a universal phenomenon. A planet is pulled not only by the sun as we assumed for the sake of simplicity; it is pulled also by all the other planets—and by their moons and by comets and by stars.

Because it has such a tremendous mass and is relatively close, the sun exerts the most significant force on any planet. Sister planets and moons may be closer, but their masses are small; stars may be very massive, but they are very far away. For this reason a planet moves very nearly in the way we predict when we assumed that only the sun pulls on it. Gravitational pulls by other planets result only in small deviations from the expected motion. The small deviations are called *perturbations* of the motion. Since all the planets are moving, the perturbing forces on any one planet are constantly changing in magnitude and direction.

Uranus, then, is perturbed by its sister planets, particularly by the neighboring (and especially massive) Saturn and Jupiter. Consider Uranus, Saturn, and Jupiter when they happen to be arranged in their orbits with respect to the sun as shown in Fig. 1.8(a). Knowing the

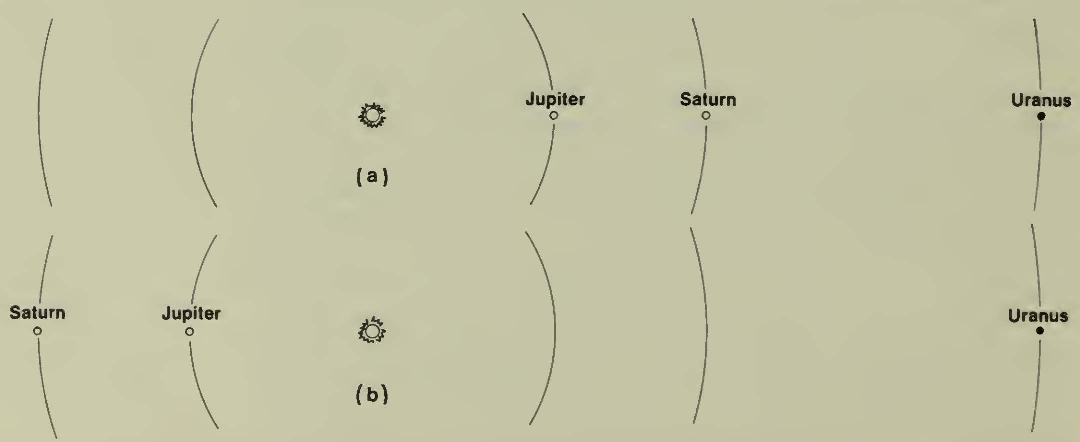


Fig. 1-6 Positions of Sun, Jupiter, and Saturn creating maximum (top) and minimum (bottom) gravitational attractions on Uranus.

masses and the positions of the four objects, we can calculate the total attraction of the three bodies on Uranus. If the gravitational attraction of the sun on Uranus is taken as 1000 units, then that of Jupiter on Uranus will be 1.5 units and that of Saturn about 1.1 units. The total force on Uranus toward the sun will be about 1002.6 units.

However, when Jupiter and Saturn are on the far side of the sun from Uranus, as in Fig. 1.8(b), the forces they exert on Uranus will have magnitudes of about 0.6 units and 0.13 units, respectively. Under these circumstances the total force on Uranus will be about 1000.6 units. Uranus, Saturn, and Jupiter are, of course, seldom arranged as in the diagrams. Ordinarily the planetary perturbing forces have components perpendicular to the line of the sun's force on Uranus, as well as along that line. All of these perturbing forces are very small; their sum is never more than 0.26% of the sun's force, but their cumulative effects distort the motion of Uranus from the perfect ellipse and time-table it would follow if the sun and Uranus were alone in the universe.

It is an interesting coincidence that Bouvard computed his elements for the orbit of Uranus in 1820, only about two years before the conjunction in 1822 of Uranus and the still-to-be-discovered Neptune. For many years before 1822, Uranus was "behind" Neptune, so the gravitational force exerted by Neptune was increasing the speed of Uranus in its orbit. Observations of Uranus from 1781 to 1820 therefore could be reasonably well fitted by an orbit (Bouvard's) which took no account of unknown perturbations due to Neptune. After the conjunction of 1822, Uranus was "ahead" of Neptune and hence was slowed down slightly so the differences between its actual motion and those predicted by Bouvard's 1820 calculations became increasingly noticeable.

Two planets are in conjunction when they and the sun are in a straight line.

1.5 The discovery of Neptune

Attraction by Jupiter and Saturn could account for part of the observed variations in the motion of Uranus. But there were some residual differences between observations and computations still to be explained. Could these residual variations be due to the presence of an undiscovered planet?

A planet that is perturbed by its sister planets perturbs them in turn, and they, from their perturbed positions, again perturb their perturbed perturber. It is not hard to see that the theory of perturbations is complicated. In fact, it is impossible to find an exact solution to the general problem of the motion of a given planet, except for the case where there are only two bodies involved: the sun and one planet. For the many-body problem there is in general only an approximate solution. Fortunately, because the planets perturb one another only slightly, approximate methods can yield sufficiently accurate predictions.

To use the small residual variations in the motion of Uranus to deduce the position of an undiscovered planet is a difficult task. While we might assume that the unknown planet is following a nearly circular orbit, we do not know anything else about the distance, position, or mass of the undiscovered planet. It is one thing to use the theory of perturbations to calculate the motion of a planet perturbed by other planets whose positions and masses are known. It is quite another thing to turn the process around and, from the small residual perturbations in the motion of Uranus, calculate where the unknown planet must be. Hence, in 1842, the Royal Academy of Sciences of Göttingen offered a prize for an adequate discussion of the motion of Uranus.

Within a few years the solution was obtained and, amazingly enough, not just once, but simultaneously by two young scientists who did not know of each other's work. One was John Couch Adams of Cambridge University in England. The other was Urbain Jean Joseph Leverrier of the Ecole Polytechnique in Paris. Adams was in his late twenties and Leverrier in his early thirties. Both had had splendid training in mathematics and physics, and Leverrier was already well known for his brilliant work in applying the Law of Gravitation to the complex interactions between planets and to the motion of comets. Adams had begun to think about Uranus while still an undergraduate in 1831, but he did not begin his calculations in earnest until 1842.

By the middle of 1845, both Adams and Leverrier separately solved the inverse perturbation problem; that is by the use of Newton's Law of Gravitation, they computed the probable mass, location, and motion of the hypothetical planet. Both men made essentially the same predictions about this new planet. Both men also ran into difficulties in persuading astronomers to search the sky in the region where their calculations indicated that a new planet should be visible with a large telescope.

Fig. 1-7 Urbain Jean Joseph Leverrier (1811–1877) who, like John Couch Adams, predicted the position of Neptune.

Fig. 1-8 Trail of an asteroid which moved during the time-exposure while the telescope followed the motion of the stars.

Adams tried for months to get British astronomers to look for his planet. He finally succeeded, for the Cambridge observatory began a long and tedious program of mapping faint stars in the predicted region of the sky. The chief observer ignored Adams' suggestion that he simply look for a faint object that had an observable (although very small) disc-shaped image rather than the point-image typical of stars. The observatory authorities planned instead to make successive observations of the positions of all the stars in the region. Then, if any one of them moved along the ecliptic between observations, it would probably be the new planet. Such a program would require several years to carry out.

Leverrier too had trouble generating enthusiasm for observations. Although he was highly honored for his brilliant mathematical ingenuity in showing how the residual perturbations of Uranus could be accounted for by the hypothetical planet, no one wanted to spend the time and effort needed to look for it. Finally he wrote to a young astronomer in Berlin, Johann Galle, describing his calculations and asked Galle to look for the planet in a specified small region of the sky. Galle received the letter on September 23, 1846, and obtained permission to use the nine-inch-diameter telescope of the Berlin observatory that very night. A preliminary search showed no disc-shaped image, but, after consulting a star map of the region recently completed at Berlin but not yet published, Galle noted that one "star" he could see was not shown on the map. Later observations made it clear that this body was moving as predicted by Leverrier, and under higher magnifying power it displayed a disc-shaped image very close to the predicted size. The "star" was indeed the missing planet.

Photography was then in its very early infancy. Modern astronomers, thanks to photographic plates, have two methods for detecting objects which are not fixed stars. If a plate is exposed for a period of time in a telescope which is moved by a clockwork or motor to compensate very precisely for the rotation of the earth, then the stars in the area of view will appear as sharp dots on the plate. If there is some object such as a comet, asteroid, or planet in the area, its image will be a line or a trail, rather than a sharp dot. This assumes, of course, that the object moves a noticeable distance across the field of fixed stars during the exposure time. Another method is useful for more distant and slow-moving objects. Two photographs are made of the area of interest in the sky several days, weeks, or months apart. They are mounted in a special viewer, called a blink comparator, so that the two photographs are viewed, apparently in the same position, in rapid alternation. If an object is visible in one photograph but not the other, it will then "blink" on and off, and it can be quickly noticed in the midst of hundreds of thousands of fixed stars.

Fig. 1-9 Neptune (greatly overexposed) and its two satellites. Triton, discovered by Lexell in 1846, is below and to the left in the glare from Neptune. Nereid, discovered in 1949, is marked with an arrow.

The news spread quickly, and Leverrier was justly honored for his impressive accomplishment. There was great chagrin in England, particularly on the part of the Astronomer Royal, George Airy, who had delayed the search for months in spite of the urging of Adams and others. Actually the Cambridge observatory's tedious survey had in fact included observations of the planet before September 23, but it had not been recognized for what it was.

In due course both Leverrier and Adams were equally honored for their achievement in predicting the location of the planet, which was named Neptune.

1.6 The orbit of Neptune

An Astronomical Unit is the length of the semi-major axis of the earth's orbit

In order to do their calculations at all, both Adams and Leverrier had to make some assumptions about the size of the orbit of the unknown planet. To predict the radius of the orbit, they used what was known as Bode's Law. Johann Bode, whom we have mentioned earlier, had discovered an empirical formula for the average radius of a planetary orbit. Although no physical basis of this formula is known, it represents fairly accurately the relative radii of the orbits of the six planets known in Bode's time. The formula, called Bode's Law, states that the average radius, R, in astronomical units, of the orbit of the nth planet from the sun is given by $R = 0.4 + (0.3 \times 2^{n-2})$.

The orbit of Mercury, for which n=1, is an exception; for it the quantity in parentheses must be set equal to zero for a correct prediction of its orbital radius. At the time Bode announced his formula, there seemed to be another defect; the radii of the orbits of Jupiter and Saturn, the fifth and sixth planets from the sun, were given correctly only if values for n of 6 and 7, instead of 5 and 6, were inserted into the formula. Bode believed that this indicated the existence of an undiscovered fifth planet in the space between Mars and Jupiter. When, beginning in 1801, a number of small asteroids were discovered at the predicted distance, Bode's Law received important support.

Table 1.1 compares the observed radii of the planets' orbits with those predicted by Bode's Law.

TABLE 1.1

Planetary Orbits: Observed and Predicted from Bode's law.

Planet	n	Observed R	Predicted R
Mercury	1	0.39	0.4
Venus	2	0.72	0.7
Earth	3	1.0	1.0
Mars	4	1.5	1.6
Asteroids	5	2.8	2.8
Jupiter	6	5.2	5.2
Saturn	7	9.5	10.0
Uranus	8	19.2	19.6

When Uranus was discovered it was found that the radius of its orbit agreed within 2% with that predicted by Bode's Law with $n = 8$. It appears that Bode's Law fairly well describes the spacing of the planets – at least as far out as Uranus; we will see that it is less accurate for more distant planets.

According to Bode's Law, the orbit of the next planet after Uranus, with $n = 9$, would have an average radius of 38.8 astronomical units and a period of 242 years. Both Adams and Leverrier assumed this figure for the orbit of Neptune.

With a period of revolution around the sun of nearly two and a half centuries, it would obviously be many years before Neptune would move over a large enough arc of its orbit for the elements of the orbit to be calculated accurately from observations, rather than inferred from the residual perturbations of Uranus. However, in 1847, an American astronomer, Sears Walker, found in a star catalog of 1795 the recorded position for a telescopically observed "star" which was no longer visible in that position. The "star" was shown to have been Neptune. As had happened with pre-discovery records of Uranus, the catalogued position of Neptune nearly fifty years earlier, together with the small amount of data obtained since its discovery, enabled Walker to calculate a reasonably reliable orbit for Neptune. Everyone was surprised to find that the elements of the orbit calculated by Walker differed considerably from those predicted by Adams and Leverrier. In particular, the orbit radius was only about 30 astronomical units instead of nearly 40, and the corresponding period was only about 160 years instead of 242. With Neptune closer to Uranus than had been predicted by Adams and Leverrier, its mass must be less than predicted in order to produce no more than the observed residual perturbations. The mass of Neptune turned out to be about half that predicted by Adams and Leverrier.

So we must ask: was Galle's discovery of Neptune – a discovery guided by Leverrier's predictions – nothing more than a gigantic piece of good luck? The question does not have a simple answer.

Scientists are often confronted with problems involving many variables for some of which they may not have accurate values. They may be forced to make intelligent guesses about the probable size of those they do not know. If they are wise – or lucky, those variables will be ones for which a moderate error in the guess will not greatly affect the final result.

This is what happened in the case of the calculations of Adams and Leverrier. It turns out that their results are not very sensitive to the value they assumed for the radius of the orbit of Neptune. In a sense, they were wise to use Bode's Law; in fact, there was no other way that they could have obtained a value for the radius so that they could start the calculations. Furthermore, they had no reason to believe that Bode's Law would not give the correct value. In another sense they were lucky, for even though Bode's Law failed for the orbit of Neptune, it did not fail badly enough to invalidate their final predictions.

Why Adams and Leverrier were successful

Why the distance of the hypothetical planet from the sun makes little difference in the solution of the problem can be seen from Fig. 1.13. Let us assume that all the planets are moving around the sun in circular orbits. Uranus is known to be 19 AU from the sun and to have a period of 84 years. The real Neptune is 30 AU from the sun and has a period of 160 years. The hypothetical planet was assumed to be 39 AU from the sun and therefore to have a period of 242 years. We also know, now, that Uranus, Neptune, and the sun were in line in 1822. The rapid build-up of discrepancy in the position of Uranus as shown in Fig. 1.5 makes clear that about 1820 the attractions on Uranus changed significantly. As Table 1.2 shows, we can work backward or forward to find approximate positions for all three planets at any date.

As you can see from the diagram, in 1781 Uranus would be pulled forward in almost the same direction by either the real Neptune or the assumed planet. The amount of the acceleration would depend upon the mass and distance of the perturbing planet. A smaller planet nearer could have the same effect as a large distant planet. By 1812 the force would be larger with components moving Uranus ahead in its motion and also outward from the sun. After conjunction in 1822 the force on Uranus would slow its orbital motion and even as late as 1846 the retardation would be considerable. It is remarkable that Bouvard computed his orbit in 1820 just before the direction of the perturbations changed from acceleration to deceleration along the orbit. No wonder his orbit showed large errors after 1822. See Table 1.2 below.

All planets and the sun were in line in 1822. Uranus with a period of 84 yrs. moves around sun about 4°/yr. Neptune, period 160 years, moves around sun about 2°/yr. Planet, period 242 years, moves around sun about 1.5°/yr.

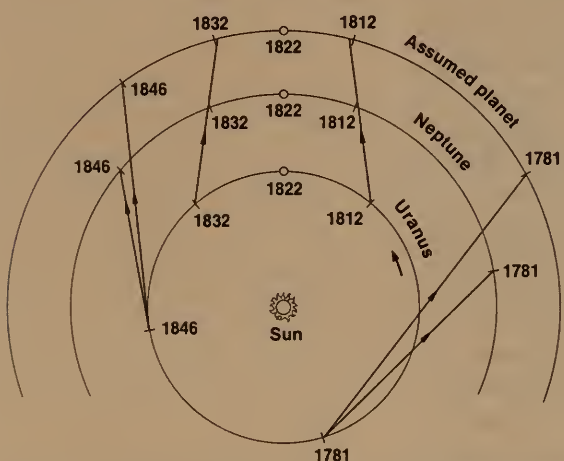


Fig. 1-10 Relative positions of Uranus, Neptune and the assumed planet from 1781 to 1846.

TABLE 1.2

Approximate positions of Uranus, Neptune and the assumed planet before and after 1822

	Interval to 1822	Angular motion around sun during interval: Uranus (4°/yr)	Neptune (2°/yr)	Planet (1.5°/yr.)
1781	41 yrs.	164°	82°	63°
1812	10	40	20	15
1822	0	all planets and sun in line		
1832	10	40	20	15
1846	24	96	48	36

Fig. 1-11 Percival Lowell (1855–1916), amateur astronomer who created the Lowell Observatory, and predicted the position for Pluto.

As years went by, and Neptune's mass was determined from the motion of its large satellite, and the elements of its orbit were more precisely calculated from the accumulating observations, the suspicion grew that the gravitational forces exerted by Neptune on Uranus could not quite account for all the residual perturbations of the motion of Uranus. Could there be still another planet beyond Neptune? Several persons tried to repeat the achievement of Adams and Leverrier, but they met with little success because the remaining residual variations in Neptune's motion were so small that accurate predictions of the location of the hypothetical planet were all but impossible.

In 1919, W. H. Pickering, at the Harvard College Observatory, specified an area of the sky in which he predicted that the new planet might be observed. He based his prediction on the residual perturbations of both Uranus and Neptune. A search of photographs which had been made at Mt. Wilson Observatory of that region of the sky did not show any indication of the planet.

The most persistent seeker of the new planet was the amateur astronomer Percival Lowell. In 1915 Lowell had completed calculations, based on the small residual perturbations of Uranus, which suggested that the new planet would be found in one of two places in the sky, one of which agreed with the position predicted by Pickering. Lowell, who was independently wealthy, had founded an observatory at Flagstaff, Arizona, designed primarily for solar system research. He died in 1916, keenly disappointed that "his" planet had not been found. The search went on, however, especially as more suitable photographic telescopes became available in the 1920's.

In 1930, a planet was finally discovered by Clyde Tombaugh, of the Lowell Observatory, near the position which Lowell and Pickering had predicted. Tombaugh used a blink comparator to compare a vast number of plates. He later wrote, ". . . on the afternoon of February 18, 1930, I suddenly came upon the images of Pluto! The experience was an intense thrill, because the nature of the object was apparent at first sight. . . . In all of the two million stars examined thus far, nothing had been found that was as promising as this object. . . . ." No public announcement was made until the planet's existence was confirmed by further observations. The announcement was made, appropriately enough, on Lowell's birthday, March 13, a little over three weeks after Tombaugh's first observation. The planet was given the name Pluto, after the god of the underworld, as befits a distant planet moving endlessly in stygian darkness and cold. Percival Lowell is commemorated in the astronomers' symbol for Pluto, ♇, a combination of the initials P and L.

Fig. 1-12 Clyde Tombaugh in 1930 when he discovered Pluto.

Pluto turned out to be much closer to the sun than was expected, and to have a mass and size smaller than those of the earth. If the residual perturbations of the motions of Uranus and Neptune are real (and not, as many astronomers now believe, simply very small observational inaccuracies), it is doubtful that Pluto is massive enough to account for them. Was there, then, an element of good luck in the discovery of Pluto? If there was, there was also an element of bad luck: Pluto had been recorded on the 1919 Mt. Wilson photographs, but it had been overlooked because it was so much fainter than had been expected.

One would be tempted to say that the actual finding of Pluto near the predicted position was simply a matter of luck, since Pluto turned out to be too small to have caused significant perturbations. Yet Lowell's and Pickering's predictions did agree, and they were based on independent calculations. There is some evidence that a passage of Uranus between the sun and Pluto in the year 1710 might have provided just enough of a perturbation of Uranus' orbit to give the results that Lowell and Pickering achieved. If so, then the luck resulted from that unknown passage, and not the sort of luck that is implied in the suggestion that Tombaugh's plates only accidentally caught an image of Pluto.

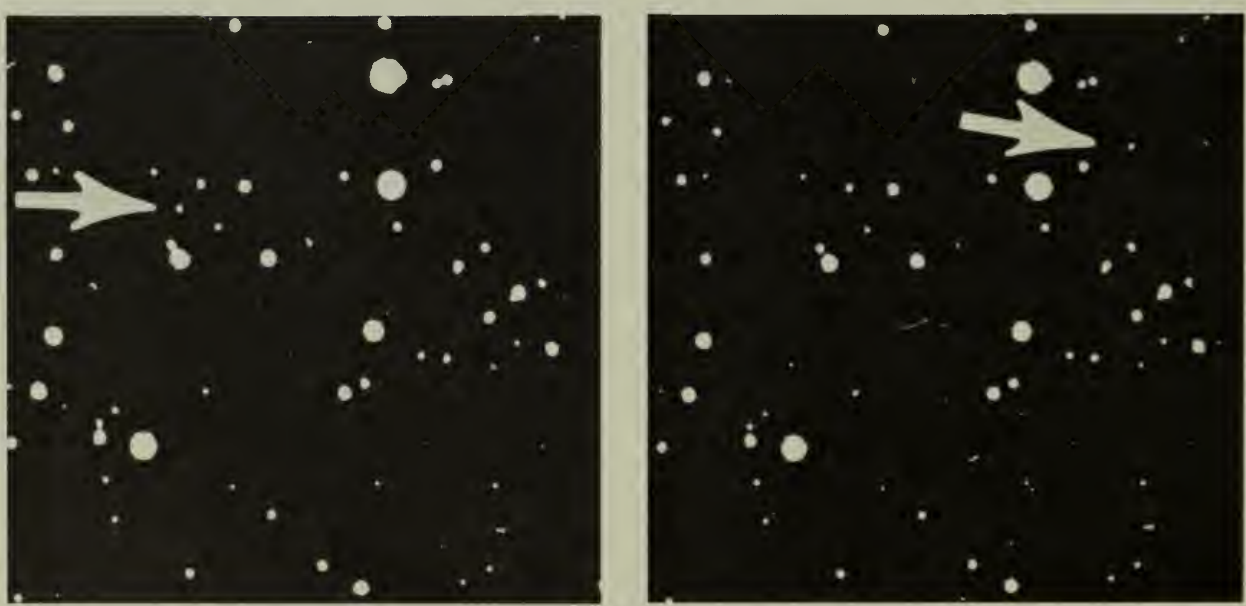


Fig. 1-13 Discovery photographs of Pluto showing displacement during six-day interval in 1930.

STUDY GUIDE

1.1 In what sense was the discovery of Uranus an accident? Discuss also the accidental aspects of the discoveries of Neptune and Pluto.

1.2 There have been many instances in science of two or more men making the same discovery, independently of each other, at about the same time. The work of Adams and of Leverrier is one such instance. In what way or ways was the time ripe for their work?

1.3 The sun's mass is 329,300 times that of the earth. Jupiter's mass is 318 times that of the earth, Saturn's 95.2 times, Uranus' 14.6 times, and Neptune's 17.6 times. The average distance from the sun to Jupiter is 5.2 astronomical units; to Saturn, 9.6 AU, to Uranus, 19.1 AU, and to Neptune, 30.1 AU. What is the ratio of the maximum force Neptune can exert on Uranus to the maximum force exerted on Uranus by Jupiter and by Saturn? These ratios will give you a rough way to compare the perturbations of Uranus' orbit produced by Neptune with those produced by Jupiter and by Saturn.

1.4 The Figure below shows the distribution of the periods of the asteroids, which move inside the orbit of Jupiter like the small planet in the laboratory activity. Note the absence of certain orbital periods among the asteroids, known as "Kirkwood's gaps," at periods exactly 1/2, 1/3, 2/5, 1/4, 1/5, 3/5, and 3/7 the period of Jupiter. What explanation do you propose for the existence of these "gaps" in the distribution of asteroid periods?

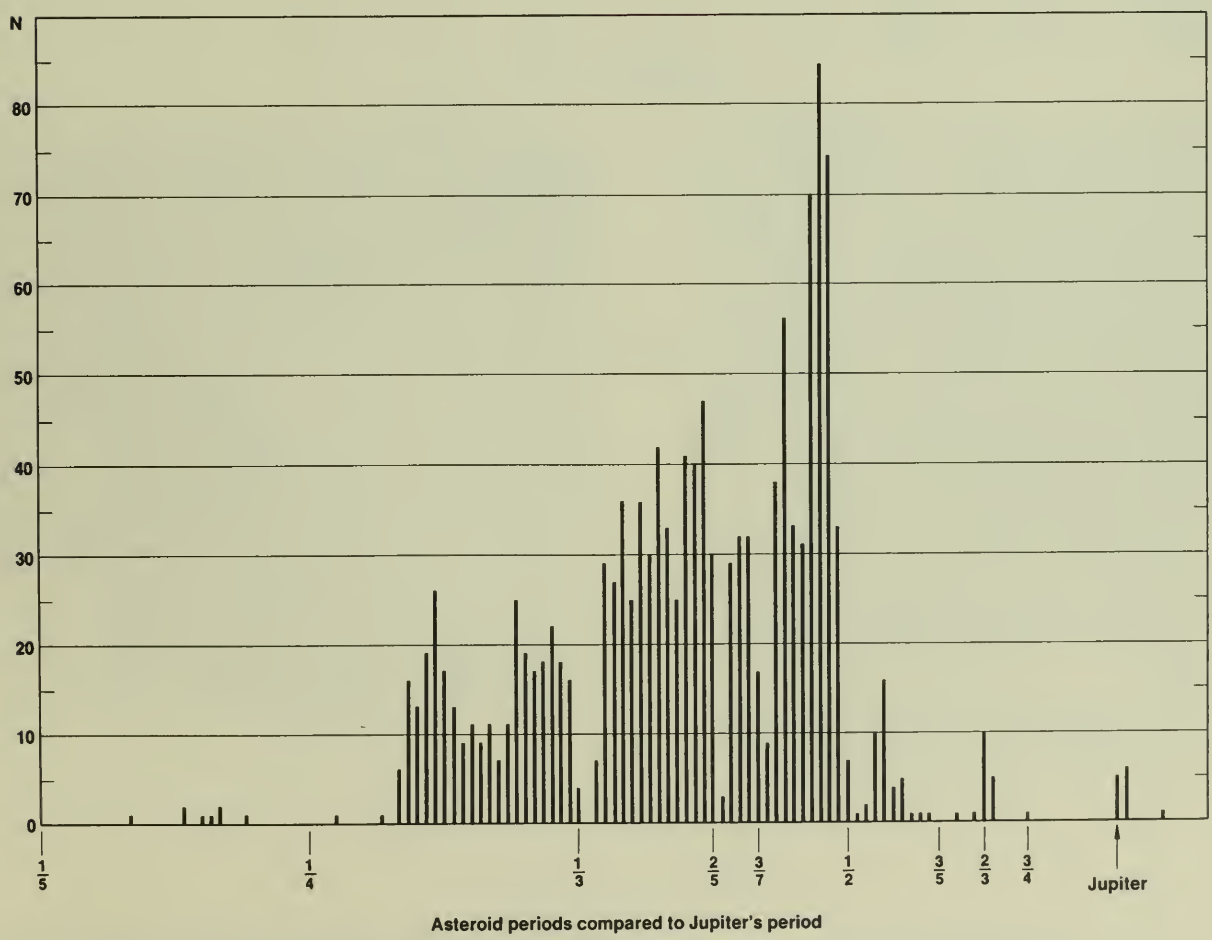


Fig. 1-14 This chart gives information which may be used to answer question 1.4 of the Study Guide above.

1.5 Given the relative sizes and distances of the planets, it is possible to make a rough estimate of their relative brightnesses. In the following table six planets are listed, together with their diameters (compared with the Earth's diameter) and their distances from the sun, in AU. Each planet will receive an amount of light from the sun proportional to the planet's area and inversely proportional to the square of its distance from the sun. Why? The planet's area is proportional to the square of its diameter. Fill in the values for the columns (4) and (5), headed "Area" and (Dist)^2. (Use no more than three significant figures). Then compute for each planet (Area)/(Dist)^2, (col. 6), which will be proportional to the light it receives from the sun. Of that light, a certain fraction will be reflected outward. An observer on the earth will perceive a brightness which will be proportional to the numbers in column 6, divided by the square of the distance from the earth to the planet? (Why?). Each planet will appear brightest when its distance from the earth is smallest—that is, when it is at a distance equal to its distance from the sun (in AU) minus one, when (in other words) the planet and earth are in conjunction. Fill in column 7.

(1) Planet	(2) Relative diameter	(3) Dist. from sun, AU	(4) (Diam)^2 = rel. area	(5) (Dist)^2	(6) $\frac{(Area)}{(Dist)^2}$	(7) Relative brightness
Mars	0.52	1.52				
Jupiter	10.97	5.2				
Saturn	9.03	9.6				
Uranus	3.72	19.6				
Neptune	3.38	30.1				
Pluto	0.45 ?	39.5				

The numbers in column 7 provide a rough estimate of the relative brightnesses of the six planets to an observer on earth. A *rough* estimate, because the actual fraction of light reflected by each planet is not the same. It ranges from about 15% for Mars to about 60% for Jupiter, Saturn, Uranus, and Neptune.

Uranus is just barely visible to the naked eye. The numbers in Column 7 should suggest why Neptune was not known to the ancients, and why Pluto was hard to find even with large telescopes.

1.6 Neptune has a diameter of about 28,000 miles. It is 30.1 astronomical units from the Sun. One astronomical unit is 93,000,000 miles. From these data compute the apparent angular diameter of Neptune as viewed from the most advantageous position along the earth's orbit. You may give your result in radians and/or degrees or minutes or seconds of arc.

1.7 There have been several examples in science of brilliant ideas or discoveries which have not been taken seriously for some time after they were originally produced or observed. Both Adams and Leverrier had difficulties in getting anyone to search for the theoretically "discovered" planet. How can one decide whether or not to take such "discoveries" seriously, particularly when taking them seriously requires considerable work and time to be taken away from other important work? For example, any college or university physics department gets mail every week or so from persons who claim to have invented a new theory of atomic structure, or a new theory of gravitation, or a disproof of Einstein's theory of relativity. One has little, if any, time to give to the writers' requests that one "check my calculations" or "teach my theory to your students," or "help me get this published." On the other hand, one does not want to be laughed at for several decades as was the stuffy Astronomer Royal who refused to pay attention to the relatively unknown John Couch Adams. What criteria can one use, if any, to "filter out" from the deluge of so called "crank letters" the potentially important one or two?

STUDY GUIDE

Suggestions for Further Reading

Armitage, Angus, *A Century of Astronomy.* London: Low, Marston and Co., Ltd., 1950. An introduction to the developments in astronomy from 1850 to 1950, including the discoveries of Uranus, Neptune and Pluto.

Gingerich, Owen, "The Solar System Beyond Neptune," *Scientific American,* Vol. 200, No. 4 (April 1959). Recounts the discovery of Pluto.

Grosser, Morton, *The Discovery of Neptune.* Cambridge: Harvard University Press, 1962. A detailed account of the discovery of Neptune.

Rawlins, Dennis, "The Mysterious Case of the Planet Pluto," *Sky and Telescope* (March 1968). Reviews the coincidences in Tombaugh's discovery and discusses current evidence for the mass of Pluto and the possibilities for finding an improved value for its mass.

Tombaugh, Clyde W., "The Discovery of Pluto," *Source Book in Astronomy, 1900–1950.* Harlow Shapley, editor. Cambridge: Harvard University Press, 1960. The author's account of his work.

Tombaugh, "The Trans-Neptunian Planet Search," *The Solar System,* Gerard P. Kuiper and Barbara M. Middlehurst, editors, Vol. 3, University of Chicago Press, 1961. Details of the photograph search that led to the discovery of Pluto. The author also describes subsequent work and discusses the difficulties of extending the search to fainter objects.

Watson, Fletcher, *Between the Planets,* Garden City: Doubleday, 1962. Treats the origins, orbits, and composition of comets, asteroids, meteors, and meteorites.

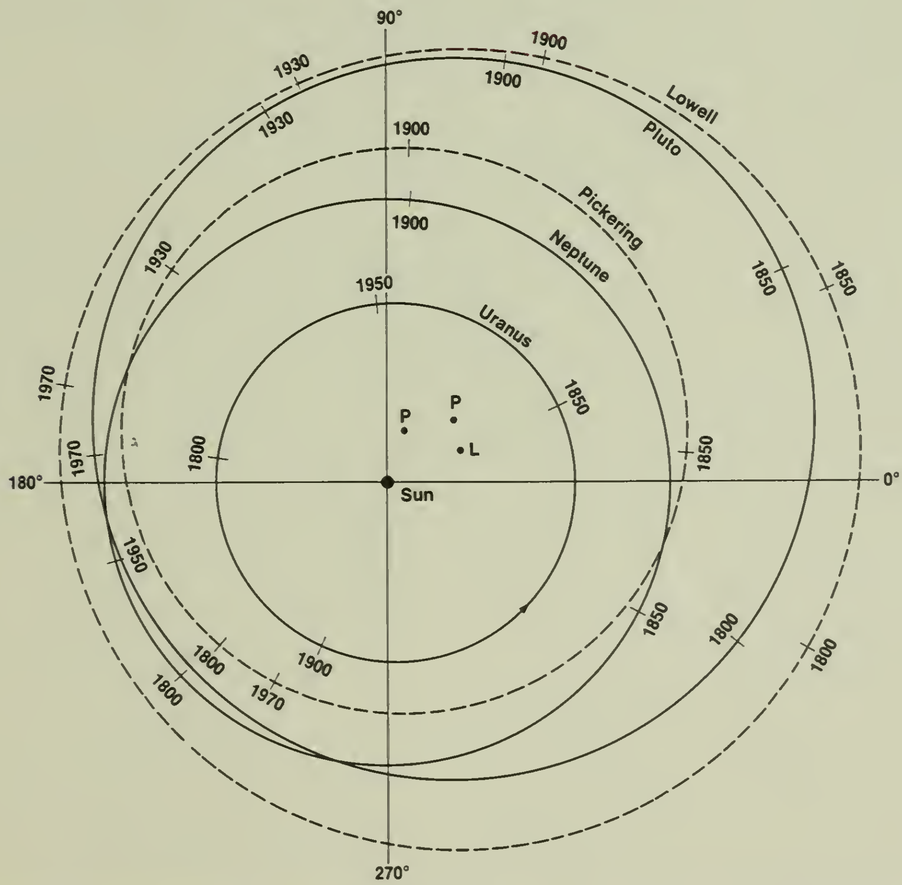


Fig. 1-15 Final orbits for trans-Neptunian planet predicted by Lowell in 1914, and Pickering in 1928, compared to orbit of Pluto.

EXPERIMENT

In this chapter you have read about the way in which deviations from the expected motion of Uranus were interpreted as resulting from the gravitational attraction of an outer and undiscovered planet. This laboratory experience will allow you to get a feel for the perturbations of a small planet by a large planet. To get first hand experience with such perturbations, we can use the method of graphical iteration.

Imagine a body under uniform motion. A dry ice disc moving on a horizontal surface could be one example. In Fig. 1-16, let xy represent in magnitude and direction the velocity of the body for a short interval of time.

Fig. 1-16

Q 1. Where would you locate the position of the body at the end of the second interval of time? Now assume that at y the body is subjected to two forces acting simultaneously for a short and equal interval of time pulling the body in the directions represented in Figure 1-17 by the arrows a and b. The length of the arrows are proportional to the changes in velocities produced by the respective forces during the very short interval of time.

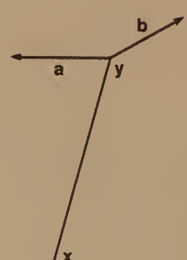


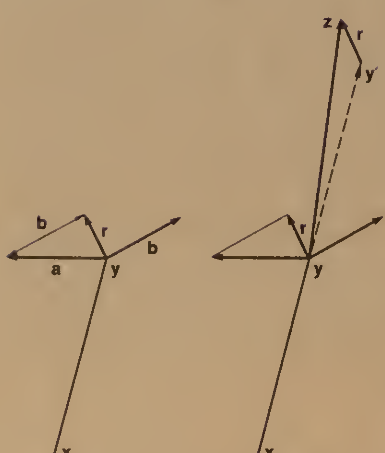
Fig. 1-17

Q 2. In what direction will the body move from the point y?

Q 3. Would the speed of the body change? If it does, would it increase or decrease?

Construction of a vector diagram, showing the direction and magnitude of the motion of the body during the second interval of time, may help you to answer the two previous questions more accurately. (This is the same analysis used by Newton.) You need to add two separate vectors. First find the resultant of the vectors a and b (Figure 1-18 left) and call this resultant r. Then extend xy an equal length to point y'. Had there been no forces acting on the body at y, it would have reached y' at the end of the second interval. (Remember the body was moving uniformly. (To find the new position we must add the resultant r and xy' (Figure 1-18 right) which gives the magnitude and direction of the velocity of the body.

If you can perform these vector additions without any difficulty, you are ready to plot the perturbed orbit of the small planet.



a b
Fig. 1-18

Initial Conditions

First we must decide what starting conditions to choose and the magnitude of the gravitational forces acting. Let us take a small planet of negligible mass, like an asteroid, initially moving in a circular orbit 3.1 AU from the sun. For the large planet let us take a body with 1/100 the mass of the sun moving in a circular orbit at 4 AU. Since the mass of the large planet is far more than that of the small one, we assume that the gravitational attraction of the small planet will not modify the motion of the large planet; but the gravitational attraction of the large planet will modify the orbit of the small planet when they are near.

Thus the small planet in orbit has two continuous forces acting on it when it is near conjunction with the large planet; the gravitational attractions of the sun and of the large planet. As the small planet moves, the magnitude and direction of these two forces change. Determination of the exact orbit of the small planet under the influence of these continually changing forces is exceedingly complicated. However, you can get a reasonable approximation to the orbit by breaking the continuous attractions into many small steps, in which the two forces act as two sharp 'pulls', one toward the sun and the other toward the large planet, once every sixty days. The magnitude of each brief pull is assumed to equal the total effect of the continuous attraction of the large planet or the sun throughout a 60-day interval. Thus the continually changing complex motion of the planet has been made to look as simple as the motion of the uniformly moving body we saw in our thought experiment at the beginning. All that we need to know to plot the orbit are the initial velocity of the planet and the magnitude and direction of the pulls (vectors a and b).

Scale

We can adopt the same scale for plotting as we did in Experiment 21 of Unit 2 in which 2.5 inches or 6.35 cms represent 1 AU.

Because the small planet does not perturb the large planet, you can step off its positions in its circular orbit at 60-day intervals. If the mean distance of the large planet from the sun is 4 AU, what is its period in days? What fraction of the period is 60 days? How many degrees around the sun will the large planet move in each 60-day interval? What is the speed of the large planet in AU/60 days? Expressed in the scale of your plot (inches or cms), what is this speed?

If there were no large planet, what would be the period of the small planet moving in circular orbit about the sun at 3.1 AU? What fraction of its period is 60 days? How many degrees around the sun will it move in each 60-day interval? What is the speed of the small planet in AU/60-days? What is this speed expressed in the scale of your plot (inches or cms)?

Effect of the force of attraction

From Newton's second law you know that the gravitational force will cause the small planet to accelerate toward the center of the source of attraction. If a force $\vec{F}$ acts for a time interval Δt on a body of mass m, you know that

$$\vec{F} = m\vec{a} = m\frac{\Delta\vec{v}}{\Delta t}$$

and therefore

$$\Delta\vec{v} = \frac{\vec{F}}{m}\,\Delta t$$

In the last equation the mass m and the change in time Δt are constant. Therefore the change in velocity is proportional to the gravitational attraction.

Computing Δv

On the scale and with the 60 day iteration interval chosen, the force field of the sun is such that the Δv given by the pull when the small planet is 1 AU from the sun is 1 AU/60 days.

To avoid computing Δv for each position of the small planet we can plot Δv against the distance R on a graph. Then for any value of R you can find the value of Δv.

Table 1 gives the values of R in AU and in inches and cms to fit the scale of your orbit plot. The table also gives for each value of R the corresponding value of Δv in AU/60-days, and in inches and cms to fit the scale of your orbit plot.

TABLE 1

Effects of the Sun's Attraction

Distance from Sun, R			Change in speed, Δv		
AU	inches	*cm*	AU/60days	inches	*cm*
0.75	1.87	*4.75*	1.76	4.40	*11.3*
0.8	2.00	*5.08*	1.57	3.92	*9.97*
0.9	2.25	*5.72*	1.23	3.07	*7.80*
1.0	2.50	*6.35*	1.00	2.50	*6.35*
1.2	3.0	*7.62*	0.69	1.72	*4.37*
1.5	3.75	*9.52*	0.44	1.10	*2.80*
2.0	5.0	*12.7*	0.25	0.62	*1.57*
2.5	6.25	*15.9*	0.16	0.40	*1.02*
3.0	7.50	*19.1*	0.11	0.28	*0.71*
3.5	8.75	*22.2*	0.08	0.20	*0.51*
4.0	10.00	*25.4*	0.06	0.15	*0.38*

Since we have taken the mass of the large planet to be 1/100 that of the sun, at 1/10 the distance it will exert on the small planet the same force as the sun does. Thus replotting of the sun's effect at 1/10 the distance can be used for establishing the perturbing effects of the large planet. Table 2 gives the distance of the small planet from the large planet and the corresponding values of Δv. It is convenient to plot both the graphs on the same graph paper.

TABLE 2

Effects of the Large Planet's Attraction

Distance from large planet			Change in speed, Δv		
AU	inches	*cm*	AU/60days	inches	*cm*
0.075	0.187	*0.475*	1.76	4.40	*11.3*
0.08	0.200	*0.508*	1.57	3.92	*9.97*
0.09	0.225	*0.572*	1.23	3.07	*7.80*
0.10	0.250	*0.635*	1.00	2.50	*6.35*
0.12	0.30	*0.762*	0.69	1.72	*4.37*
0.15	0.375	*0.952*	0.44	1.10	*2.80*
0.20	0.50	*1.27*	0.25	0.62	*1.57*
0.25	0.625	*1.59*	0.16	0.40	*1.02*
0.30	0.750	*1.91*	0.11	0.28	*0.71*
0.35	0.875	*2.22*	0.08	0.20	*0.51*
0.40	1.00	*2.54*	0.06	0.15	*0.38*
0.45	1.125	*2.86*	0.049	0.123	*0.31*
0.50	1.25	*3.18*	0.04	0.10	*0.254*
0.60	1.5	*3.81*	0.028	0.07	*0.18*
0.70	1.75	*4.45*	0.020	0.05	*0.13*
0.80	2.00	*5.08*	0.016	0.04	*0.10*
1.00	2.50	*6.35*	0.010	0.025	*0.064*

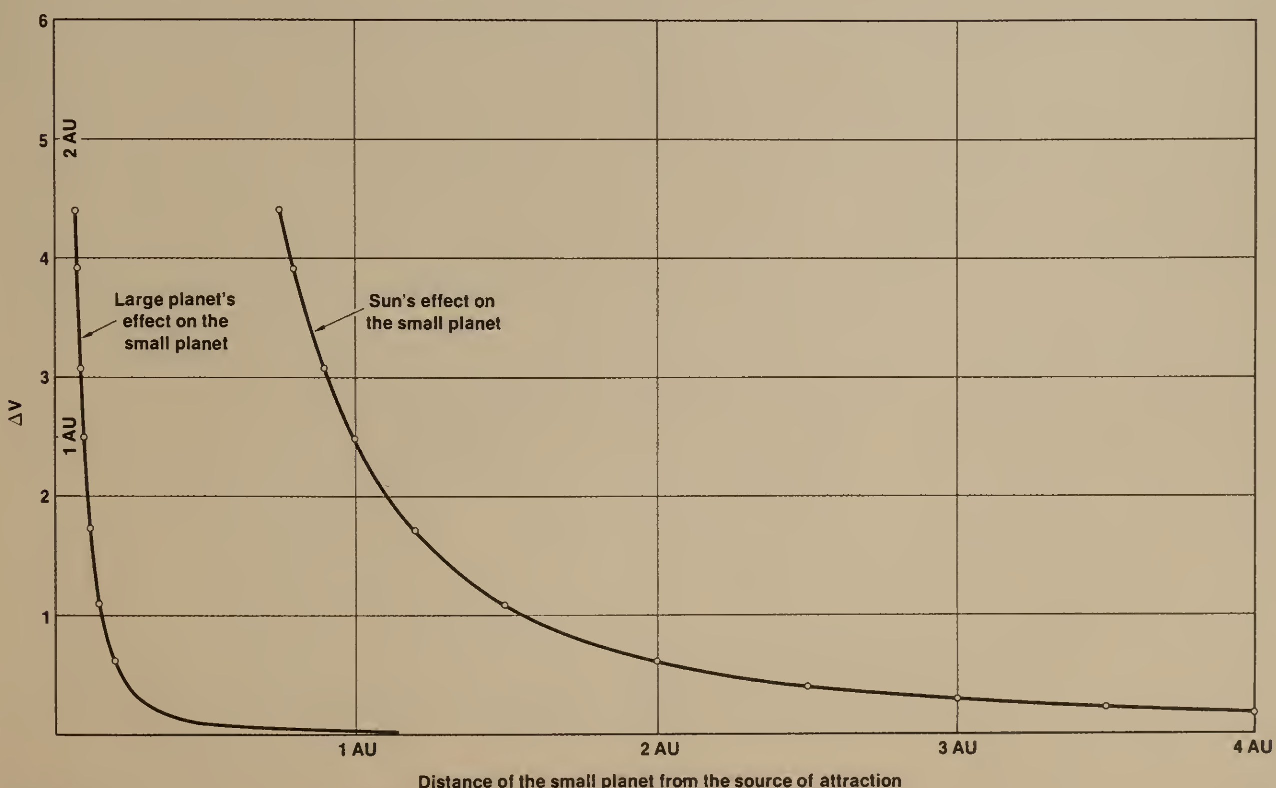


Fig. 1-19

Starting the plot

To start the plot we need to locate the two planets and the sun. Also we shall need the expected unperturbed positions of the planets at 60-day intervals.

On a large sheet of graph paper (16″ by 21″) make a dot, to represent the sun, in approximately the center as shown in Fig. 1-20. With this 'sun' as the center draw two concentric circles of radius 10″ (25.4 cms) for the large planet L, and 7.75″ (19.7 cms) for the small planet S. The two circles represent the initial orbits of the two planets. From the 'sun' draw a straight line to intersect the orbits of the two planets as shown in Fig. 1-20.

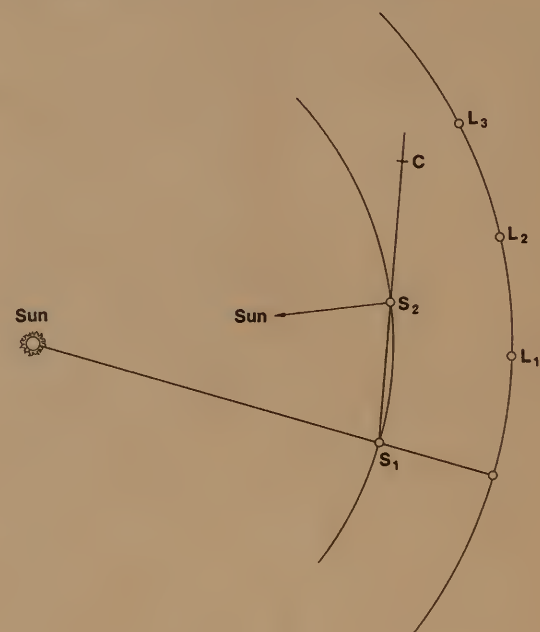


Fig. 1-20

Along the orbit of the large planet, from the point of intersection step off the positions of the large planet at 60-day intervals. Similarly locate unperturbed positions at 60-day intervals along the orbit of the small planet. These are the positions at which it would have been if there had been no perturbation by the large planet. See Fig. 1-20.

Let us assume that at the beginning of our observation the large planet is in one position or 60 days ahead of the small planet, which therefore is being pulled forward. Mark the starting positions of the small and the large planets S_1 and L_1 respectively. See Fig. 1-21.

It is important for us to start the small planet moving properly in its circular ortbit. To do this, draw a line from the point S_1 to the second point (call it S_2), which it would reach after 60 days. This line S_1S_2 is the initial velocity vector. Extend S_1S_2 an equal length to a point marked C to which the small planet would move if it were not attracted toward the sun or the large planet.

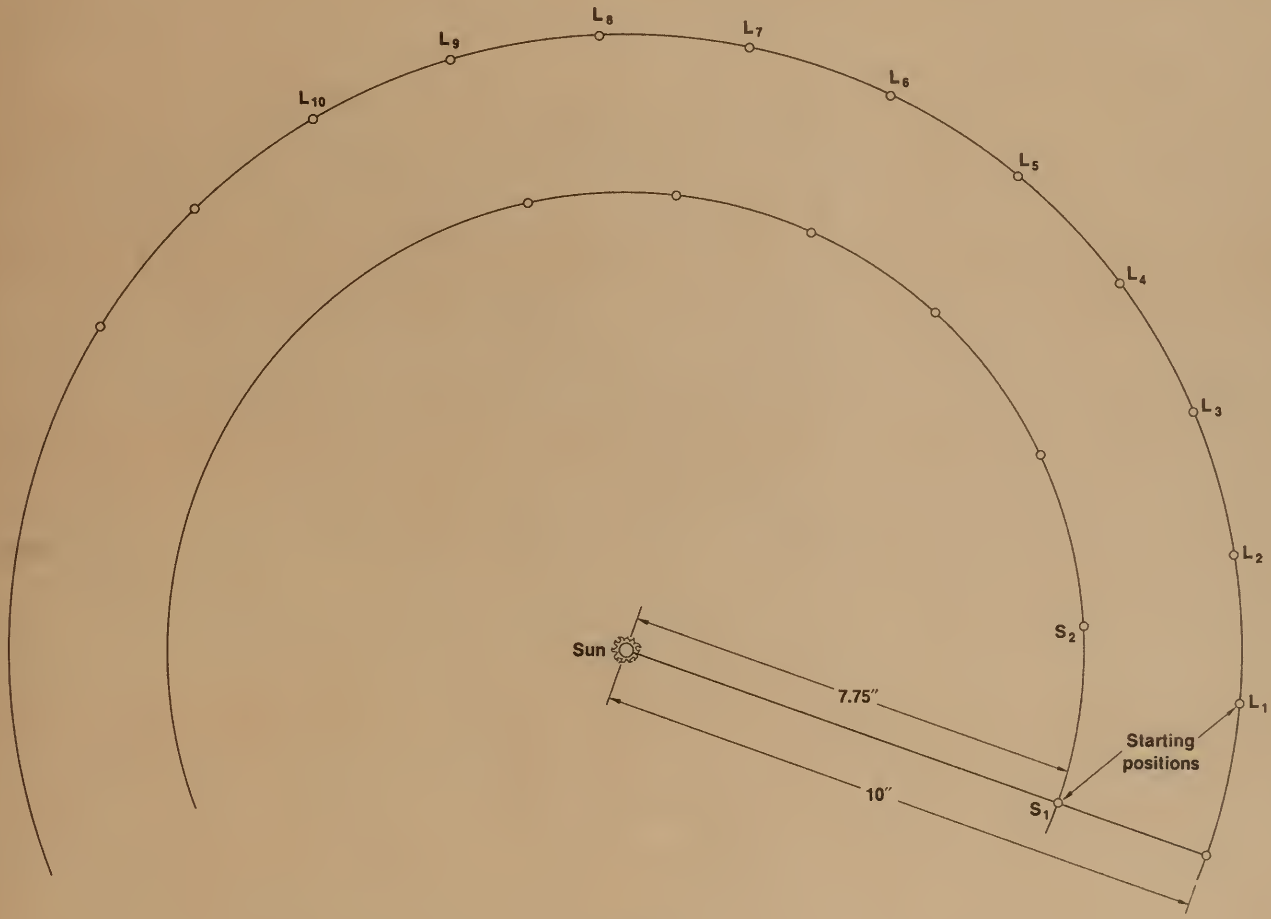


Fig. 1-21

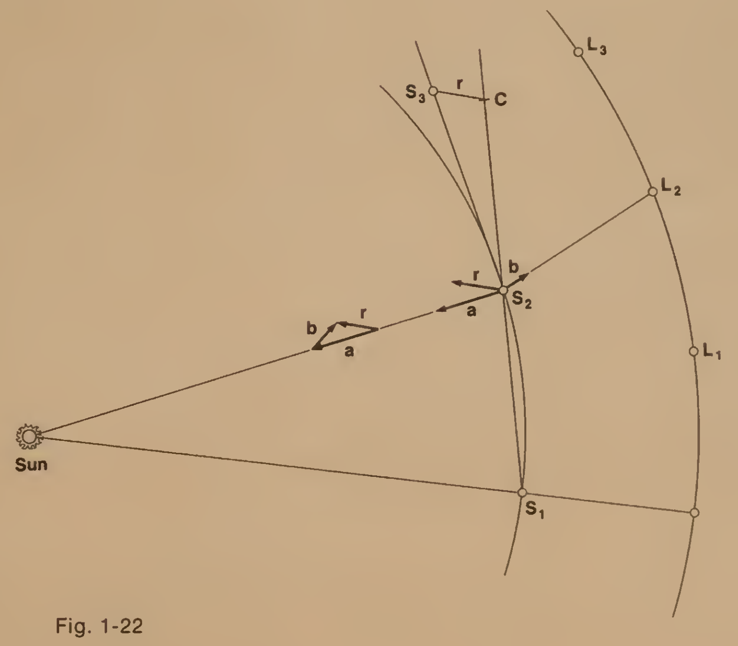


Fig. 1-22

The small planet moves from S_1 to S_2 with its initial velocity. At point S_2 we apply vectorially the total effects of the continuous attractions of the sun and the large planet throughout the 60 day interval as two pulls, one toward the sun and the other toward the large planet at its second position L_2. The vector addition of these two pulls will determine how the velocity of the small planet is changed. Use the graphical plotter to derive the effective pull toward the sun. (If you have forgotten, see Figures 1-17a and b). Then use the plotter to determine the effective pull toward the large planet at its second orbital position L_2. Plot the change in velocity vector toward the sun and then graphically add the velocity vector toward the large planet to obtain the resultant effect.

Apply the resultant (R) of these two attractions to the small planet's vector at point C and locate the new position S_3 on its orbit.

Extend the line S_2S_3 for an equal length to point D. Find for point S_3 the effective pulls towards the sun and toward the large planet, at its third position L_3. Add the vectors and apply the resultant to D to establish S_4.

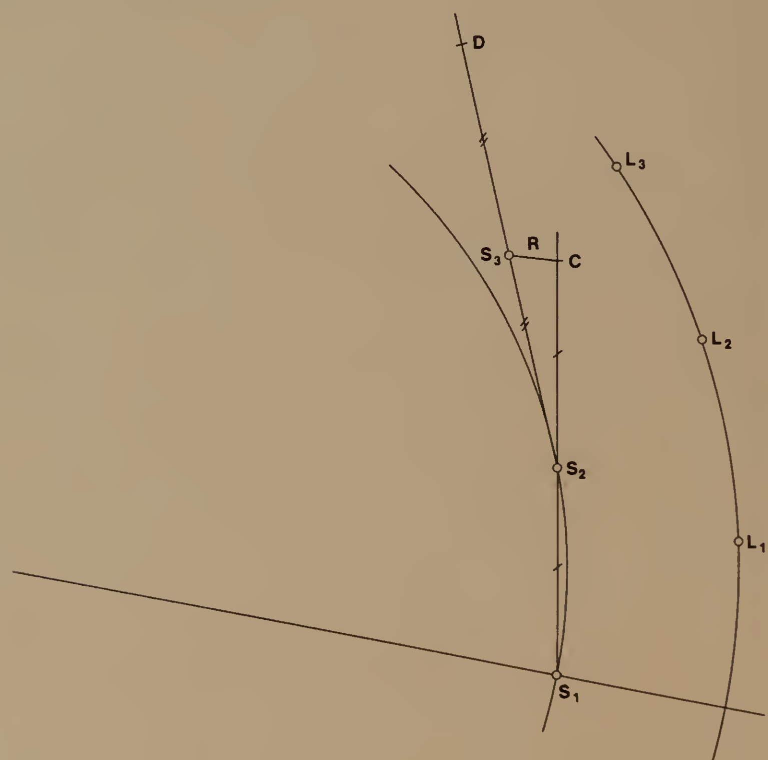


Fig. 1-23

Continue the above process for at least twenty steps.

How to use the Graphic Computer

Cut off the bottom margin of the graph paper, or fold it under along the R axis. Lay this edge on the orbit plot with zero at the sun, then move along R to distance from the sun to the small planet. With a pair of dividers pick off the value of Δv corresponding to this R from the curve showing the sun's effect on the small planet. Lay off this distance along the radial line toward the sun.

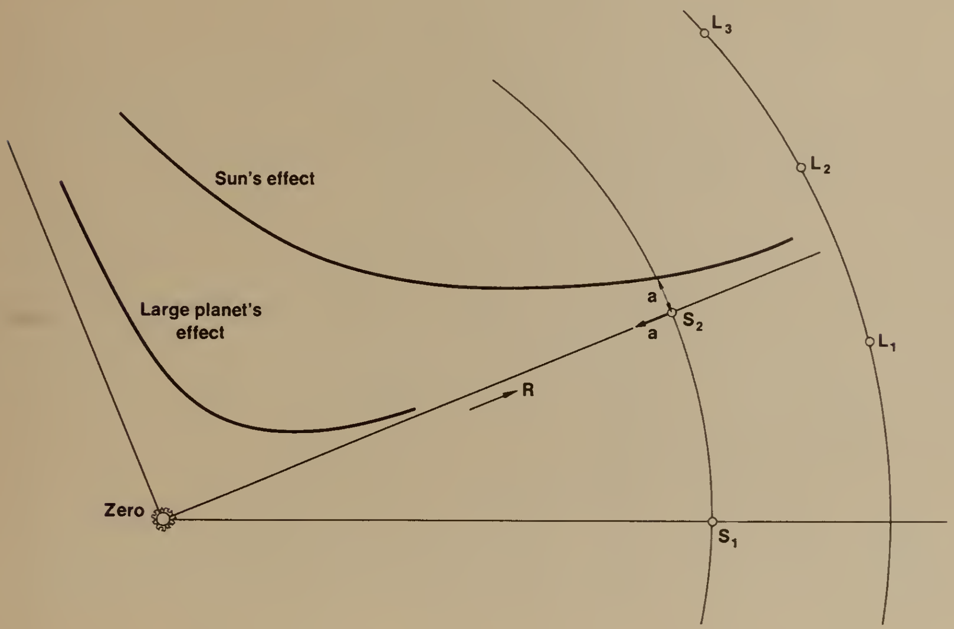


Fig. 1-24 Use of graphical plot to give gravitational effect of sun on small planet.

Similarly place the zero point at the small planet and, for the distance to the large planet, find the Δv corresponding to this distance from the large planet curve. Lay off this distance along the line joining the corresponding positions of the two planets. (Why doesn't it matter whether you put the zero point at the large planet or the small planet?)

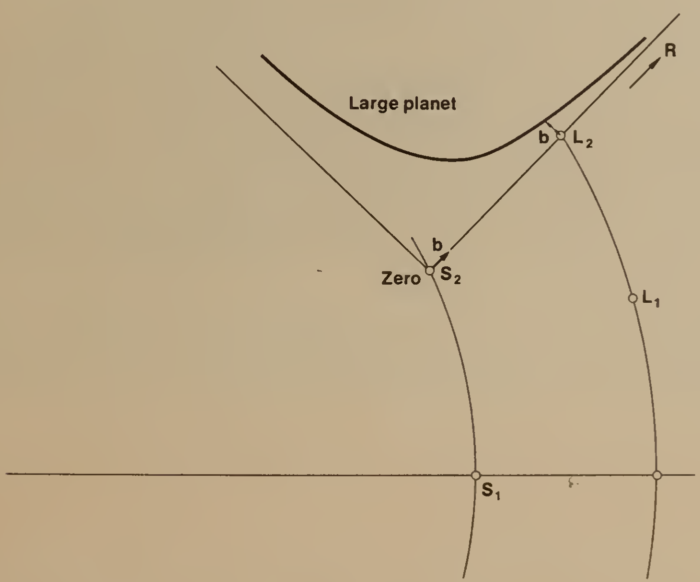


Fig. 1-25 Use of graphical plot to give gravitational effect of large planet on small planet.

As you can see from the graphical computer, the perturbing effect of the large planet becomes insigificant when the distance between the two planets becomes greater than 1 AU. Thus if you want to carry the orbit of the small planet beyond its 21st position and make one complete trip around the sun, you will only have to take into consideration the gravitational attraction of the sun.

If you do not develop the orbit past point 21, you can get some idea of the total orbit by plotting the following approximate points: All angles are measured in a *clockwise* direction from the line passing through the sun and point S_1.

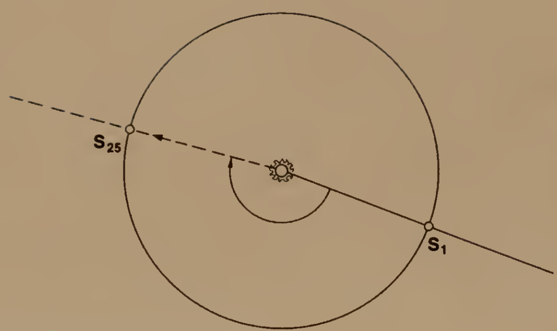


Fig. 1-26

Position	Dist. from Sun	Angle from S_1
S_{21}	3.25 AU	215°
S_{25}	2.30	174
S_{28}	1.36	98
S_{29}	1.27	48
Perihelion	1.25	63
Aphelion	3.25	241

Q 1. What is the average distance of the small planet from the sun in the new orbit?

Q 2. What is the new period in years?

Q 3. What is the eccentricity of the new orbit?

Q 4. Would you expect the small planet to follow this new orbit for as long as 100 years? Why?

Q 5. Within how many years will the small planet and the large planet again come fairly near together?

Q 6. Suppose that you were at the sun and could not for some reason, see the large planet. You knew of the small planet and expected it to move uniformly in the circular orbit. What unexpected results would you observe in its motion across the sky after it passed through the point S_3?

Q 7. Consider the orbit you constructed in three sections: From S_1 to S_4, from S_4 to S_{15}, and beyond S_{15}. In a few words describe the differences you observe in the motion of the small planet in each of these three sections.

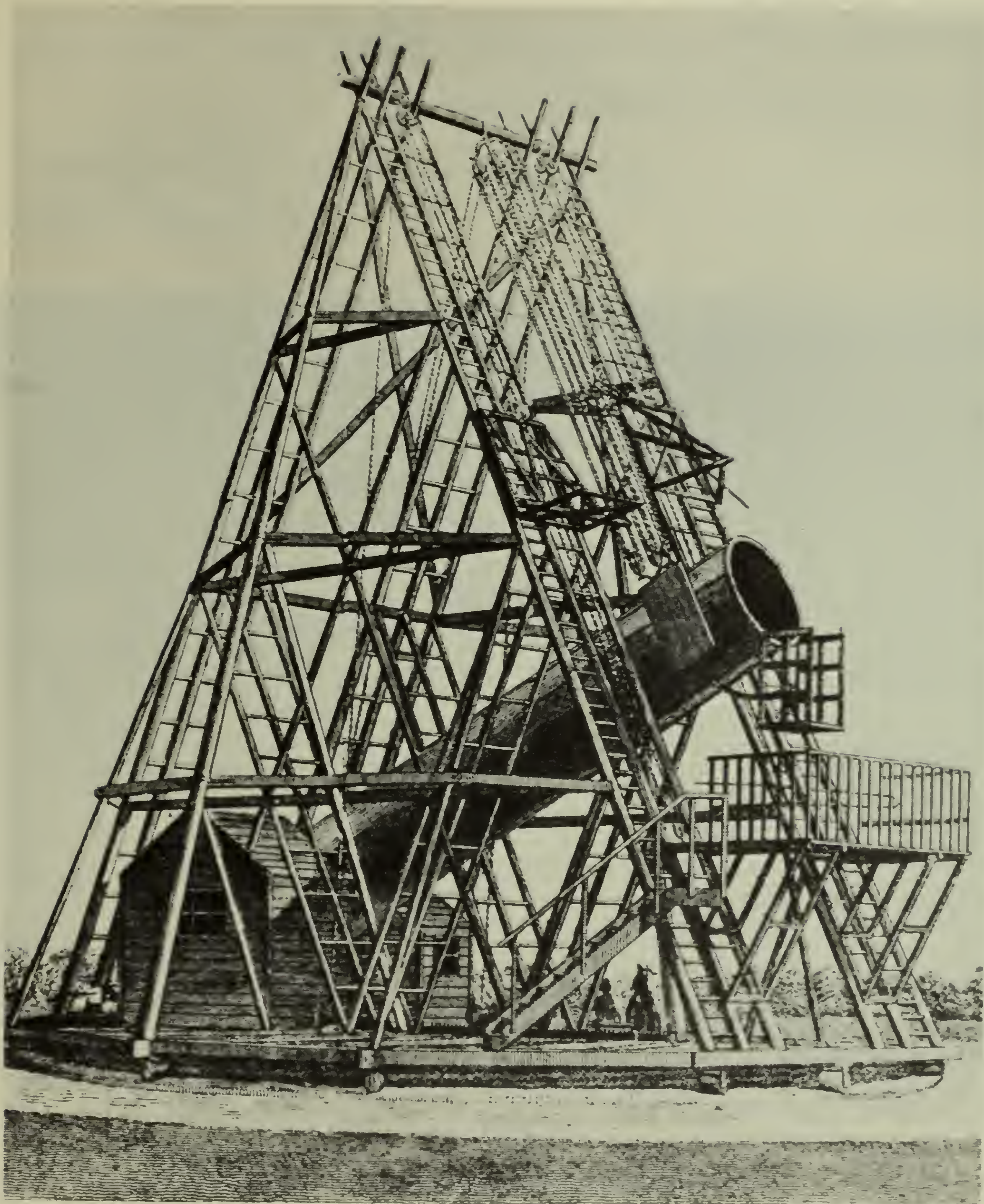


Fig. 1-27 The English astronomer, William Herschel, the discoverer of the planet Uranus, built this giant but unwieldy 40-foot reflecting telescope which had a 4-foot mirror.

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S.W. Richardson. J. Henry.

E.B.H. Wade. G.A. Shakespear. C.T.R. Wilson. E. Rutherford. W. Craig-Henderson. J.H. Vincent. G.B. Bryan.

J.C. McClelland. C. Child. P. Langevin. Prof. J.J. Thomson. J. Zeleny. R.S. Willows. H.A. Wilson. J. Townsend.

Professor J. J. Thomson in 1898 with research students who contributed to many discoveries, including the electron.

CHAPTER TWO

Cathode Rays and the Discovery of the Electron

2.1 The discovery of cathode rays

For a quick review, see Unit 5, Section 18.2 of the Project Physics *Text*.

The discovery that cathode rays could be produced under certain circumstances occurred in 1858, very soon after the technology of vacuum pumps had been greatly improved. The controversy that soon arose as to the *nature* of cathode rays, in contrast, took many years to settle. This chapter will be concerned primarily with that controversy.

First, however, we must consider the initial discovery of the rays themselves. As far back as 1748, scientists had carried out experiments to find out what happens to an electric spark when the pressure of the surrounding air is reduced. Air pumps were rather primitive, but by 1800 the pressure in a glass tube could be reduced sufficiently for a current to pass between electrodes at the two ends of the tube, as a glow that filled the tube rather than as a thin streak, or spark. (Such tubes were the predecessors of the modern neon sign tubes.) Then in 1855 a new kind of vacuum pump was invented which used a column of mercury as a piston to avoid the use of leaky pistons. With these new pumps the pressure could be decreased to one-thousandth of the normal atmospheric pressure, or even less.

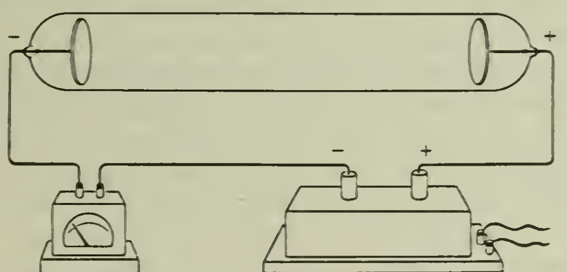


Fig. 2-2 A schematic diagram of a Plücker tube used to study electric currents conducted through gases at low pressures.

A German physicist, Julius Plücker, and his student Hittorf used such a pump to evacuate a glass tube fitted with sealed electrodes at each end, as shown in Fig. 2-2. When the electrodes were connected to a source of high electrical potential, such as an induction coil, Plücker and Hittorf found that the usual reddish glow of the gas, visible when the air pressure in the tube was moderately low, all but disappeared when the pressure was made as low as possible by the new pumps. However, the glass at the end of the tube opposite the negative electrode glowed with a strange greenish fluorescence. By further experimenting they found that this fluorescence was caused by rays of some sort coming from the negative electrode, or cathode – hence the name cathode ray. They also found that the rays traveled in straight lines, and were deflected by magnetic fields. This was a new type of phenomenon that caused considerable excitement.

Other physicists began studying the rays. Goldstein, another German physicist, published in 1871 reports of a series of experiments that showed that the rays are emitted perpendicularly from the surface of the cathode. This meant that the rays could be concentrated or focused by use of cathodes with a concave shape. Goldstein also found that the properties of the rays did not seem to depend on the chemical nature of the cathode material; the rays behaved the same way for all sorts of cathodes. He also found that the rays could produce chemical reactions similar to the photochemical reactions produced by ultraviolet light.

2.2 The wave theory of cathode rays

What was the nature of these rays? As often happens, two types of explanations were proposed. One group thought that the rays were beams of electromagnetic radiation. James C. Maxwell, a British physicist, had just been brilliantly successful in showing that all the known properties of light waves could be described in terms of electromagnetic waves. Maxwell's equations were based on the assumption that electric currents were continuous – that is, smoothly variable, without granularity.

This assumption did not automatically rule out the possibility that there might be some exceedingly fine granularity to electricity, any more than the equations of hydrodynamics (which describe, for example, the flow of water in a pipe) rule out the possibility that water is composed of molecules. But since there was then no experimental evidence for any granular structure of electrical charge, and since Maxwell's equations were so successful in describing a vast array of electrical, magnetic, and optical phenomena, an explanation in terms of electromagnetic waves was appealing. Furthermore, most of the observable properties of cathode rays were certainly also the observable properties of beams of light. Although beams of light were not bent by magnetic fields as cathode ray beams were, this bending was the only property in which light rays and cathode rays seemed to differ significantly.

But even then, it was known that magnetic fields do have *some* effect on the transmission of light beams. If you send a beam of polarized light through certain materials within a magnetic field, the plane of polarization will be shifted when the field is changed. Thus the proponents of the wave theory thought that perhaps cathode rays could be some new and peculiar form of electromagnetic waves that could be deflected by magnetic fields.

Fig. 2-3 William Crookes (1832–1919) the English radiologist. This photograph was taken around 1910.

2.3 A particle theory is proposed

In 1879, Sir William Crookes, one of the leaders of a group of English physicists, showed that cathode rays could heat up thin foils and could exert enough force to move thin vanes. (Light can do the same things.) Crookes, unlike many of his colleagues, believed that these cathode rays were streams of negatively charged particles—negatively charged because of the way the rays were deflected in a magnetic field. He went on to suggest a possible mechanism by which the rays might be formed. He suggested that molecules of the residual gas in the tube, upon hitting the cathode, might pick up a negative charge. They would then be strongly repelled by the cathode. These molecules might behave in the same way as small bits of paper, originally electrically neutral, are sometimes attracted to a negatively charged plastic rod (or pocket comb) and then suddenly repelled vigorously when they have acquired some of the negative charge. The cathode ray beam, Crookes thought, might well be composed, as he put it, of a "torrent" of negatively charged molecules. Such an hypothesis could account for many of the known properties of the rays. Thus the two alternate explanations: electromagnetic waves or particles, developed.

But opponents of the particle theory quickly thought of an objection to Crookes' idea. Goldstein pointed out that the mean free path of a molecule, charged or uncharged, in Crookes' cathode ray tubes would be about 0.6 cm—about 1/4 inch, far less than the length of the tubes. If we know the pressure and density of a gas and the diameter of the gas molecules, we can calculate the mean free path of the molecules. Even with the good vacuums Crookes was able to achieve, enough residual gas molecules remained for their mean free path to be only slightly more than half a centimeter. Thus Crookes' hypothetical negatively charged molecules would have approximately 150 collisions before hitting the glass at the far end of the tube from the cathode. The observed straight-line travel of the beam, under such circumstances, was clearly impossible. Crookes replied that perhaps the torrent of molecules simply pushed the other, randomly moving molecules out of the way. One might think, for example, of a squad of rapidly moving soldiers pushing a milling mob of onlookers off to the side.

But another argument against Crookes' hypothesis was provided by the faint glow emitted from the beam itself. If the glow came from

The mean free path of a particle in a gas is the average distance a particle travels between collisions with other particles. The mean free path running the 100-yard dash is usually more than 100 yards. The mean free path of a blindfolded person trying to run across New York's Times Square at midnight on New Year's Eve would be perhaps two feet.

At ordinary temperatures and pressures, the mean free path of a molecule in air is about 1/100,000 of a centimeter.

Notice the argument by analogy.

In modern tubes one sees little, if any, such glow. But in the 1870's vacuum pumps were less effective, and a glow due to the residual gas was quite common.

For a review of the Doppler shift, see Section 12.11 in Unit 3 of the Project Physics *Text.*

Crookes' "torrent of molecules," the wavelength of spectral lines, observed when light from that glow was sent through a spectroscope, should be shifted by the Doppler effect as shown in Fig. 2-4. However, no such shifts were observed in the spectral lines of the light from the cathode ray glow. Actually this argument against the "torrent" model is relevant only if the glow is assumed to be produced by the particles moving in the torrent. We now know that the glow is produced by ordinary gas molecules, which just happened to be standing around, as it were, in the path of the beam.

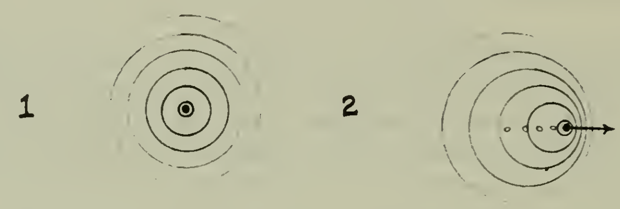


Fig. 2-4 (1) When a source of waves is stationary, the waves emitted in all directions have the same wavelength. (2) However, when the source of waves is moving, the wavelengths ahead of the source become shorter and those behind become longer. Such a Doppler shift for a moving source occurs for electromagnetic waves as well as for sound waves.

2.4 Properties of the particles: Schuster's calculations

By 1884, another Englishman, Arthur Schuster, had carried out some experiments which supported the particle model. Schuster suggested that the cathode ray beams might not be composed of whole molecules that had acquired a negative charge at the cathode, but rather of negatively charged fragments of molecules that had broken up on hitting the cathode. Schuster further pointed out that the observable bending of the beam in a magnetic field could be turned into a quantitative experiment which would give information about the particles. In a magnetic field, B, perpendicular to their line of motion, charged particles of a given speed will move in a path which is part of a circle of radius R. (R can be determined by observation of a faint glow along the beam, if some gas is present, or by observing the endpoint of the beam as it hits a fluorescent screen.) If we assume that gravitation and other forces may be neglected, the centripetal force which bends each particle into a circular path must be provided by the magnetic force of the field on the moving particle. By equating the centripetal force to the magnetic force, we may write

$$F_{mag} = F_{cent} \tag{2.1}$$

$$Bqv = \frac{mv^2}{R} \tag{2.2}$$

in which m is the mass of the particle, q its charge, and v its speed. Equation (2.2) can be rearranged to give

$$\frac{q}{m} = \frac{v}{BR} \tag{2.3}$$

This equation says, then, that the ratio q/m of the charge to the mass of the beam particles (presumably an intrinsic characteristic of the particles) can be expressed in terms of B and R and of v, the speed of the particles. Both R and B could be measured; the difficulty was in determining or estimating the value of v.

By 1890 Schuster had established upper and lower limits for the magnitude of q/m. By assuming that all the energy, V_q, acquired by the charged particles from the electric field between the cathode and the anode (of potential difference V) is turned into kinetic energy of the particles, $1/2mv^2$, he could write another relationship:

$$Vq = \tfrac{1}{2}mv^2 \tag{2.4}$$

Since some of the energy provided by the electric field might be lost in collisions or other processes, Schuster could be sure that the original energy of the charged particles equalled or exceeded their final kinetic energy, or

$$Vq \geqq \tfrac{1}{2}mv^2 \tag{2.5}$$

This second relationship between q/m and v could be used simultaneously with Eq. (2.3) to find numerical values of q/m and v, in terms of measurable quantities. In this way, Schuster was able to conclude that q/m was not greater than about 10^{10} coulombs/kilogram (coul/kg).

To determine a lower limit for q/m, Schuster assumed that the speed of the beam particles would surely be greater than that of the residual gas molecules. The average speed of such molecules could be computed by use of the kinetic theory of gases and is about 1000 m/sec for hydrogen molecules at room temperature. This value for v, inserted in Eq. (2.3), gives 5×10^6 coul/kg as a lower limit for q/m. Admittedly, it is not completely satisfying merely to know that an important physical characteristic of the particles—their ratio of charge to mass—is between two values so far apart as 5×10^6 and 10^{10} coul/kg. However, even such limited knowledge is better than no knowledge at all. Schuster pointed out that by electrolysis the ratio of charge to mass for hydrogen atoms had been found to be about 10^8 coul/kg, which is in the middle of his range of possible values for the q/m ratio for cathode ray particles. Hence the idea that cathode ray particles were charged molecules, or fragments of molecules, is to some extent supported by his results.

2.5 Hertz' experiments in support of the wave theory

The German physicists, being firm believers in the wave theory of cathode rays, began a brilliant series of experiments designed to contradict the particle theory and to support the idea that the rays carried no charge and were in fact some form of electromagnetic ray.

In 1877 Heinrich Hertz had succeeded in demonstrating the existence of the electromagnetic waves that Maxwell had predicted would be emitted by oscillating electric charges, and in showing that these waves had the properties predicted by Maxwell. Beginning in 1883, he and his colleagues carried out several experiments with cathode rays. In one experiment, Hertz used a cathode ray "tube" consisting of two flat glass plates about 1 cm apart and 12 cm square. In one arrangement of such a tube, the cathode and anode were situated as shown in Fig. 2-6. By measuring the magnetic field (presumably due to the flow of electrical charge from C to A) outside the tube, Hertz found that the current followed the curved paths between cathode and anode indicated by solid lines in the diagram. From the location of the fluorescence on the glass he concluded that the cathode rays moved along the straight lines indicated by the dotted path. This experiment seemed to show quite conclusively that the flow of electricity was unrelated to the direction of the cathode ray beam.

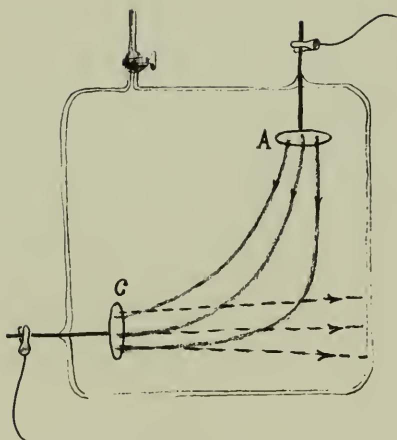


Fig. 2-5 A sketch showing an arrangement of the cathode-anode terminals for an experiment of the type conducted by Hertz to demonstrate the electromagnetic characteristics of cathode rays.

Hertz did another expermiment, this one designed to detect the charge, if any, carried by the cathode ray beam. He designed a tube with the cathode and anode at the same end (what we would now call a cathode ray gun), arranged, as in Fig. 2-7, to project a beam of cathode rays down toward the other end of the tube. The end of the tube could be inserted into a shielded metal container inside which was an insulated metal can or collector electrode connected to a sensitive electrometer. (An electrometer is a charge-detecting and measuring device.)

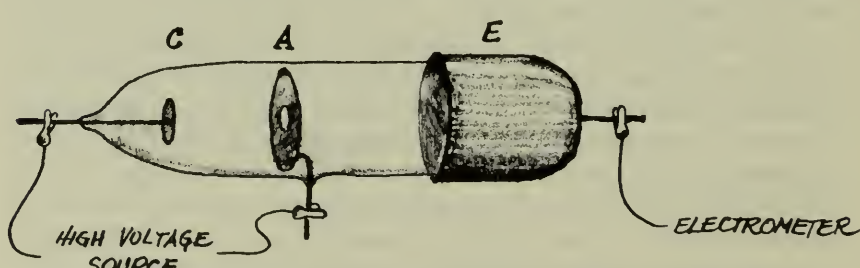


Fig. 2-6 A sketch of another arrangement of anode-cathode placement used by Hertz to show that a cathode ray beam carried no electric charge.

Hertz reasoned along these lines: if the cathode rays convey negative charge, then the inside of the glass cathode ray tube should become coated with negative charge. These charges will attract positive charges from the electrometer to the insulated can and cause the electrometer to deflect. To test the equipment he removed the cathode ray tube and inserted a very, very small amount of negative charge into the collector can; the electrometer responded strongly. Then when he inserted the cathode ray tube and sent cathode ray beams down the tube, the electrometer responded only feebly, except for a transient response when the cathode ray was first turned on. These results, like his earlier results with the bent discharge, certainly seemed to suggest that the cathode ray beam carried no electrical charge.

Hertz did still other experiments. In one of them he tried to detect bending of a cathode ray beam in a transverse electric field. If the beam consisted of charged particles, surely it would be deflected by an electric field as well as by a magnetic field. He found no deflection.

By 1891, Hertz and his pupil Lenard had shown that cathode ray beams could penetrate very thin metallic films. Such films were moderately transparent to visible light—to electromagnetic waves, in other words—but were too thick to let atoms through. The conclusion seemed inescapable that the cathode rays could not be particles, because the rays could go through thin foils which stopped even the smallest known particles.

Fig. 2-7 Sir Joseph John Thomson (1856–1940), one of the greatest British physicists, attended Owens College in Manchester, England, and then Cambridge University. He worked on the conduction of electricity through gases, on the relation between electricity and matter, and on atomic models. His greatest single contribution was the discovery of the electron. He was the head of the famous Cavendish Laboratory at Cambridge University, where one of his students was Ernest Rutherford.

2.6 The wave theory collapses: the experiments of Thomson

Yet by 1896 virtually the whole scientific world agreed that Hertz, Lenard, and the other proponents of the electromagnetic wave theory of cathode rays had been wrong, and that the rays were, indeed, negatively charged particles.

First, Jean Perrin in France and then J. J. Thomson in England repeated Hertz's experiment to detect the charge carried by the beams. But instead of putting the collector electrode outside the cathode ray tubes, they put it inside. Any charge carried by the beam could be conveyed by a wire connection through the glass tube to the electrometer. Perrin found that when the beam was on, the electrometer did register a negative charge. Thomson's version of the same experiment used a collector electrode displaced from the straight-line path of the cathode ray beam. By bending the beam with a magnetic field the beam could be directed onto the collecting electrode. The results revealed that the negative charge carried by the beam was in fact also responsible for the bending of the beam in a magnetic field.

Why had Hertz's experimental results been so misleading? The explanation is easy to see now, but it was by no means obvious at the time the experiments were being done. At the time the results fitted in so nicely with what Hertz and his colleagues thought *ought* to happen. In the tube shown in Fig. 2.3 the cathode rays probably represented a very small fraction of the total current in the tube. In comparison with the magnetic field produced by the current conducted along the curved path, the magnetic field due to the cathode rays was too small to be detected by Hertz.

Similarly, the electrometer experiment (Fig. 2.4) failed to detect any charge deposited on the wall of the tube because most of the charges carried by the beam moved along the inner glass walls of the tube so that very few charges accumulated on the outside walls within the electrometer can. When the electrometer was connected to a collecting electrode *inside* the cathode ray tube, as Perrin and Thomson did, quite different results and conclusions were reached.

Hertz's inability to detect any deflection of a cathode ray beam by means of an electric field occurred because his fields were not strong enough. (In Hertz's defense it should be said that he was sabotaged, as it were, by the unsuspected conductivity of the residual gas, which kept the potential differences across his electric-field-producing plates from being as high as he believed they were.)

Thomson succeeded in producing a deflection of the beam by means of electric fields. In an apparatus somewhat like that shown in Fig. 2-5 the beam traversed a region, between the two flat plates, in which a strong electric field, E, could be created by a potential difference, V, across the plates. If the plate separation, d, is small compared to the length and width of the plates, then $E = V/d$.
By providing a magnetic field, B, in the same region in which there was an electric field, Thomson could carry out the following sequence of operations:
(a) After arranging the directions of E and B appropriately, he could adjust their magnitudes until no net deflection of the beam occurred. Under those circumstances, for each particle,

$$F_{elec} = F_{mag} \tag{2.6}$$

or

$$Eq = Bqv$$

which may be rearranged to give

$$v = \frac{E}{B} \tag{2.7}$$

Thus the velocity, v, of a given beam could be determined.
(b) By changing either the electric field or the magnetic field alone, he could then find q/m. For example, when he used the magnetic field alone and observed the deflection which gave the radius of curvature of the path R of the beam, he could use Eq. (2.3) to find q/m, since

$$\frac{q}{m} = \frac{v}{BR} \tag{2.3}$$

You will recall that Arthur Schuster had proposed that the value of q/m was expected to lie in the range between 5×10^6 and 10^{10} coulombs per kilogram. However, Thomson's first experiment gave the value of q/m as approximately 10^{11} coul/kg, and later refinements in the apparatus gave results much closer to 1.76×10^{11} coul/kg. It is difficult to tell from Schuster's papers why even his maximum value turned out to be only a tenth as much.

The value that Thomson ultimately obtained for q/m is 1840 times the value of the charge-to-mass ratio for hydrogen ions in electrolysis. There are three possible ways to account for the larger value of q/m for electrons. Perhaps the charge on the cathode ray particle is 1840 times the charge on a hydrogen ion. Or perhaps the charges are the same, but the mass of the cathode ray particle is 1/1840 the mass of a hydrogen ion; or perhaps both the charge and the mass differ from those of the hydrogen ion. Thomson suggested that the mean free path argument, originally used against the Crookes hypothesis, and Lenard's experiments, in which cathode rays penetrated thin foils, were both evidence that the size (and presumably the mass) of the cathode ray particle must be very small. He therefore favored the second of the above possibilities, and suggested that cathode ray particles, or electrons, as they came to be known, were in fact constituents of all atoms.

2.7 Enter the electron

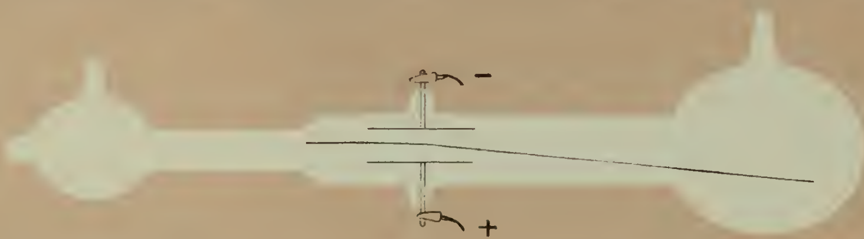
In the two decades before Thomson's experiments of 1895 and 1896, other scientists had discovered that negative particles were emitted by metals in apparatus other than cathode ray tubes. Edison had found that white-hot metals, such as incandescent lamp filaments, gave off negatively charged particles. Hertz had discovered, while showing that Maxwell's electromagnetic waves were emitted by accelerating electric charges, that light could knock negatively charged particles out of certain metals. This was the photoelectric effect. Thomson was able to show that the negative particles from hot filaments and those produced in the photoelectric effect had the same ratio of charge to mass as did his cathode ray particles.

In late 1895 and early 1896 Wilhelm Röntgen, in Würzburg, Germany, discovered x rays while performing experiments with a cathode ray tube. Later in 1896, Henri Becquerel, in Paris, while investigating x rays, accidentally discovered radioactivity. Soon thereafter, radioactive materials were found to emit one or more of three different sorts of rays. One of these, called the beta ray, was found to be composed of negatively charged particles. These, too, were found to have the same ratio of charge to mass as cathode ray electrons had.

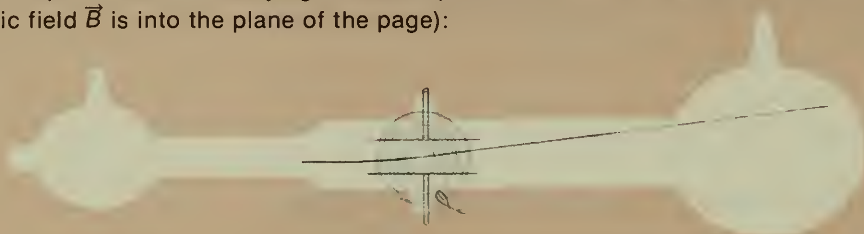
Another intriguing experiment involving charge-to-mass ratios of charged particles was also made in 1896, clearly a vintage year of im-

J. J. Thomson measured the ratio of charge q to mass m for cathode-ray particles by means of the evacuated tube shown in the sketches shown below. A high voltage applied between two electrodes in the left end of the tube produced cathode rays. Those rays that passed through both slotted cylinders in the narrow neck of the tube formed a nearly parallel beam. The beam produced a spot of light on a fluorescent coating inside the large end of the tube at the right.

The path of the beam was deflected by an electric field applied between two horizontal plates in the mid-section of the tube; (note that direction of electric field $\vec{E}$ is upward along plane of page):

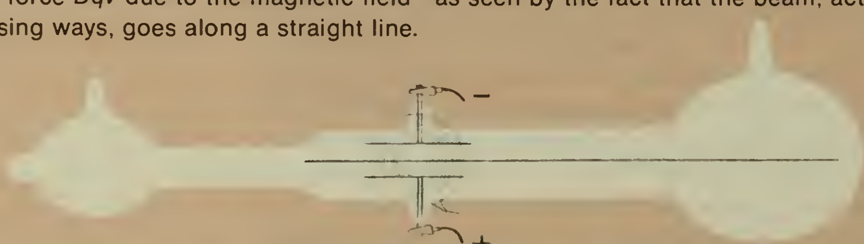


The beam's path was also deflected when there was no electric field but when a magnetic field was set up by means of a pair of current-carrying wire coils placed around the midsection of the tube; (the direction of the magnetic field $\vec{B}$ is into the plane of the page):



When only the magnetic field $\vec{B}$ is turned on, particles in the beam, having charge q and speed v, would experience a force Bqv; because the force is always perpendicular to the direction of the velocity vector, the beam would be deflected in a nearly circular arc of radius R as long as it is in the nearly uniform magnetic field. If the particles in the beam have mass m, they must be experiencing a centripetal force mv^2/R while moving in a circular arc. Since the centripetal force is provided by the magnetic force Bqv, we can write $Bqv = mv^2R$. Rearranging terms: $q/m = v/BR$.

B can be calculated from the geometry of the coils and the electric current in them. R can be found geometrically from the displacement of the beam spot on the end of the tube. To determine v, Thomson applied the electric field and the magnetic field at the same time, and arranged the directions and strengths of the two fields so that the electric field $\vec{E}$ exerted a downward force Eq on the beam particles exactly equal to the upward force Bqv due to the magnetic field—as seen by the fact that the beam, acted on by both fields in opposing ways, goes along a straight line.



If the magnitudes of the forces due to the electric and magnetic fields are equal, then $Eq = Bqv$. Solving for v we have: $v = E/B$. E can be calculated from the separation of the two plates and the voltage between them; so the speed of the particles v can be determined. Now all the terms on the right of the earlier equation for q/m are known, and q/m can be computed.

portant discoveries. A Dutch physicist, Zeeman, asked whether the spectra emitted by atoms in gases were influenced by the presence of a magnetic field. Zeeman put gas discharge tubes (tubes containing gas, at low pressure, through which electricity was flowing) in a strong magnetic field. Light from the tubes was examined through a spectroscope. Zeeman found that the spectral lines were slightly broader when the magnetic field was turned on than when it was off. With better spectroscopes of higher resolving power, both Zeeman and Crookes found that the apparent broadening of the lines was really a splitting of the lines into doublets (close pairs) or triplets and were polarized. Zeeman and another Dutch physicist, Lorentz, soon worked out a theory to explain this effect. If one assumes that atoms emit light by means of oscillations of charged particles having a certain ratio of charge to mass, then the theory predicts that in the presence of a strong magnetic field the wavelengths of the emitted polarized light are shifted in such a way as to show the observed splitting of the lines. The ratio of charge to mass necessary to fit the observed amount of splitting turned out to be the same as q/m already found for cathode ray electrons.

All these experiments, then, supported Thomson's idea that electrons were parts of atoms and that all electrons have the same ratio of charge to mass, no matter from what sort of atoms they were emitted, and no matter what physical process was used to break them loose from the atoms. Zeeman's experiment was, in addition, convincing evidence that electrons existed within atoms and played a crucial role in the emission of light. The arguments were over; cathode ray beams were undoubtedly composed of a stream of very small, negatively charged particles, and these particles were constituents of atoms.

See Film Loop entitled "Thomson Model of the Atom".

It was some years before the actual role of electrons in atoms was satisfactorily understood. Thomson thought that perhaps they were distributed within some sort of positively charged cloud, as (to use his analogy) raisins are distributed in a raisin cake. Such a model was not very satisfactory; it was hard to understand how atoms with such a structure could be stable, or how they could emit line spectra. Experiments with alpha particles, conducted by Rutherford in 1911, showed that atoms had very small positive nuclei. In 1913 the young Danish physicist Niels Bohr proposed a theory that showed how one might imagine hydrogen atoms to consist of a charged nucleus plus one orbiting electron. Bohr's atoms of hydrogen would emit and absorb light at the right wavelengths. More complicated but more general theories describing the behavior of electrons in atoms and their roles in the emission of light and in chemical bonding began to be developed about 1926.

With such theories came a better understanding—or at least a more detailed description—of electrons. Robert Millikan and others had developed a series of experiments by which one could show that electric charges were multiples of some basic and very small unit of charge, and by which one could determine that charge: 1.60×10^{-19} coulomb. Bohr's theory, as well as the later more general theories, assumed electrons with that charge, and with q/m of 1.76×10^{11} coul/kg. These theories all contributed to the firm conviction that such electrons are among the basic building blocks of the universe.

Certain experiments and theories suggested that the electron was not simply a tiny bit of charge and mass, but also had angular momentum and a magnetic moment. These properties would result if we thought of an electron as spinning, for a spinning charge—like a current-carrying coil—behaves like a bar magnet.

Two other developments should be mentioned briefly for the sake of completeness. One was the discovery of positively charged electrons found first as a consequence of the absorption of high-energy gamma rays occurring in cosmic rays and later as positive beta rays from certain artificially produced radioactive isotopes. The other was the discovery that cathode ray particles were not, after all, simply particles, but rather that in certain experiments a beam of cathode rays seemed to behave like a stream of waves! This does not mean that the old electromagnetic wave model for cathode rays was in any sense right, but simply that the particle theory was too simple. Modern physical theory suggests that *all* "particles" (including locomotives and jet airliners) have associated with them a wavelike nature. In everyday experiences this wave nature is irrelevant; the wave lengths are much too small to have noticeable effects. But electrons accelerated through potential differences of a few hundred volts have associated wavelengths roughly comparable to the spacing between layers of atoms in a crystal, so beams of such electrons can be diffracted by such crystals.

Cathode rays are now used in a host of devices: television cameras and picture tubes, electron microscopes, cathode ray oscilloscopes, computer output displays, and many others. (In such devices the rays are formed by electrons emitted from hot filaments and accelerated by potential differences of up to more than 30,000 volts.) Thus, while the development of a new technology in the 1850's (good vacuum pumps) made the discovery of cathode rays possible, the discovery and understanding of cathode rays, in turn, provided the basis for many technical developments from 1920 onward—and not technical developments alone, but a new understanding of the nature of matter.

Suggestions for Further Reading

Anderson, David L., *The Discovery of the Electron.* Princeton: D. Van Nostrand Co., Ind., 1964. A full account of the development of the atomic concept of electricity.

Boorse, Henry A., and Lloyd Motz, editors, *The World of the Atom.* New York: Basic Books, Inc., 1966. These articles in Vol. 1 are concerned with the discovery of the electron: William Crookes, "Cathode Rays—A fourth State of Matter"; J. J. Thomson, "The Discovery of the Electron"; Robert A. Millikan, "Atoms of Electricity".

Millikan, Robert A., *The Electron,* facsimile edition edited by J. W. M. DuMond. University of Chicago Press, 1963. A detailed account of the author's own work.

STUDY GUIDE

2.1 Summarize the evidence that cathode rays are *not* electromagnetic waves. Indicate as clearly as you can how this evidence disproves the wave hypothesis.

2.2 What experimental evidence was there, around 1900, for saying that the electric charge of the cathode ray particle (the electron) was equal in size to the charge carried by a hydrogen ion? Did the experimental evidence give the size of the charge directly?

2.3 In what ways was the time ripe for the discovery of the electron in the 1890's? What difficulties would a scientist have had testing the electron hypothesis a half century earlier?

2.4 In Thomson's experiment on the ratio of charge to mass of cathode ray particles (p. 42), the following might have been typical values for B, V and d: with a magnetic field B alone, the deflection of the beam indicated a radius of curvature of the beam within the field of 0.114 meters for $B = 1.0 \times 10^{-3}$ tesla.* With the same magnetic field, the addition of an electric field in the same region ($V = 200$ volts, plate separation $d = 0.01$ meter) made the beam go on straight through.
(a) Find the speed of the cathode ray particles in the beam.
(b) Find q/m for the cathode ray particles.

2.5 (a) The difference in potential between the cathode and the anode in a certain cathode ray tube is 5000 volts. Given that the ratio of charge to mass for cathode ray particles is 1.76×10^{11} coul/kg, show that the velocity of the particles as they emerge from the hole in the anode in the cathode-ray gun is 4.2×10^{7} m/sec.
(b) The two deflecting plates in the tube are at a potential difference of 300 volts and are 1 cm apart. Show that the electric field strength, E between the plates is 3×10^{4} newtons/coulomb.
(c) Given that the charge on an electron is 1.6×10^{-19} coulomb, find the force on an electron in the cathode ray beam between the plates.
(d) Given the mass of the electron (9.1×10^{-31} kg), find the vertical acceleration of the electron while it is between the plates.
(e) How long does it take the electron to travel horizontally through the region between the plates which are 5 cm long.
(f) What vertical component of velocity will the electron acquire during that time?
(g) Show that it will "drop" 0.375 cm while between the plates and therefore will not hit the plate toward which it is deflected.
(h) After the electron emerges from the region between the plates, it will have both its original horizontal component of velocity (why?) and its newly acquired vertical component of velocity. The electron will hit a fluorescent screen, located 30 cm from the point at which it emerges from the plates. What is the distance of that impact point from the point where the electron would have hit had there been no electric field between the plates?
(i) Suppose one had wished to counteract the effect of the electric field by superimposing, in the same region, a magnetic field of strength B. What direction and magnitude for B would one need?

* The MKSA unit for B is N/amp · m and is now called the *tesla*, after the electrical engineer Nikola Tesla.

2.6 In one of Lenard's experiments in which he sent cathode rays through very thin metallic foils, he used an aluminum foil 0.003 millimeter thick.
(a) How does this thickness compare with that of a typical sheet of paper? (Hint: how thick is a ream of typing paper or a 100-page section of a book?)
(b) One cubic centimeter of aluminum has a mass of about 2.7 grams. The atomic weight of aluminum is 27. What is the volume of a gram-atom of aluminum (i.e. of 27 grams of aluminum)? How many atoms does that volume contain? How much volume is occupied by an average aluminum atom? If this volume is cubical, how long is one edge of such a cubical volume?
(c) About how many layers of aluminum atoms did the cathode rays penetrate in Lenard's experiment?

2.7 Consider a cathode ray tube 90 cm long, in which the air pressure is such that the mean free path for molecules is 0.60 cm; therefore the tube is 150 mean free paths long. A large number of cathode ray particles start out from the cathode. *If* they are electrically charged molecules (as Crookes originally thought), then half of them will have suffered collisions and have been deflected in the first 0.60 cm. Half of the remaining ones would have been deflected in the next 0.60 cm. About what fraction would survive for a total straight-line path of 90 cm? (Note: this is a rather crude argument which would need to be modified to take into account the motions of the other air molecules and other complicating factors. But the answer will be a rough estimate, good enough to show why many physicists did not believe Crookes' idea.)

2.8 A cathode ray tube is connected to an induction coil which provides 40 pulses per second. During each pulse the anode is at 20,000 volts positive with respect to the cathode. The average current to the cathode, as measured by a milliammeter, is 0.50 milliamps. Each pulse lasts approximately 0.001 sec. Calculate:
(a) the actual charge conveyed by the beam during each pulse;
(b) the number of electrons per pulse;
(c) the energy that the beam of cathode rays could give, per second, to a thin foil. Assume that the cathode is cup-shaped, so that all the rays from the cathode hit the foil. Does your result indicate that the foil might be noticeably heated? (Hint: think about small light bulbs.)

2.9 In what ways were the discovery of electrons dependent upon prior technical developments?

2.10 Sketch or diagram the arguments and evidence used to support the proposals that cathode rays were (a) waves, (b) particles.

2.11 Trace the history of the determination of the mass and charge of the electron from the work of Schuster through that of Millikan. Separate the arguments and conclusions from the experimental results.

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Enrico Fermi and an assistant testing the first atomic pile at the University of Chicago in 1942.

CHAPTER THREE

Nuclear Fission

3.1 Introduction

For a brief review, see Project Physics *Text*, Unit 6 Sections on Nuclear Fission and on Chain Reactions.

The discovery of nuclear fission was a fascinating drama with many participants and many misleading developments. Furthermore, the results have shaped human history with a suddenness and a profundity almost unique in the history of science and technology. This discovery could have happened at any time between 1934 and 1939, and one might even say that it was a discovery that went around rapping at many laboratory doors, only to be ignored again and again because no one was expecting it. Indeed, when one scientist did suggest, in 1934, that certain unusual experimental results could be explained by assuming that uranium nuclei could split apart, no one paid any attention. The possibility that a nucleus could be split into two nearly equal parts by the addition of a neutron went against all previous experience with nuclear disintegrations. The most massive particle known to be ejected from a nucleus was an alpha particle, with less than two per cent of the mass of the uranium nucleus. Because the alpha particle is a uniquely stable composite of two neutrons and two protons, it was understandable that this particular combination was emitted from nuclei. But all the existing theories of the nucleus indicated that no other combination of nuclear particles could hang together during the process of nuclear disintegration.

It is only natural to try to explain or understand unusual experimental results or observations in terms of the best theories and ideas already available, rather than by changing theories. Science grows by building upon the current body of knowledge and existing accomplishments. Its development is analogous to the slow evolution of an animal species, which continuously produces organisms that are the direct results of their antecedents. But biologic evolution also leaves behind a fossil trail of trials that failed, and science too must discard its unfit or outworn products in favor of new evolving, dominantly useful concepts and theories.

3.2 Bombarding nuclei with neutrons

The discovery of the neutron had taken only about two years, from the first finding of a strange new kind of "ray" by Bothe and Becker in 1930, to its identification by Chadwick in 1932 as an electrically neutral particle of mass very nearly equal to that of the proton. Neutrons are normal constituents of all nuclei (except that of ordinary hydrogen, the nucleus of which is simply a proton). Since neutrons are uncharged, they are not repelled, as protons are, when they approach a nucleus. Soon after their discovery it therefore became clear that neutrons could be used to bombard stable nuclei, with very interesting results. Experiments showed that a neutron captured by a nucleus may cause the nucleus to react in various ways by emitting a proton, an alpha particle, one or two other neutrons, or a gamma ray. The actual outcome depends on the energy of the incoming neutron and on the nature of the bombarded nucleus. In any event, after emitting the particle or particles, the *remaining* nucleus is often left with an excess of energy in what is called an "excited state." Such a nucleus can settle down to a stable state by emitting a beta ray or a gamma ray or both.

If the bombarding neutron has little kinetic energy, its capture is very likely to result only in the emission of a gamma ray, leaving a nucleus with the same charge as before, but with one more mass unit. Such a nucleus is often unstable and decays, with a half-life characteristic of the particular isotope, by emitting a negative beta ray. The nucleus (called the "daughter") which remains after the beta emission has one additional positive charge and so is displaced in the periodic table by one atomic number — that is, it is chemically one position higher in the periodic table. The daughter products in such cases are almost invariably stable.

Fig. 3-2 Enrico Fermi, 1901–1954.

3.3 The special problem of uranium

Beginning in 1933 a young and vigorous group of Italian physicists, among them Enrico Fermi, began using neutrons to bombard samples of all the known elements. In doing so, they produced many previously unknown radioactive elements, and measured for many elements the relative chance that a neutron would be captured by an atom. This chance of capture is described as a target area having a certain "cross section." When Fermi and his collaborators began bombarding uranium with neutrons, an interesting question arose. Would isotopes be produced (by the beta decay process described above) which would be a step higher than uranium in the periodic table? No such transuranic elements were known to exist in nature, presumably because their nuclear structure would make them unstable. If such isotopes existed, they would be exceptions to the generalization that the daughters resulting from neutron bombardment products are usually stable. Sure enough, when Fermi and his collaborators bombarded uranium with neutrons, they found that they produced a radioactive material that was not just a single radioactive isotope with a single half-life. It behaved as a mixture of isotopes, with at least four (and probably more) half-lives. Since there were only three isotopes in the uranium that was bombarded, it seemed odd that at least four isotopes were produced. At least one of them might be a transuranic element: element number 93. Such an element would be chemically rather like manganese (element 25), technetium (element 43), and rhenium (element 75). When some manganese was added to the solution containing the bombarded uranium, and then precipitated out as MnO_2, it carried with it some of the radioactivity. This and other chemical tests showed that one or more of the radioactive isotopes was chemically similar to manganese and could be presumed to be an isotope of element 93.

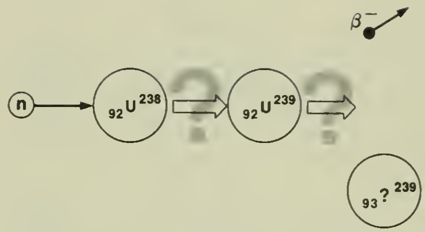

Fig. 3-3

Fermi's work aroused considerable interest, but not everyone was convinced that his group had really produced a transuranic element. A German chemist, Ida Noddack, suggested that Fermi had not actually ruled out, by chemical tests, the possibility that the radioactive isotopes that he had produced were elements in the middle of the periodic table. She suggested, in fact, that perhaps uranium nuclei were somehow broken into large fragments when bombarded with neutrons, and that these fragments were radioactive. Literally no one took this suggestion seriously. There was no experimental evidence that such fragmentation could happen, and there were good theoretical reasons for believing that a bombarded nucleus could emit nothing larger than an alpha particle. But Miss Noddack insisted that for Fermi to be sure that the radioactivity was due to a transuranic element, he would have to perform chemical analyses that would rule out all other chemical elements, not just those in the immediate neighborhood of uranium. No one took her advice.

3.4 The search for transuranic elements

Several other physicists and chemists did, however, try experiments designed to find how the several radioactive products by neutron bombardment of uranium and thorium were related, if at all, to each other. Otto Hahn and Lise Meitner, in Berlin, found that certain "activities" produced by neutron bombardment of thorium were chemically like radium. One of them, with a half-life of one minute, seemed to decay into an actinium-like isotope with a half-life of 3.5 hours.

Such an "activity" in some radioactive isotope is specified in terms of its half-life.

In 1936 and 1937 Hahn, Meitner, and Fritz Strassmann carried out in Germany an extended series of experiments which seemed to show quite conclusively that neutron bombardment of uranium (U^{238}) produced a whole collection of transuranic elements—including

Nuclear isomers have the same charge and mass, but differing half-lives.

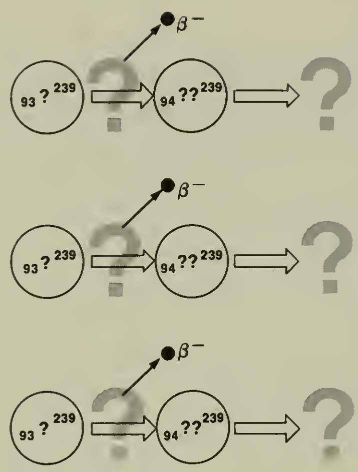

Fig. 3-4

three different isotopes of element 93, which then decayed by beta emission into three different isotopes of element 94, which in turn beta-decayed into isotopes of element 95, and so on. This was indeed puzzling, for ordinarily one would not expect a single material, presumably element 93 with mass number 239, to have three isomers. In ordinary artificially-produced radioactive isotopes, isomers do occasionally occur. For example, indium^{116}, made by bombarding the most abundant stable isotope of indium, In^{115}, with slow neutrons, exists in two isomeric states having different activities. Both decay by emitting beta particles, one with a half-life of 54 minutes, the other with a half life of 13 seconds. Both decay into Tin^{116}, which is stable.

Some cases of triple isomerism are now known, but in 1937 triple isomers seemed strange. Even stranger was the apparent inheritability of this triple isomerism—that is, the apparent existence of chains of successive decays. Expressed in another way, it was surprising that a single neutron put into a relatively stable uranium nucleus could produce such a disturbance that as many as five successive emissions of beta rays were necessary before the nucleus became stable.

3.5 A discovery missed

A substance, like lanthanum in this experiment, used to provide an adequate quantity of material to permit the manipulation of radioactive isotopes, is called a *carrier.*

In 1937 and 1938 Irène Joliet-Curie and Paul Savitch, in Paris, carried out extensive investigations of the activities produced by neutron bombardment of uranium. When they added the nonradioactive element lanthanum to the bombarded uranium, dissolved the mixture, and chemically separated out the lanthanum by precipitating it, they found that a substance with a half-life of 3.5 hours was carried along with the lanthanum. Since actinium was the heaviest element with chemical properties like those of lanthanum, they assumed that this activity was a form of actinium, the 89th element in the periodic table. They did notice that this activity was chemically more like lanthanum (the 57th element in the table) than like actinium, but they thought that they had been able to separate it from lanthanum.

As we shall see later, what they were dealing with was not actinium (an element close to uranium in the periodic table), but actually an isotope of lanthanum 35 elements away from uranium. If they had correctly identified this activity, they would have established that uranium does break up into pieces with one of the fragments (lanthanum) having about two-thirds the mass of uranium. They failed to make the correct identification because they believed that they had proved they had actinium by chemically separating the activity from lanthanum. In retrospect it seems likely that among the products of the bombarded uranium was still another fission product in the same chemical family as lanthanum and actinium, an isotope of yttrium, element 39, with a half-life of about 3.6 hours, very close to

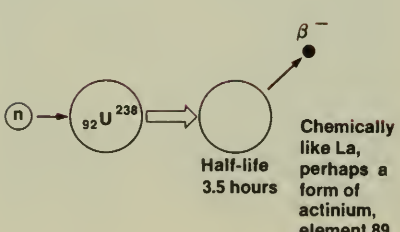

Fig. 3-5

the half-life of the lanthanum isotope. If this surmise is correct, they were the victims of an unfortunate coincidence. Otherwise they surely would have been driven to accept their other chemical evidence that the 3.5-hour activity really was an isotope of lanthanum which must have resulted from a major fragmentation of the uranium nucleus, not the emission of a few particles. (The nuclear fragment picks up enough electrons to form a neutral atom.) The discovery of uranium fission was in their grasp, but it slipped away.

3.6 Alpha particles and another near-discovery

In 1938 Hahn and Strassmann repeated the work of Irène Joliot-Curie and Paul Savitch, this time without Lise Meitner, who had fled from the Nazis to Sweden. Hahn had been working with problems in the identification of radioactive substances since his early days as a student under Rutherford in England and in Montreal. He, Miss Meitner, and Strassmann were superbly equipped for this work by training and experience. From a solution of neutron-bombarded salts of uranium they were able to precipitate with barium carriers at least three activities with half-lives of 25 minutes, 110 minutes, and several days. From these activities they found daughter products, precipitated with lanthanum carriers, with half-lives of 40 minutes, 4 hours, and 60 hours. They attributed the first set to isomers of radium^{231} (because radium is chemically like barium) and the second set to actinium^{231} isomers, since actinium is chemically like lanthanum. They suggested that the Ra^{231} was formed from U^{238} by the emission of two

Fig. 3-6 Professor Otto Hahn (center) is pictured in 1962 behind the laboratory equipment used for his experiments in 1938 on the irradiation of uranium with neutrons. The equipment is now in the German Museum in Munich. To the left of Hahn is his former assistant, Fritz Strassmann.

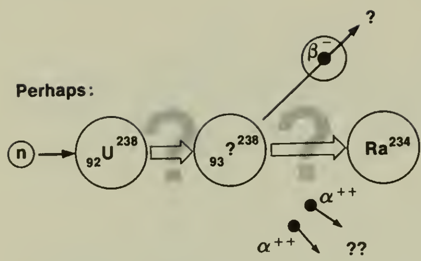

Fig. 3-7

alpha particles after the capture of a neutron. This would reduce the charge of the nucleus by four units, two for each alpha particle, and its mass by seven units, four for each alpha particle emitted less the added one for the incoming neutron, and would account for the charge and mass of the Ra^{231}.

These results, like those of the group's 1936 and 1937 experiments, raised the questions of threefold isomerism and the inheritability of isomerism. In addition, they appeared to involve the rather unlikely emission of two alpha particles after bombardment by a single neutron. Because it is relatively hard for even a single alpha particle to escape from uranium^{238}, its normal half-life is so long, 4.5 billion years. But Hahn, Meitner, and Strassmann found somewhat similar results when thorium^{232} was bombarded by neutrons. (In the case of thorium, only a single alpha particle would need to be emitted in order to produce a radium isotope.)

Attempts were made, beginning in 1937, to detect the alpha particles presumably ejected when neutrons hit thorium and uranium. More than once, this search led scientists to the brink of discovering nuclear fission.

The technique used in testing for alpha particles was to put a thin layer of thorium or uranium in an ionization chamber and bring a neutron source nearby. Any alpha particles emitted from the thorium or uranium into the gas in the chamber will ionize a great many molecules of the gas. The more energetic an alpha particle, the more ionization it produces. The ionized molecules can be collected by an electrically charged plate, and the pulses of current initiated by each alpha particle can be observed. In 1937 Braun, Preiswerk, and

Fig. 3-8 Lise Meitner and Otto Hahn, photographed in 1925.

Scherrer, in Germany, found in this way alpha particles with energies of about 9 million electron volts, about twice the energy commonly associated with ordinary alpha rays from naturally radioactive materials. It is surprising, in fact, that they did not observe much larger pulses of current, corresponding to particle energies of the order of 100 million electron volts, for there should have been some fission fragments present with energies of that order. Here again, a stupendous discovery was narrowly missed. But even if such pulses had been observed, they would have been extremely difficult to interpret. (It would be like noticing your speedometer jumping up to 100 miles per hour from time to time when you were inching your way along in a traffic jam. Since you would know that cars just do not behave that way, you probably would assume that something was wrong with the instrument.)

One electron volt is the energy required to move one electronic charge through a potential difference of one volt. It is equal to 1.6×10^{-19} joule.

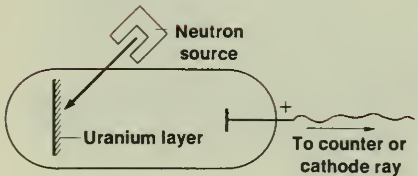

Fig. 3-9

Droste, in Germany in 1938, tried similar experiments, but he adopted a very sensible refinement. He covered his uranium and thorium with very thin foils, just thick enough to stop the (low-energy) alpha particles due to the natural radioactivity of uranium and thorium. He found very few high-energy alpha particles. But neither did he find any high-energy pulses from fission fragments, since the thin foils could easily stop any heavy highly charged particles even if they did have a lot of kinetic energy. Once again the particular experimental design blocked a major discovery.

3.7 The discovery is made

Since the reaction, proposed in explanation of the 1938 Hahn-Strassmann results,

$$_{92}U^{238} + _{0}n^{1} \longrightarrow _{2}He^{4} + _{2}He^{4} + _{88}Ra^{231}$$

with its assumption that two alpha particles are emitted, seemed unlikely to Hahn and Strassmann, they began a systematic chemical study of the "radium" products of the reaction, and of the daughter products.

Hahn and Strassmann finally found themselves driven by their careful experiments to announce that the activities were due not to radium and actinium, but to barium and lanthanum. They had found that they could easily separate radium and actinium isotopes from barium and lanthanum carriers, but they simply could not separate the new activities from such carriers. Apparently the bombardment of uranium with neutrons must have produced the lighter elements barium and lanthanum. On January 9, 1939, they published their results, remarking that "On the basis of these. . . . experiments, we must, as chemists, really rename the previously offered scheme and set the symbols Ba, La, Ce in place of Ra, Ac, Th. As 'nuclear chemists' with close ties to physics, we cannot decide to make a step so contrary

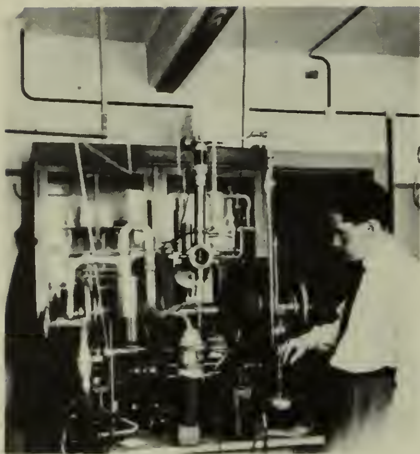
Fig. 3-10 Otto Frisch.

to all existing experience of nuclear physics. After all, a series of strange coincidences may, perhaps, have led to these results."

While preparing this paper for publication just before Christmas in 1938, Hahn wrote to his former colleague, Lise Meitner. As an Austrian citizen Miss Meitner, although Jewish, had been able to work safely in Berlin. But in March of 1938 the Nazis had taken over Austria, and all Austrians had been declared to be Germans. Miss Meitner escaped with the help of an international committee headed by Niels Bohr. She went first to Holland and then to Stockholm, where she took a research position at the Nobel Institute. Her nephew, Otto Frisch, a brilliant physicist, was then working in Copenhagen. They agreed to meet in southern Sweden during the Christmas holidays. Miss Meitner showed Frisch the letter she had received from Hahn. He thought there must have been some mistake in the experiments, but she knew that Hahn was too careful – that his results had to be taken seriously. They asked themselves how one could get barium out of uranium. It seemed ridiculous; too much energy would be needed.

But then they began to think about some suggestions Bohr had made, that atomic nuclei could be thought of as "liquid drops" in which various forces interacted – such forces as the mutual repulsion of the protons, the attractions between the nucleons (protons and neutrons) at close range, and so forth. One could even consider the nucleons at the surface of a large nucleus to interact with each other in a manner similar to the way that molecules at the surface of a liquid interact to produce surface tension. Could it be possible, they wondered, for the incoming neutron to set up some sort of oscillation in the "liquid drop" nucleus of uranium, elongating it enough so that the electrostatic repulsion between the protons at one end and the protons at the other could overcome the nuclear attractive forces and "surface tension" and actually break the elongated drop into two parts? In that case, because of the strong electrostatic repulsion between them, the two parts would fly apart with enormous energy. Einstein's theory of relativity would require that the combined mass of the original nucleus plus the incoming neutron should be greater by an appropriate amount than the masses of the two product nuclei. Miss Meitner did some calculations on the back of Hahn's letter, and sure enough, the masses of uranium nuclei and of the product nuclei would differ by about the right amount to provide that enormous energy.

After their two-day holiday, the aunt and nephew returned to Stockholm and Copenhagen. Frisch immediately informed Niels Bohr of this new development, just as Bohr was on his way to take a ship for America. By the middle of January 1939, Frisch had shown that massive fragments with enormous energies did indeed emerge from uranium which had been bombarded by neutrons, and he immediately sent off a paper containing his ideas to the British journal *Nature*. In this paper he and Miss Meitner introduced the word "fission," borrowing it from biologists, who use it to describe the splitting of cells.

Meanwhile, Hahn and Strassmann were similarly convincing themselves that the barium and lanthanum activities really were due to radioactive isotopes of those elements and were the result of an actual break-up of uranium nuclei. They correctly deduced that other fragments must exist and quickly identified strontium and yttrium. Also they found evidence of the radioactive noble gases, xenon and krypton, among what we may now call the fission products. As soon as the Frisch-Meitner interpretation became public, Frédérick Joliot (husband of Iréne Joliot-Curie) and several Americans almost simultaneously confirmed that fission was indeed occurring when neutrons hit uranium or thorium.

3.8 The study of nuclear fission begins

Attention to the work of Meitner and Frisch's interpretation of Hahn and Strassmann's experiments was world-wide in a few days. Frisch had told Bohr of their ideas as Bohr was hurrying to catch a ship for New York. On the transatlantic voyage, Bohr discussed the new discovery with Rosenfeld, a young colleague from Copenhagen. When the liner arrived in New York on January 16, 1939, Bohr and Rosenfeld were met by John Wheeler of the Princeton University physics department and by Enrico and Laura Fermi, who had recently fled from Fascist Italy to Columbia University in New York. That night Rosenfeld discussed fission at a meeting of physicists at Princeton. The next day Bohr became alarmed that this informal communication of the news would result in publications about fission before Frisch and Meitner's account would be published in Europe, so he and Rosenfeld quickly prepared a short report, giving Meitner, Frisch, Hahn, and Strassmann full credit, and sent it off to *Nature* shortly after Frisch had sent his own paper from Denmark to the same journal.

A few days later, on January 26th, at the Fifth Washington (D.C.) Conference on Theoretical Physics, a reporter showed Bohr a copy of Hahn and Strassmann's first publication of their research. Bohr then felt free to report to the Conference both the work of Hahn and Strassmann and the ideas of Meitner and Frisch. Within a few hours physicists in Washington, New York, Princeton, and many other places were setting up experiments on fission. In many of these experiments, ionization chambers were used to show that the fission fragments did have large amounts of kinetic energy. Others used cloud chambers to show the heavy tracks of the fission particles. Ingenious experiments showed that the fragments were indeed radioactive when separated from the uranium foil in which they were formed by the fission process.

Another set of experiments confirmed the chemical identifications of the fission products by means of the x rays emitted by some of them. Certain radioactive decay processes (capture of an electron by the nucleus from the inner electron orbits, or the knocking of such an electron out of its orbit by a gamma ray emerging from the nucleus) leave an electron vacancy in the inner orbits of the atom. As electrons "fall" into that vacancy, x rays are emitted which have wavelengths characteristic of the element. Abelson, in America, had in fact already measured some of these wavelengths for fission products before January of 1939, that is, when they were still thought of as transuranic elements or as radium isotopes and their decay products. He had interpreted his results, quite naturally, as appropriate for x rays emitted in transitions to the second set of orbits (the L orbits) of heavy elements. After fission was recognized, he realized very quickly that his measured wavelengths could be much better understood as due to transitions to the first set of orbits (the K orbits) of elements such as iodine and tellurium—that is, of fission products. Here again, a scientist had been very close to an important discovery, but he interpreted his data in a way consistent with the accepted ideas of his time. It is unlikely that Abelson even considered the possibility that the x rays could be due to elements in the middle of the periodic table.

3.9 The chain reaction

Once the discovery of fission was announced, many investigators continued the work of Hahn, Strassmann, Meitner, Abelson, and others in attempts to sort out the bewildering array of possible fission products. All of these products would have had, presumably, an excess of neutrons in their nuclei, since a U^{239} nucleus—while it lasted—would have about 1.6 neutrons in it for every proton, whereas the stable elements in the middle of the periodic table are known to have about 1.3 neutrons per proton. The fragments or fission products, then, probably have too many neutrons and are highly radioactive. They can turn into stable nuclei most easily by successive emissions of electrons (negative beta rays), that is, by turning some of their neutrons into protons and electrons and emitting the electrons. But a few physicists began to wonder whether a few free neutrons might not also emerge during the fission process. In France, von Halban, the Joliot-Curies, and Kowarski were able to show that possibly as many as three or four neutrons were emitted, on the average, for each neutron-induced fission. Similar experiments were carried out in America by Anderson, Fermi, and Hanstein.

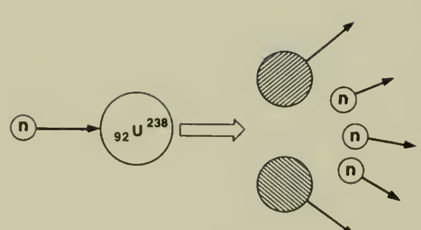

Fig. 3-11

The discovery that neutrons are emitted when fission occurs immediately raised an intriguing question: could a self-sustaining chain reaction occur? It was quickly recognized that such a reaction would be possible if, on the average, at least one of the neutrons emitted during fission could hit another uranium nucleus and cause that nucleus to split. Since neutrons could also escape to the surroundings, or be absorbed in non-fission-producing ways, it was not at all obvious that a chain reaction would be possible. In 1939 and 1940 many papers appeared discussing the relative probabilities for such events. More and more physicists in all parts of the world became convinced that a chain reaction, with production of an enormous amount of energy, might well be possible.

3.10 The war intervenes

Early in 1939 many of these physicists became concerned that a weapon using nuclear fission might be developed by Nazi Germany. As World War II came closer, efforts were made to interest the United States government in supporting research in this area. By early 1940 there was a voluntary agreement among most physicists in America to stop publication of significant results. (In this connection, it is interesting to look at the list of papers quoted in L. A. Turner's comprehensive review of the discovery of uranium fission, in the January 1940 issue of *Reviews of Modern Physics*. In his review Turner lists three papers published in 1934, two by Fermi and his group and one by their critic, Ida Noddack. In 1935, there were seven; in 1936, five; in 1937, five; in 1938, nine; and then, in 1939, there were 117. By the end of 1940 the number of papers being published had dropped virtually to zero. There have been other discoveries or new ideas in science which have caused a sudden explosion of published papers – the discovery, in 1958, of the Mossbauer effect, for example, or the invention of masers and lasers, but one cannot think of any other case in which the papers suddenly *stopped* appearing.)

By the time the publication of fission research stopped, the basic problems were clear. Bohr and Wheeler had worked out a good theory of the process by which fission occurs. In terms of that theory, it could be understood why some nuclei (the abundant U^{238}, for example) undergo fission only when hit by a very fast-moving neutron, while others (the rare isotope U^{235}, for instance) would be more likely to undergo fission when hit by a relatively slow neutron. By the end of 1939 the basic questions had been asked, and many of them had been answered.


The Evening Star
JAPS ADMIT GREAT ATOMIC BOMB DAMAGE
Weapon Sent Down By 'Chute, Exploded In Air, Enemy Says

THE SUN FINAL
ATOMIC BOMB DROPPED ON JAPAN
125 Superfortresses Attack Nipponese Naval Arsenal
Frightful Weapon Loosed In Reply To Rejection Of Big-3 Ultimatum

The New York Times.
FIRST ATOMIC BOMB DROPPED ON JAPAN; MISSILE IS EQUAL TO 20,000 TONS OF TNT; TRUMAN WARNS FOE OF A 'RAIN OF RUIN'

Fig. 3-12

The subsequent development of nuclear bombs and of peaceful applications of nuclear energy is a fascinating story, well told now in many books. It is a story interesting from many standpoints, especially because it makes us think about the interaction between science and technology and between science and government. The technological developments stemming from nuclear fission confronted all statesmen with inescapable problems and raised many issues – which are by no means settled – about the role of scientists in a modern state. If you are interested in these issues, you will want to read some of the books and articles listed in the bibliography at the end of this chapter.

3.11 Some thoughts for our models of discovery

The discovery of nuclear fission does not fit very well any of the models of scientific discovery suggested in the introductory section. It was not a single event in history, like the discovery of Pike's Peak or the Victoria Falls. It was not a jigsaw puzzle in the usual sense, although there were certainly many puzzling pieces. The murder novel model is fairly close; there were many clues, and an "obvious" solution which ended up being wrong, as well as a surprising burst of activity at the end of the story. But there were accidents which delayed the solution; if similar accidents had happened in a detective story, impatient readers would accuse the author of padding the plot merely to prolong the story.

What were some of those accidents? One accident occurred when Droste used thin foils to cut down background in a search for alpha particles, and thereby stopped the fission fragments from reaching the ionization chamber. Another was the possible presence of the 3.6-hour yttrium fission products mixed with the 3.5-hour lanthanum discovered by Joliot-Curie and Savitch. The yttrium made the radioactive material seem slightly different from lanthanum in the chemical separations. Sometimes scientists are helped by fortunate accidents, but occasionally chance occurrences hinder them.

A more important lesson to be learned is that it is often terribly difficult for a new scientific idea to be born. As Conant, Holton, Kuhn, Barber, and many others have pointed out, scientists do not leap to an unusual explanation for some newly observed phenomena if there is an ordinary explanation handy. When Fermi and his colleagues found the radioactive by-products of neutron bombardment of uranium to be unlike the chemical elements just below uranium in the periodic table, the only obvious answer was that transuranic elements had been produced. Ida Noddack pointed out the flaws in this logic, but to follow her suggestions would have meant taking at least two steps that seemed unacceptable: exhaustive chemical tests would have had to be made for all 92 elements, and scientists would have had to suspend their reliance on some of the most productive and valuable existing theories on the behavior of nuclei. There are those who say that "the scientific method" requires that any theory be tossed out the moment a single contradictory experimental fact comes along. Scientists, however, know that a single contradictory experimental fact may be an experimental mistake, or if not, then possibly the old theory can be changed to include the new fact. The apparent triple inheritable isomerism of the "radium" and the "actinium" activities was rather extraordinary, but not nearly so extraordinary as nuclear fission would have seemed.

The final understanding of nuclear fission came about through the work of many persons in many countries. Crucial roles were played in Italy, Germany, France, Denmark, Sweden, and America. Scientists of many countries and nationalities were involved. This is not to say that there was not intense competition for priorities. A scientist, like anyone else, enjoys the fame of being the first to make an important observation or to have an important idea. But the competition was embedded in a context of cooperation.

The international scientific community was, of course, divided by World War II. One of the great ironies of history is that American technology and science, especially the study of nuclear energy, were so much advanced by the distinguished scientists who fled the tyrannies of Hitler and Mussolini.

A minor irony in the history of science is that the discovery of nuclear fission did not, after all, require any convulsive revision of older concepts of atomic and nuclear structure. Once scientists got used to the idea of what for five years had been dismissed as impossible—nuclear fission—it turned out to be quite understandable, after all, in terms of the theories of nuclear structure that had been developed by Bohr and others during those same five years. But then, "Monday morning quarterbacking" has always been easy.

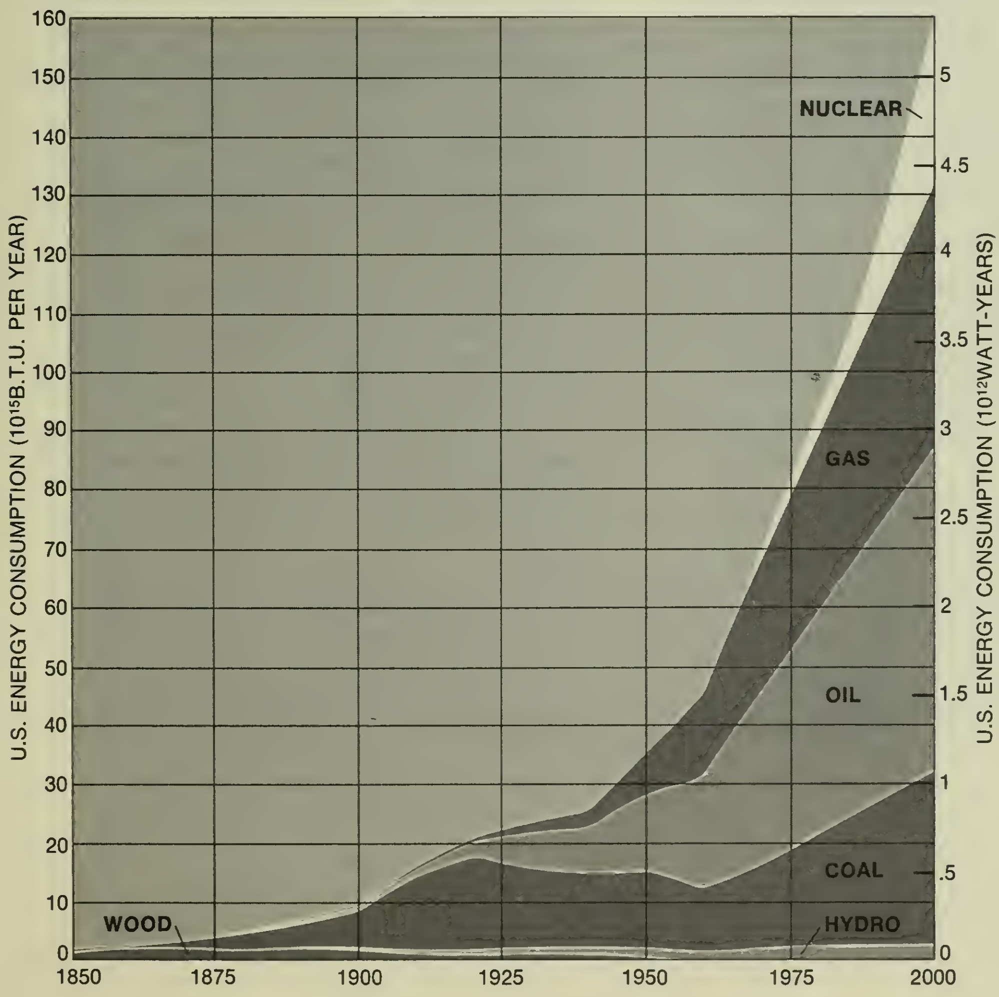

Fig. 3-13

STUDY GUIDE

3.1 List the experiments performed after 1930 that you consider of critical importance in the discovery of nuclear fission. Indicate the part played by each experiment in preparing for this discovery.

3.2 Prepare a brief glossary of the terms used in this chapter for someone who had not studied Unit 5 or Unit 6. Include at least the following terms: cross section, carrier, activity, half-life, transuranic element, fission, alpha particle, neutron.

3.3 How do you think the world would be different if nuclear fission had been discovered in 1930? Not until 1950?

3.4 To what extent do you think the date of a significant discovery, such as the discovery of nuclear fission, is influenced by deliberate human decisions? What changes in society might have accelerated the discovery by 10 years? Delayed the discovery by 10 years?

3.5 Give examples of discoveries in which the discoverer had a conviction that he would find what he, in fact, did find. Also give examples in which the discovery was unexpected and surprising. In which category do you place the discovery of nuclear fission? Of Neptune? Of the electron? Why?

3.6 Find the answer to problem 24.16, Unit 6, or to the modified version of that problem presented here. The end products in one particular mode of fission of U^{235} when that nucleus is bombarded with slow neutrons are $_{57}La^{139}$ and $_{42}Mo^{95}$. This mode may be described by the equation

$$_{92}U^{235} + {_0n^1} \longrightarrow {_{57}La^{139}} + {_{42}Mo^{95}} + 2{_0n^1} + 7{_{-1}e^0}$$

The mass of $_{57}La^{139}$ is 138.9061 atomic mass units (amu), that of $_{42}Mo^{95}$ is 94.9057. How much energy is released per atom in this particular fission mode? The mass of the seven electrons may be neglected. The mass of a U^{235} nucleus is 235.04393 amu, and that of a neutron is 1.00867 amu. According to Einstein's relativistic mass-energy relationship, $\Delta E = \Delta mc^2$, the energy equivalent of one amu is 931 million electron volts.

3.7 One way in which a U^{235} nucleus hit by a neutron may undergo fission is by splitting into two radioactive nuclei, $_{54}Xe^{138}$ and $_{38}Sr^{95}$, plus three neutrons. Suppose we could somehow see the two daughter nuclei just after the split has occurred. We would see two charged objects very close to each other. According to Coulomb's law, there would exist a strong force pushing them apart. As the two objects fly apart, the force will, of course, diminish rapidly, but we can calculate the electrical potential energy that will be converted to mechanical kinetic energy of the particles in the process. By use of Coulomb's law, one can show that the work required to bring a charge Q_1 up to a distance R from a charge Q_2 is given by kQ_1Q_2/R. This same amount of work can be done, then, by two charges that find themselves a distance R apart. (You will recall from Unit 4 that k is about 9×10^9 newton-meters²/coulomb².) Suppose that, just after the fission, the above fission fragments are approximately 2×10^{-14} meters apart, and virtually at rest. Find the sum of their kinetic energies after they have flown apart, in joules and in electron volts. (Note: the electronic charge is 1.6×10^{-19} coulomb and 1 electron volt $= 1.6 \times 10^{-19}$ joule.) Probably your answers in of the same order of magnitude as your answer to problem 3.6. Why isn't it exactly the same?

3.8 Calculate approximately how the total kinetic energy will be shared by the two fission fragments. (Hint: use conservation of momentum to find the ratio of their velocities.)

3.9 When an alpha particle goes through the gas in an ionization chamber, it loses an average of about 30 electron volts of energy each time it produces an ion pair by disrupting neutral atoms and molecules. An alpha particle of total energy 4 MeV would come to rest after producing about how many ion pairs? How many ion pairs would be produced by a 100-MeV fission fragment? If all the ions are singly charged, about how much negative charge would be collected by the positive plate of the ionization chamber from ion pairs caused by a fission fragment?

In a certain ionization chamber the collection of the ions by the positive plate might take on the order of 1/1000 second. What is the average current in the pulse that would flow from the positive plate to the power supply as a result of the collection of the ions' charge? How might this pulse be detected?

3.10 In order for radium to be produced by neutron bombardment of uranium, two alpha particles would have to be emitted by the bombarded nuclei. The chemical evidence, until the end of 1938, seemed to indicate that radium isotopes were produced in this way.

(a) What sorts of chemical evidence were used?

(b) What was the prevailing opinion among physicists about twofold emission of alpha particles under such circumstances?

(c) Was there any other reason for hesitation among physicists in accepting the chemical evidence for the radium-actinium isomers?

Suggestions for Further Reading

Fermi, Laura, *Atoms in the Family.* University of Chicago Press, 1954. (Now in paperback.) A good biography of Enrico Fermi by his wife, with an excellent account of the early work on fission.

Graetzer, H. G. and Anderson, D. L., *The Discovery of Nuclear Fission.* New York: Van Nostrand-Reinhold Company, a Momentum Paperback, 1971. A documentary history of the discovery of nuclear fission, including many of the original papers, translated (when necessary) into English.

Grodzins and Rabinowitch, Editors, *The Atomic Age.* New York: Basic Books, Inc., 1963. Essays from "The Bulletin of the Atomic Scientists", 1945–1962, by a wide variety of important scientists such as Bethe, Born, Oppenheimer, Goudsmit, Teller, and Bertrand Russell.

Lang, Daniel, *From Hiroshima to the Moon.* New York: Dell Laurel Edition LX134, 1961. A collection of essays on various aspects of the making of the atomic bomb.

Moore, Ruth, *Niels Bohr.* New York: A. A. Knopf, 1966. A popular biography of Bohr; especially good as a portrait of a truly great man and a great scientist.

Turner, L. A., in "Reviews of Modern Physics" Vol. 12, January, 1940, conveys something of the excitement of the early months of fission research.

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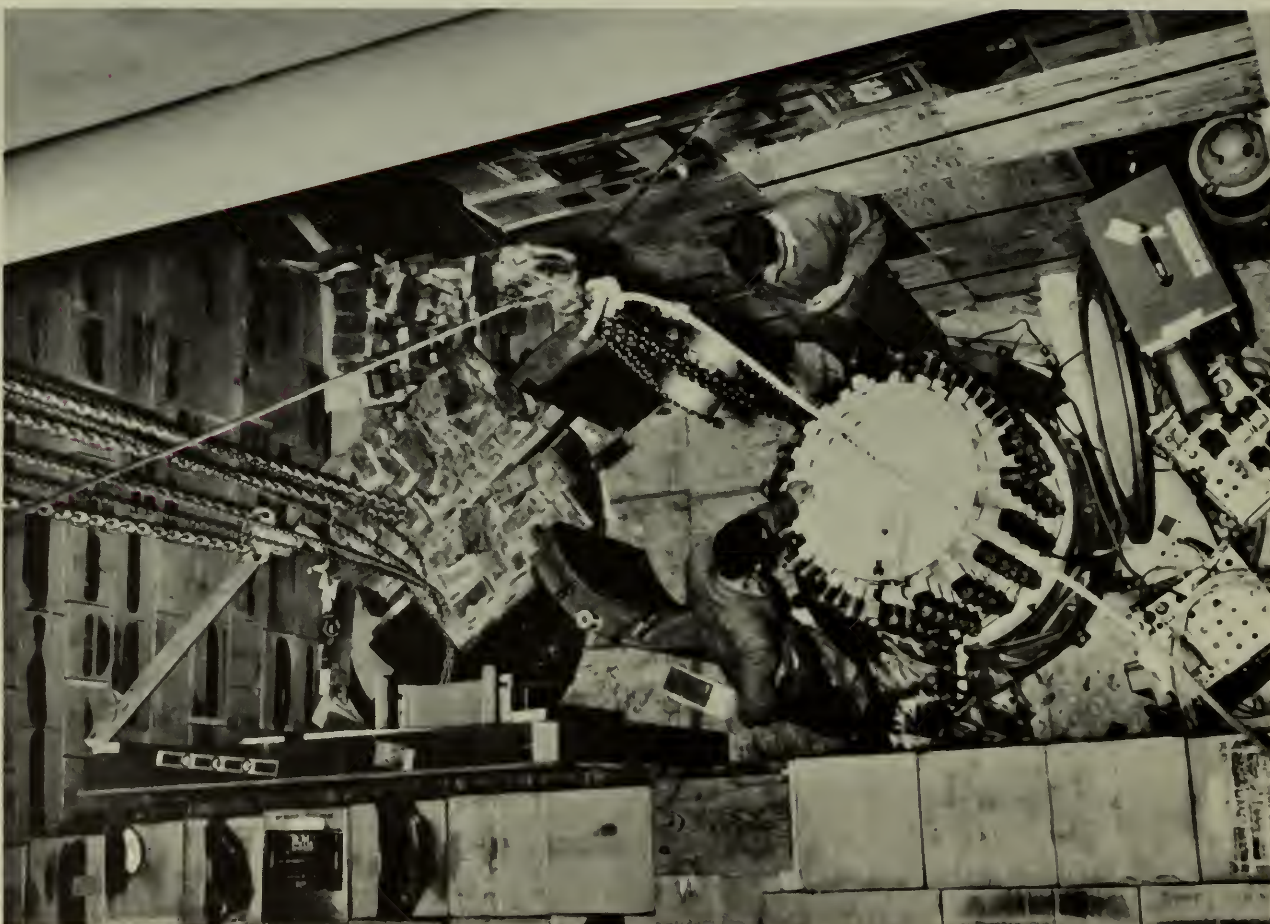


Scintillation counter detector used by Reines and Cowan in their first neutrino experiment at Hanford, Washington, in 1953. The counter, which weighed ten tons, is the cylindrical object at the bottom of the pit.

CHAPTER FOUR

The Neutrino

4.1 Introduction

The planet Neptune was discovered because astronomers took seriously Newton's Law of Gravitation and his Laws of Motion. If one accepted Newton's laws, then one consistent way to account for the very slight deviations of Uranus from its expected orbit was to postulate the existence of a planet beyond that orbit. If one were to give up the inverse square law of gravitation and see whether some other exponent for the distance might account for the deviations, it would mean modifying physical laws which by 1840 had been abundantly verified in countless physical situations.

Nearly 200 years after the discovery of Neptune, the neutrino was discovered because physicists took seriously two other physical principles – conservation of energy and conservation of angular momentum. Experimental nuclear physicists found evidence of an apparent violation of these principles. In order to save the principles, a new particle was invented. We say "invented" because for many years there was no direct experimental evidence for the properties or even the existence of the particle. It was as though Neptune had been "invented" by Leverrier and Adams to save Newton's laws in the face of the peculiar behavior of Uranus – and had then turned out to be totally invisible for many years.

4.2 Products of radioactive decay

Not long after the discovery in 1896 of radioactivity, radioactive materials such as radium and uranium were found to emit three different sorts of rays. Those with shortest range were called alpha rays and in due course were identified as helium nuclei with kinetic energies of up to several million electron volts. The second group, beta rays, could penetrate thicker layers of absorbers; these were found to be negative

See Unit 6, Chapter 21, of the Project Physics *Text* for the story of the discovery of radioactivity and the identification of the products of radioactive decay.

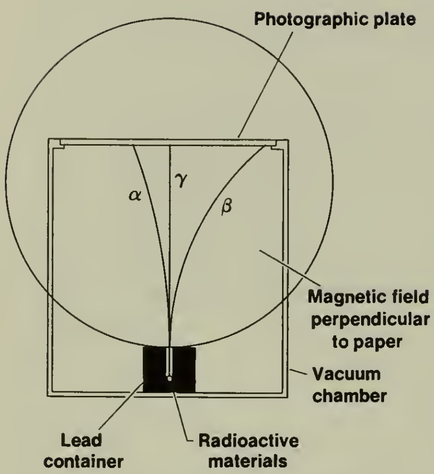


Fig. 4-2 A diagrammatic representation of the behavior of α, β, and γ radiation in a magnetic field.

electrons with energies comparable to those of alpha rays. A third group, gamma rays, could penetrate even further; they were found to be, like x rays, electromagnetic radiation, but they usually had shorter wavelength and higher energies than typical x rays.

Many experiments were devised to measure the relative intensity at various wavelengths of the gamma rays emitted and the relative numbers at various energies of the alpha or beta particles emitted. These experiments describe the spectrum of each of the rays emitted by radioactive nuclei, much as the experiments of Fraunhofer and others described the spectrum of the light emitted by excited atoms. Radioactive isotopes were found to emit line spectra of alpha or gamma rays, with different isotopes emitting different spectra. All the alpha rays emitted by polonium 218, for example, have a kinetic energy of 6.11 million electron volts. Polonium 212 emits gamma rays at a number of different wavelengths, the most intense correspond to energies of 1.80 MeV, 1.6 MeV, 1.51 MeV, 0.953 MeV, and 0.785 MeV.

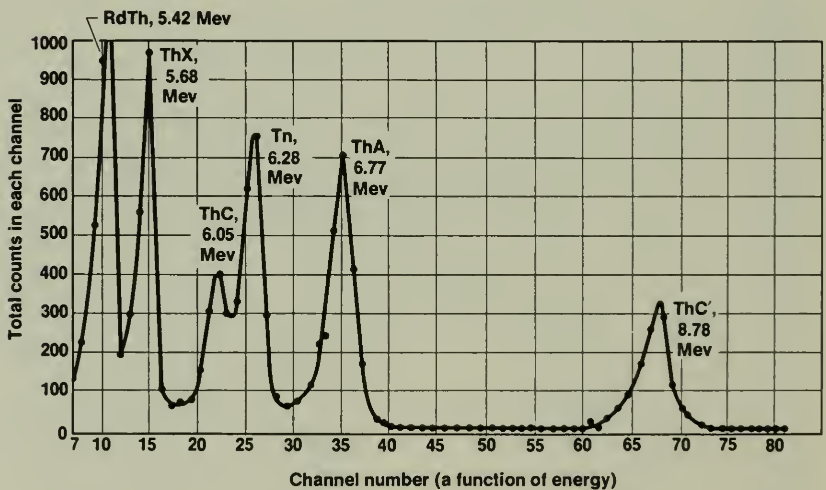


Fig. 4-3 The energy distribution of radiations from various heavy nuclei.

The observation that radioactive nuclei emit line spectra indicated that these nuclei can assume only certain definite energies, just as the existence of spectral lines in the optical spectrum of hydrogen and other atoms indicates that their electrons and nuclei can assume only certain definite energies. In the same way that a study of optical spectra led to the development of much of our modern theory of atomic and molecular structure, so a study of the energy spectra of alpha, beta, and gamma rays has contributed to the development of nuclear theory. The emission of line spectra by both nuclei and atoms indicated that the quantum ideas useful for understanding the behavior of atoms would be important for understanding nuclei.

4.3 Beta decay seems to violate conservation laws

Beta ray spectra produced a puzzle. As early as 1919, James Chadwick, a young English physicist, showed that, unlike alpha and gamma ray spectra, the typical beta ray spectrum was *continuous;* beta rays of all energies from zero up to some maximum energy, E_m, appeared as shown in Fig. 4-4. Some beta ray spectra showed additional sharp lines at definite energies. These were soon found to be not electrons emitted from the nucleus, but orbital electrons from outside the nucleus and will not concern us further here. The beta rays which produce a continuous spectrum come from the nucleus itself.

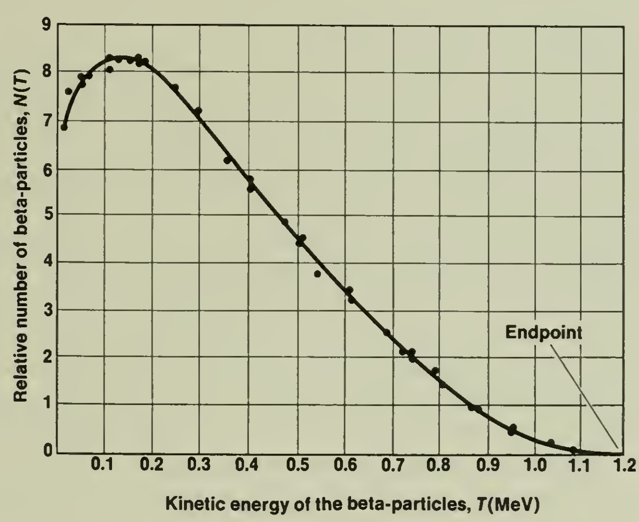


Fig. 4-4 The energy spectrum of the beta particle.

Since the evidence from alpha and gamma ray emission shows that nuclei exist in states with a definite energy, any change that occurs in a nucleus should result in a change in energy equal to the difference between the energy of the original and that of the final state. Specifically, when nuclei in a given state change to a lower energy state by emitting beta rays, each of the nuclei should lose the same energy. Therefore we would expect that each of the beta rays would be emitted with the same energy. The beta rays should show line spectra, but they don't. However, the difference in energy between the parent and daughter nuclei is equal to the *maximum* beta ray energy, E_m, and that, on the average, the energy carried off by a beta ray was considerably *less* than that.

For example, consider the isotope $_{84}Po^{218}$, which occurs in nature as one of the isotopes in the decay chain which includes U^{238} and Ra^{226}. Most Po^{218} nuclei emit an alpha particle of energy 6.11 MeV, becoming $_{82}Pb^{214}$, which in turn sooner or later emits a beta ray, so that it becomes $_{83}Bi^{214}$. The beta ray spectrum has an E_m of 1.03 MeV. The total difference in energy between Po^{218} and Bi^{214} is therefore 6.11 +

1.03 or 7.14 MeV. But how can we account for those beta rays emitted by Pb^{214} with less than the maximum energy of 1.03 MeV? Since the sum of the energies of the alpha particle and the beta ray now is less than 7.14 MeV, it appears that some energy has been lost. One possible answer is that the Bi^{214} has more than one energy state, so that, depending on which state the Bi^{214} is produced in, the beta rays will have different energies.

The existence of another mode of decay of Po^{218} indicates that this is probably not the case. About two out of every 10,000 Po^{218} nuclei decay by emitting a beta ray first. The resulting nucleus, ${}_{85}At^{218}$, then emits an alpha particle, becoming ${}_{83}Bi^{214}$. The maximum beta ray energy here is $E_m = 0.39$ MeV, and the alpha particle energy is 6.75 MeV; the energy difference between the Po^{218} and the Bi^{214} is 0.39 + 6.75 or 7.14 MeV, the same as before.

This makes it apparent that the decays occur from one specific, well-defined energy state of Po^{218} to one specific well-defined energy state of Bi^{214}. In both modes of decay, when the beta ray is emitted with less than the maximum energy, some energy seems to be lost. Furthermore, this "lost energy" can have any value up to 1.03 MeV.

In the 1920's many guesses were made as to what might be happening to the missing energy. Some physicists thought that it might be carried off by unnoticed gamma rays, but careful searches failed to detect them. Another possibility was that not all beta rays are alike; the missing energy might be accounted for by having different masses of beta rays. Much experimentation, however, had shown that all beta rays had the same ratio of charge to mass. To believe in a variety of masses would require a belief in a variety of electric charges – and there was strong experimental evidence against that idea. Finally, one might believe that the principle of conservation of energy simply does not hold for nuclei when they are emitting beta rays. To give up this principle would be an appalling idea; it would shake the very foundations of physics. We shall see that physicists were prepared to go to considerable lengths to preserve the principle of conservation of energy in beta decay.

The study of beta ray spectra also posed a threat to a second conservation principle, the conservation of angular momentum. In your previous work in physics you have used the principle of conservation of linear momentum, which has been a powerful tool for scientists in understanding motion and especially in understanding collision processes. You may also have studied rotational motion and learned that for any system of particles one can define a quantity, angular momentum, which remains constant provided no external torque acts upon the system. A ballet dancer or figure skater can change her rate of rotation by moving her arms in and out – the position of her arms changing the distribution of her mass, one factor in her total angular momentum. If she brings her arms close to her body, her angular momentum remains constant, but her rate of rotation increases.

Theory and experiment in the 1920's had indicated that atoms and subatomic particles, including electrons and nuclei, possessed angular momentum. Just as the electron in a hydrogen atom can have only certain amounts of angular momentum, so nuclei and nuclear particles can have only certain amounts of angular momentum. But there was a difficulty in the beta decay of a typical isotope: the total angular momentum carried by the beta ray and daughter nucleus together after the emission was different from the angular momentum of the parent nucleus before the emission. Therefore, what became of the "missing" energy and also the "missing" angular momentum?

4.4 The neutrino is "invented"

In the early 1930's Wolfgang Pauli, an Austrian theoretical physicist, suggested that in order to save the principles of conservation of energy and of conservation of angular momentum, one would have to assume the existence of a new particle that would be emitted along with the beta ray. This particle would have no electric charge and would have little or no mass, but it would be capable of carrying energy and angular momentum.

Enrico Fermi took Pauli's suggestion and worked out its implications. In a sense, Fermi did for the neutrino (he gave it the Italian diminutive for neutron) what Adams and Leverrier had done for Neptune. The question Fermi asked and answered was essentially, "Can modern theoretical quantum mechanics account for the shape of the beta ray spectrum and the half-life of a given isotope, if we assume that neutrinos exist and have the properties proposed by Pauli?" The analogous question for Adams and Leverrier was, "Assuming that a hypothetical planet beyond Uranus exists, can it account for the observable behavior of Uranus?" The problem faced by Adams and Leverrier required the application of classical Newtonian mechanics and the law of gravitation. The problem faced by Fermi required the use of the then newly developed quantum mechanics and certain assumptions about the interactions between nuclear particles, beta particles and neutrinos.

Fermi succeeded. He showed that if one assumed that a neutrino was emitted along with a beta ray and that the neutrino had the characteristics suggested by Pauli, then the predicted shape of the beta ray spectrum would agree with what was observed experimentally. Further, his theory gave physicists some understanding of how the half-life of a given isotope should be expected to be related to the maximum energy, E_m, of the beta spectrum and to certain other characteristics of the parent and daughter nuclei.

Fermi's work made the neutrino respectable. From 1934 onward, the neutrino was accepted as real on two theoretical grounds: it preserved the laws of conservation of energy and angular momentum, and a theory based on its existence predicted the right shape for beta ray spectra. However, all other known particles—protons, neutrons, electrons, positrons, and photons—could be experimentally detected in one way or another. The neutrino, by virtue of its peculiar characteristics, was, it seemed, undetectable.

4.5 The problem of experimental detection

Detecting a particle means observing its influence on a medium through which it travels. This is easiest if the particle is charged, for then it can exert electric forces on the molecules or atoms or nuclei in its surroundings. For example, a charged alpha particle ionizes the gas along its path in a cloud chamber, and the condensation of water vapor on the ions reveals its path. A charged proton ionizes the gas in a Geiger counter, and the ions, accelerated by the electric field in the counter, produce more ions by collision, which in turn produce still more ions; the ensuing avalanche of ions constitutes a large enough pulse of charge to be detected electrically.

Uncharged particles are detected more indirectly. A neutron shot into paraffin can knock protons forward. The moving proton, being charged, can then be detected in a number of ways, and its detection implies the presence of the neutron which hit it.

With no electric charge and essentially no mass, the neutrino cannot directly affect molecules or atoms. It is, according to the theories of Pauli and Fermi, immune to the nuclear force, and therefore it cannot affect protons as the neutron does. Since it has little or no mass, even if it did interact with another particle, the other particle would be virtually unaffected; it is the virtually undetectable neutrino which would be deflected—like a ping pong ball thrown at an elephant.

Since it interacts almost not at all with other particles, the range of motion for the neutrino is huge. We now know that before interacting with another particle, a typical neutrino from a beta decay would travel about 100 light years in a material like liquid hydrogen—that is, about 1 1/2 million round trips to the sun:

Such a peculiar particle was, of course, a challenge to the experimental physicist. Surely there must be some way to detect it! And eventually there was—but it had to wait a good many years for certain technological developments. From time to time in science a good theory will have to wait, sometimes years, before technology has developed enough to provide the tools needed for an experimental test. To understand what technology had to develop, let us go back and look at the reactions in which neutrinos are produced. A typical beta ray decay process might be

ν is the Greek letter nu.

$$ {}_{85}Pb^{214} \longrightarrow {}_{83}Bi^{214} + {}_{-1}e^{0} + {}_{0}\nu^{0}(-) \qquad (4.1) $$

in which $_{-1}e^0$ represents the negative beta ray, and $_0\nu^0(-)$ represents the neutrino. The minus sign in parenthesis is not the neutrino's charge (it is uncharged); it is to remind us that the neutrino was formed in a negative beta decay—an important reminder, as we shall see.

One can think of the decay process represented in Eq. (4.1) as involving the conversion of a neutron, within the Pb^{214} nucleus, into a proton. Such conversions occur, in fact, with free neutrons:

$$_0n^1 \longrightarrow {}_1p^1 + {}_{-1}e^0 + {}_0\nu^0(-) \quad (4.2)$$

Fermi's theory suggested that a converse reaction might occur: a neutrino and a proton might combine to produce a neutron and a positron ($_{+1}e^0$).

$$_1p^1 + {}_0\nu^0(-) \longrightarrow {}_0n^1 + {}_{+1}e^0 \quad (4.3)$$

One could estimate from Fermi's theory, and from the characteristics of free neutron decay, that what physicists call the cross section for the process indicated in Eq. (4.3) would be about 10^{-43} cm^2. In Section 3.3 we said that the cross section for a process is a measure of the probability that the process will occur under given circumstances. In the case of a target particle being hit by an incoming particle, the cross section for the event is the effective area of the target particle as seen from the direction of the incoming particle. (If the target were a large object, this would be equivalent to the area of its shadow on a wall immediately behind it.) The cross section depends on the process as well as the target. The cross section for scoring with a basketball is smaller than the cross section merely for hitting some part of the basket, just as the cross section for blowing out a candle with a puff of air is smaller than the cross section for making it flicker. The cross section of a proton for interacting with a relatively slow-moving neutron is of the order of 10^{-24} cm^2.

To observe the reaction described by Eq. (4.3), then, one would need to have a very large number of protons, and a huge number of neutrinos flowing among the protons, because the cross-section is so small. The large number of protons requires a large volume. A large volume means long distances between the events and the detectors, and hence some very sensitive detecting devices (scintillation counters) are needed to detect the reaction products. Neither the large flux of neutrinos nor the very sensitive scintillation detectors became available until after World War II. Finally, in 1956, Frederick Reines and Clyde Cowan, than at the Los Alamos laboratory, were able to announce that they had actually "found" some neutrinos reacting as in Eq. (4.3).

When a high energy particle (such as a beta particle or a gamma ray photon) is absorbed in certain liquids or solids, some of the energy of the particle is converted into a very weak flash of light, or *scintillation.* Some of the early research in radioactivity was carried out by observing and counting these scintillations with no tools but the human eye and brain. Modern apparatus observes the scintillations by use of very sensitive photoelectric cells.

4.6 The Reines-Cowan experiment

To obtain a large flux of neutrinos, Reines and Cowan needed enormous numbers of beta decays going on. These were produced by one of the nuclear reactors that were a development of nuclear fission research during World War II. Fission products, as we saw in Chapter 3, are strongly radioactive. When a huge nuclear reactor is turned on and off, the amount of beta activity in the reactor goes up and down. It does not disappear immediately when the reactor is turned off, because, as in all decay processes, a time constant is involved. But the intensity of the neutrino flux is strongly dependent upon the power level at which the reactor is working – which, of course, is directly related to the number of fission processes per unit time.

The experiment carried out by Reines and Cowan, using the large reactor at Savannah River as a neutrino source, was designed to detect events described by Eq. (4.3). The reactor provided a large flux of neutrinos (about $1.3 \times 10^{13}/cm^2/sec$ as calculated from the fission reaction rate). The detector consisted of a tank containing 1400 liters (about 370 gallons) of an organic liquid which included 8.3×10^{28} protons and a small amount of a cadmium compound. The detector also included counters to record the scintillations produced by the gamma rays released upon the creation of a neutron and a positron – the products of the hoped-for reaction.

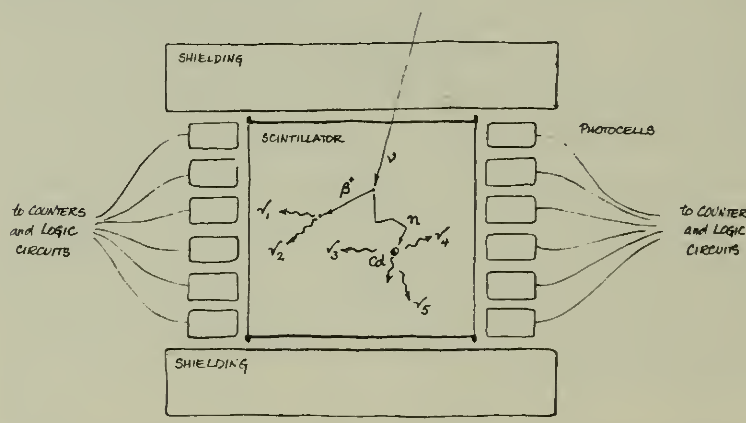


Fig. 4-5 Schematic example of neutrino reaction in a scintillation tank.

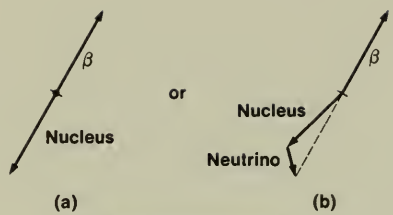
Fig. 4.5 shows a sequence of events in which a neutrino interacts according to Eq. (4.3) with a proton in the scintillation tank. The positron, β^+ or ${}_{+1}e^0$, moves off a short distance, but slows down very rapidly and meets an orbital (negative) electron. The positron and the electron annihilate each other, and their energy emerges in the form of two gamma rays, γ_1 and γ_2, each with an energy of approximately 0.5 MeV. These gamma rays are absorbed by the scintillator liquid, and a flash of light appears in the tank – the intensity of the flash depending upon the gamma ray energy. This flash is detected by two banks of large photomultiplier cells. If both banks "see" the light flash, and if the flash is within the expected range of gamma-ray energies, then a signal is accepted which alerts the logic circuits of the associated equipment. Meanwhile, the neutron ${}_0n^1$ loses energy as it bounces from proton to proton. Eventually (and that means, on the average, after 5 to 20 microseconds) the neutron will be going slowly enough to be absorbed by a cadmium nucleus. A group of gamma rays, represented by γ_3, γ_4, γ_5, and γ_6 in Fig. 4-5, are emitted during the absorption process. These, in turn, are absorbed by the scintillator liquid, with each producing a flash detected by the photocells. The alerted logic circuits then register an "event" when a neutron-absorption-by-cadmium pulse is received in an appropriate time interval (from 0.75 to 30 microseconds) after an electron-positron annihilation pulse. Another big scintillation tank, with associated photocells and circuits, is used to screen out, or prevent the counting of, spurious events caused by highly energetic cosmic rays coming through the apparatus. Such devices, plus careful shielding, reduced the number of spurious events counted.

When the reactor was operating, Reines and Cowan found that there were 36 ± 4 events per hour more than when the reactor was not running. By taking into account the size of the flux and the number of protons in the target tank, they concluded that the cross section for the reaction was $(1.1 \pm .26) \times 10^{-43}\text{cm}^2$, as predicted by the theory. This cross-section is about 10^{20} times smaller than that for ordinary nuclear reactions.

This experiment provided the first relatively direct experimental evidence that neutrinos exist and are produced during beta decay of radioactive materials. One says "relatively" direct because, of course, one could not see, hear, or feel the neutrinos directly. But then we do not see, hear, or feel electrons or protons or neutrons, either. Of course, in the case of these more familiar particles, the experimental and conceptual steps which lead us to say, "These observable phenomena are surely due to such-and-such a particle," are rather more straightforward. But Reines, Cowan, and their colleagues at least succeeded in clothing the neutrino with a reality beyond that provided only by faith in the conservation laws and a theoretical prediction. In addition, the cross section they measured was more than just an impressively small number. It was useful in helping physicists to decide between two opposing theories which had developed as to the basic nature of the neutrino.

4.7 Neutrinos conserve linear momentum

There had been other attempts to demonstrate the existence of neutrinos by experiment. Beginning in 1936, a series of experiments by many people, had been carried out to show that neutrinos carry away linear momentum as well as energy and angular momentum. The idea behind such experiments is simple. If a nucleus emits a beta ray and a neutrino, then the beta ray track should be detectable, as in a cloud chamber, going in one direction and the recoiling daughter nucleus in another. If there were no neutrino, or if it carried no linear



Momentum diagrams

momentum, then the law of conservation of linear momentum would require that the beta ray and the nucleus go in opposite directions and that the vector sum of their momenta be zero. If there is an undetectable neutrino emitted along with the beta ray, the beta ray track and the recoil nucleus track would go off at some angle less than 180° from each other, and the vector sum of their momenta would be opposite to the momentum of the neutrino.

Even simpler in theory are those cases in which an isotope decays not by beta ray emission, but by the capture of one of the inner orbital electrons into the nucleus. The net effect is much like emission of a positive beta ray, so presumably a neutrino is emitted in the process. The observable recoil momentum of the atom after the event in one direction is numerically equal to the momentum of the neutrino in the other. In this case, since all captured electrons had a definite energy, the neutrinos will also have a definite fixed energy and form a line-spectrum rather than a continuous spectrum as in ordinary beta decay. If recoil atoms could be observed, and if all of them (for a given isotope) were found to have a definite momentum, this would confirm the idea held by most physicists that only one neutrino is emitted during a decay process.

Experiments designed to detect such recoils are difficult because such a recoiling nucleus has a small amount of energy. Each one, therefore, travels only a short distance through the gas of a cloud chamber. (The energy can be calculated from the conservation laws, as in any collision or two-body explosion problem.) The recoil energies come out to be of the order of 100 electron volts or less, compared with, for example, energies of 4000 times that much for the recoil energy accompanying the emission of a typical alpha particle.

By 1948 a variety of experiments had shown that recoils could be observed. Such observations confirmed what people expected—that the neutrino would obey the law of conservation of linear momentum as well as those of conservation of energy and angular momentum. All of these experiments, of course, dealt with the *emission* of neutrinos. The experiments of Reines and Cowan were first to show unambiguously an effect due to the *absorption* of a neutrino.

4.8 The antineutrino

In 1955 Raymond Davis, of the Brookhaven National Laboratory, reported a different sort of experiment in which he had attempted to find reactions caused by neutrinos. More exactly, his experiment had best be thought of as an attempt to *rule out* a certain kind of reaction. It was known that an isotope of argon, A^{37}, decays with a half-life of 34 days, by orbital electron capture, to become an isotope of chlorine and, it was thought, emit a neutrino. Such a reaction may be represented by the equation

$$_{18}A^{37} + {}_{-1}e^0 \longrightarrow {}_{17}Cl^{37} + {}_0\nu^0(+) \qquad (4.4)$$

One writes ${}_0\nu^0(+)$ because the neutrino thought to be produced in this reaction would be the same sort of neutrino as is produced in positron (${}_{+1}e^+$) emission.

Neutrinos ought to be able to produce the converse reaction:

$$ {}_{17}\text{Cl}^{37} + {}_0\nu^0(+) \longrightarrow {}_{18}\text{A}^{37} + {}_{-1}e^0 \tag{4.5} $$

But meanwhile theoretical physicists had suggested that there were probably two kinds of neutrinos – those emitted during decays producing *negative* electrons and those emitted during decays producing *positrons* – and that one would not be able to make A^{37} from Cl^{37} with $\nu(-)$ neutrinos, the wrong neutrinos for this process. Davis' experiments, then, were an attempt to show that an intense flux of $\nu(-)$ neutrinos (from a uranium reactor) would have little or no effect in going through large amounts of Cl^{37}. First at Brookhaven, and then later with two 500-gallon tanks of chlorine-rich carbon tetrachloride at the Savannah River reactor, Davis first bubbled very pure helium through to pick up and carry off any argon already in the tanks from reactions produced by cosmic rays or other contaminants. Then after the tank had been irradiated for several weeks by the neutrino flux from the reactor, a small amount – about 0.1 cm^3 – of pure (nonradioactive) argon (A^{40}) was introduced as a carrier for any radioactive argon nuclei that had been formed by the reaction described in Eq. (4.5). The argon was then flushed out with helium, purified, and then inserted into a small Geiger counter. (Quite literally "into" – that is, the argon was added to the gases already inside the counter itself.) Careful shielding of the counter was provided to limit the background counting rate. Davis' results showed that, within the limits imposed by his very small background counting rates, there was no measurable activity that would indicate the presence of argon 37 produced from the chlorine. He could express his results numerically by saying that the cross section for the reaction given by Eq. (4.5) rewritten for $\nu(-)$ was less than 0.9×10^{-45} cm which is about a factor of 100 smaller than the cross section for the reaction of these neutrinos with protons.

Davis, then, provided experimental confirmation for the idea that there really are two different sorts of neutrinos. We have called them $\nu(+)$ and $\nu(-)$, but the generally accepted usage now is to call $\nu(+)$ the *neutrino* and $\nu(-)$ the *antineutrino*. The symbols for the neutrino and the antineutrino are ν and $\bar{\nu}$ respectively.

Like most fundamental particles, neutrinos and antineutrinos possess angular momentum; they can be pictured as spinning on an axis. The difference between neutrinos and antineutrinos is their direction of spin. If you could see a neutrino moving away from you, you would see it spin around the axis of its direction of travel in a clockwise sense, whereas you would see an antineutrino spin around the axis of its direction of travel in a counterclockwise sense.

We have seen, so far, that the neutrino provided us with a good example of the sort of scientific discovery that came about because experimental observations (in this case, the beta ray spectrum) contradicted what was expected on the basis of well-established principles (in this case the principles of conservation of energy and of angular momentum). The particle "invented" by Pauli in order to avoid giving up these laws then turned out to be useful in Fermi's theory of beta ray emission. The theory prompted other experiments, particularly the nuclear recoil experiments, that gave results which strengthened belief in the particle. But not until twenty years had elapsed—and a whole new technology had developed—was it possible to detect neutrinos by their interactions with matter. Meanwhile, theory had suggested that there might be two sorts of neutrinos—neutrinos and antineutrinos, a suggestion confirmed by experiments such as those by Davis.

4.9 The muon's neutrino and antineutrino

The story does not stop there. The neutrino has turned out to be both useful and intriguing in many areas of physical research. And it has turned out that there are not just two kinds of neutrinos, but at least four. This discovery owes itself to a number of developments that have taken place in particle physics since the neutrino was "invented."

After World War II there were spectacular advances in the development both of accelerators to produce high-energy particles and of methods for observing the behavior of particles. In the postwar years, cyclotrons and other accelerators were built with higher and higher output energies—first with tens of millions of electron volts, then with hundreds, then, in the mid-1950's, with a billion electron volts or more, and on up to 20 and 30 billion electron volts in the mid-1960's. Meanwhile, in addition to Geiger counters and ionization chambers, new devices such as scintillation counters, photographic emulsions, bubble chambers, spark chambers, and highly complex electronic control circuits were developed.

One result of these developments was that many new particles were discovered. As early as the middle of the 1930's, particles with masses between the mass of the electron and that of the proton had been found in cosmic rays. Originally they were called *mesotrons* (meaning intermediate-mass particles) and later *mesons.* When more and more such particles were discovered as increasingly effective equipment became available after World War II, it became apparent that the so-called *mu-mesons,* which were the lightest members of the family (with masses about 200 times that of the electron) were not members of the meson family at all. They were much more closely related to electrons. They are now called *muons*. Muons, it was found, decayed into positive or negative electrons. A typical muon decay could be written as

$$\mu^+ \longrightarrow {}_{+1}e^0 + \text{energy} + \text{momentum} \tag{4.6}$$

Cloud chamber and other observations indicated that the energy and momentum from a muon decay probably would have to be carried away, not by one, but by two neutral particles. One of them would no doubt be a neutrino associated with the production of the ${}_{+1}e^0$, while the other was thought to be an antineutrino associated with the disappearance of the μ^+. But the theory of such interactions predicted that if both neutrinos were of the same sort (although one of them an antineutrino), then on at least some occasions the muon decay process ought to produce a gamma ray. But such gamma rays were not found. So here again theory suggested a new kind of neutrino, which we shall denote by ν_μ, and its antiparticle, denoted by $\overline{\nu}_\mu$.

In 1962 Gordon Danby, Leon Lederman, and their collaborators at Brookhaven carried out an experiment suggested by other physicists to check this hypothesis. The accelerator at Brookhaven was used to produce a beam of protons with an energy of 15 billion electron volts. These protons, upon hitting a suitable target, produced a fairly intense beam of pi-mesons, which are particles somewhat heavier than muons. In traveling about 20 meters (in a few hundredths of a microsecond), some of the pi-mesons decayed into muons and high-energy neutrinos. The remaining pi-mesons and the muons were stopped in steel shielding forty feet thick. Few neutrinos would be absorbed by this shielding. (The steel was armor plate from a dismantled battleship. If prophets in an older culture dreamed of turning swords into plowshares, it is pleasing to know that in our day battleships can be turned into apparatus for scientific research.) The neutrinos – all but a very few – went right on through.

What the experimentalists were trying to detect were reactions between the neutrinos and some protons. If the neutrinos from the pi-mesons were the same as the beta-ray-produced neutrinos, then a neutrino-proton collision should produce high-energy electrons.

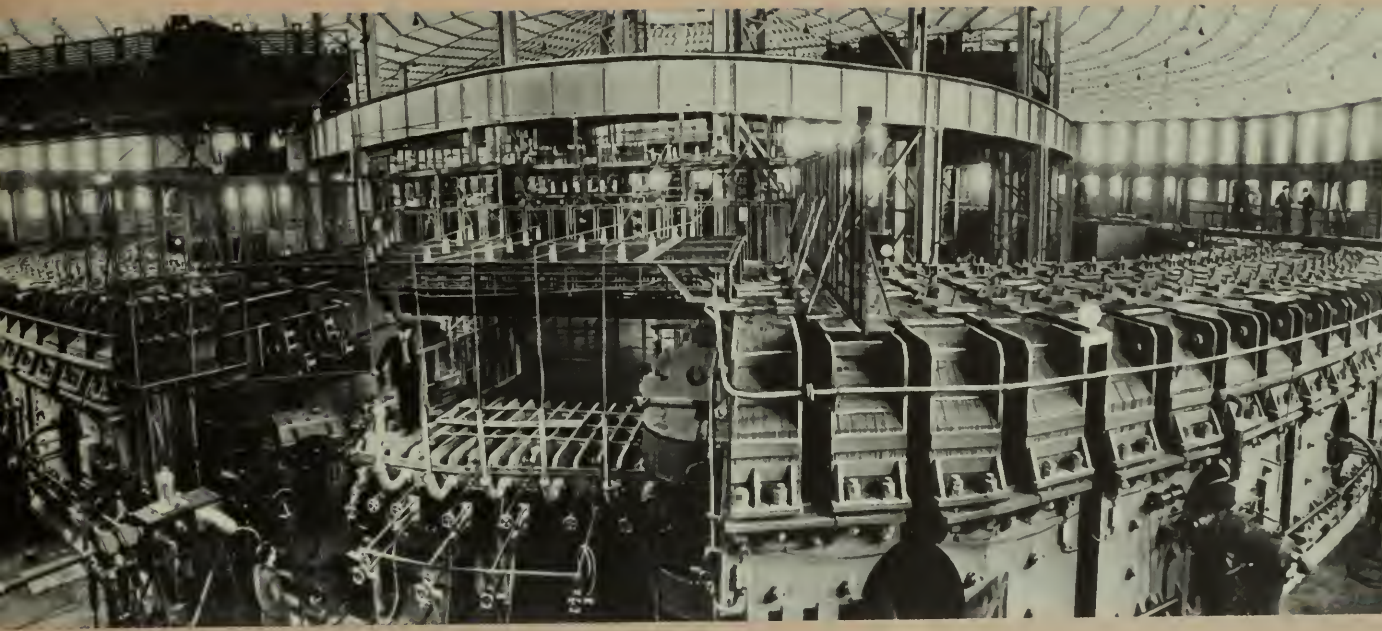
$$\nu_\pi + p \longrightarrow e \tag{4.7}$$

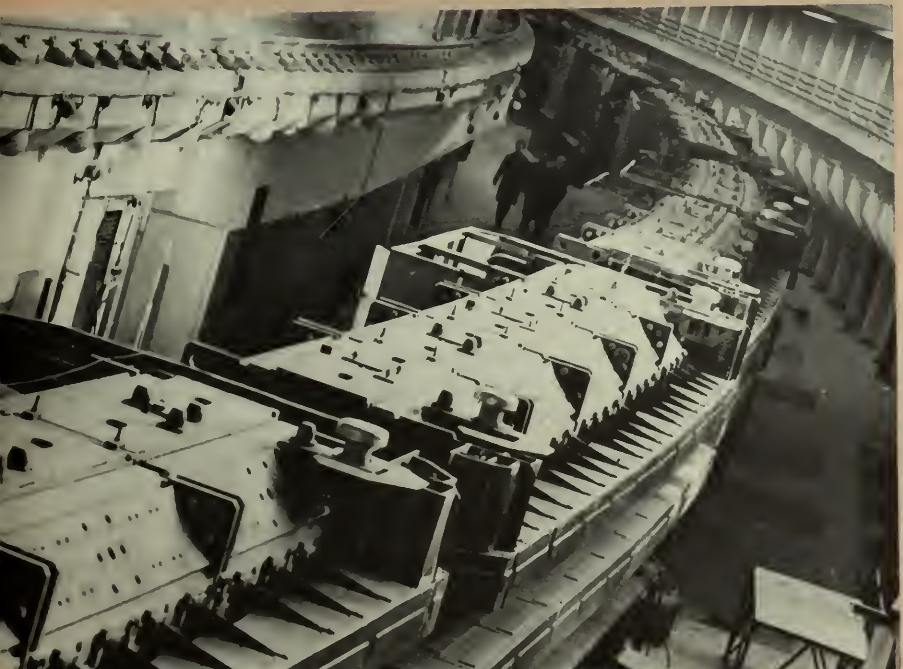
If they were not, then the neutrino-proton collisions should produce high-energy muons.

$$\nu_\beta + p \longrightarrow \mu \tag{4.8}$$

(In its search for neutrino-proton collisions, the experiment was like the Reines-Cowan experiment, with high-energy accelerator-produced neutrinos, rather than relatively low-energy, nuclear-reactor-produced neutrinos.)

On these pages are shown some of the important nuclear research laboratories where American and Russian physicists are probing the basic structure of matter. The photograph at the right shows the bending magnets in a section of the National Accelerator Laboratory located in Illinois. The aerial view below gives some idea of the area occupied by this enormous particle accelerator, 1.24 miles in diameter, and with a circumference of four miles. Within this giant ring, protons are accelerated to energies which are expected to reach 500 BeV.





Russian nuclear physicists are doing important research at the two installations shown on this page. Above, is the 10 BeV capacity proton synchrotron accelerator located at the Dubna Joint Nuclear Research Institute. Below, is the proton synchrotron at Serpukhov which began operation in 1968. Its capacity is rated at 70 BeV.

How did they detect the reactions? Behind the shielding was a spark chamber containing 90 aluminum plates, each an inch thick and four feet square, and spaced 3/8 inch apart. The space between plates was filled with neon gas. When a charged particle goes through the plates of a spark chamber, it leaves many free electrons and ions in its path in the gas between each plate. The alternate plates can be charged quickly to a high potential difference, which makes a visible spark jump just where the electrons and ions were. Stereo photographs can then be made to record the path of the original high-energy charged particle.

Elaborate precautions had to be taken to avoid photographing thousands of useless tracks made by muons from cosmic rays and by other background phenomena. The spark chamber, for example, was made to be sensitive only during beam pulses, which occurred every 1.2 seconds and which lasted for only 3 microseconds each. The experiment continued for some eight months, for a total of about two million pulses—so the equipment was actually sensitive for a total of only about six seconds during the eight months. But as many as 10 million neutrinos passed through the spark chamber for every pulse, and about 10^{14} traversed it during the whole run. About 50 of them interacted with protons within the spark chamber, and produced muon tracks. If the pi-meson-produced neutrinos were identical with the beta-ray-produced neutrinos, then one would have expected about half of the tracks to have been due to electrons. The gratifying thing, however, was that virtually no *electron* tracks were produced. (Electron tracks are readily distinguishable from muon tracks.) Therefore, the reaction described, equation 4.7 does not occur, while the reaction described by equation 4.8 is confirmed. The experiment, which in more recent years has been extended to higher energy sources, firmly established the idea that there were two quite different kinds of neutrinos, each with its own antiparticle. The question remains as to how the two kinds of neutrinos are related to each other.

4.10 Questions the neutrino may help answer

One delightful aspect of science is that quite often the solution of one puzzle raises other questions. But in some cases, the solving of a puzzle makes it possible to understand phenomena which had been confusing in other areas of physics, or to verify experimentally some hypothesis which, until that time, could not be checked directly. It is thought, for example, that ordinary stars produce their heat energy by means of certain nuclear reactions. Such reactions must produce large numbers of neutrinos and antineutrinos. It would be nice to be able to test the hypothesis by detecting the neutrino flux from the sun. Frederick Reines has designed a detector, with a mass of about a thousand tons, as a step toward the detection of neutrinos from the sun.

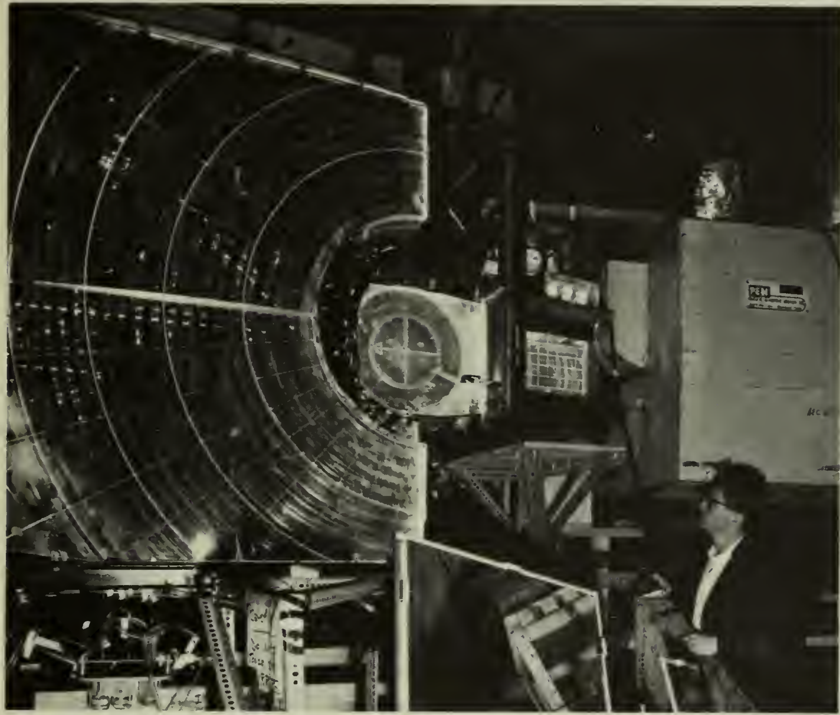


Fig. 4-8 Left, a spark chamber at the Bevatron, Berkeley, California. Right, particle tracks photographed in a spark chamber.

On a more speculative level, astrophysicists have recently been considering reactions that might take place in the interiors of large stars with exceptionally high interior temperatures—temperatures of the order of a billion degrees Kelvin or more. The very short-wavelength photons inside such stars would produce large numbers of electron-positron pairs. It has recently been suggested that under such circumstances many of these electrons and positrons can suddenly recombine, or annihilate each other, not only by the usual process in which two gamma rays (i.e., high-energy photons) are produced, but by producing two neutrinos. Gamma rays, which interact with stellar material easily, would only slowly transfer their energy up to the surface of the star and beyond. The neutrinos, however, interact so rarely that most of them would escape from the star, traveling with the speed of light.

Thus it would be possible for a star, once it achieves such a high interior temperature, to lose vast amounts of energy almost instantaneously by emitting neutrinos. Such a star would shrink, and the gravitational energy associated with the collapse would cause—at least temporarily—the production of even higher interior temperatures. Such a theory may account for at least some of the behavior of supernovae. H. Y. Chiu has calculated that a supernova 1000 light years away would give off enough neutrinos in such a process that about ten of them might be detected on our planet, in a time span of from 100 to 1000 seconds, by a detector containing some 10,000 tons of sensitive material.

4.11 Some themes in scientific discovery

The "invention" and the detection of the neutrino have illustrated for us, then, several themes that are common in scientific discovery. One theme is the interaction among theory, physical experiment, and technology. Two well-established physical laws are apparently violated. Theorists therefore hypothesized a new particle to preserve the laws. The particle turned out to have considerable utility in the development of the theory of beta ray decay in radioactivity. Then the development of technological devices (in particular, large scintillation counters and sophisticated electronic circuits) made it possible to detect the absorption of the particle in spite of its elusiveness. Meanwhile, the growing understanding of the role of the neutrino in the theory of particle interactions has raised further questions both in physics and in astronomy.

A second theme we should note is that the experiments required tremendous resources, both in sheer bulk and consequent expense, and also in pushing available techniques to extremes of sensitivity. (In the Danby experiment with the pi-meson-produced neutrinos, the apparatus muons had to be selected from cosmic ray muons which appeared at a rate of about 80 per second, when the sought-after events were occurring at a rate of only 50 in eight months.) By no means all important theories in physics need experimental tests requiring such staggering equipment and effort—even in these days of "big science." But some do.

Meanwhile, if it took you an hour to read through this chapter, some 10^{18} neutrinos from the sun's nuclear reactions streamed through you during this time. But even with this large number there is less than one chance in a hundred that a single one of these neutrinos interacted with one of the perhaps 10^{28} protons in your body. When such a reaction does occur it produces no detectable changes in your body.

STUDY GUIDE

4.1 State in your own words an argument that begins with the observation that atoms emit a line spectrum and concludes that atoms exist in states with a definite energy.

4.2 How does the evidence that polonium-218 decays to bismuth-214 by two distinct paths support (a) the conclusion that only one energy level of polonium and one energy level of bismuth is important, and (b) the conclusion that in cases of beta decay, the radioactive nucleus loses energy equal to the maximum energy of beta rays emitted?

4.3 In addition to accounting for the missing energy, what other experimental findings did Fermi's theory of beta ray emission help explain?

4.4 What characteristics of the neutrino made it expecially difficult to detect? How did Reines and Cowan overcome these difficulties?

4.5 Recoils were observed for atoms undergoing orbital electron capture as early as 1948. Why are Reines and Cowan credited with being the first to detect the neutrino when these recoils indicated that the nucleus must have emitted a neutrino?

4.6 List the four types of neutrinos and indicate a reaction for producing each one of them. What sort of evidence indicates that we cannot get along with three or fewer neutrinos?

4.7 How might neutrinos account for stellar novae? What additional evidence would you want before concluding that neutrinos play an important role in stellar novae?

4.8 Bismuth-214 ($_{83}Bi^{214}$) nuclei usually decay by emission of negative beta rays with a maximum kinetic energy of 3.26 MeV, and turn into polonium-214 ($_{84}Po^{214}$). Polonium-214 emits an alpha particle almost at once (half-life 0.00016 sec.), with a kinetic energy of 7.83 MeV.

A small fraction of the Bi^{214} nuclei decay by another route, first emitting an alpha particle of energy 5.61 MeV and turning into thallium-210 ($_{81}Tl^{210}$). The Tl^{210}, in turn, decays by emission of a negative beta ray with a maximum energy of 5.48 MeV.

Show that both decay routes lead to the same end product, and that the total energy available in going from Bi^{214} to that end product is the same for both routes.

4.9 One can estimate very roughly that the average energy for the beta rays in the spectrum represented in Fig. 0.0 is about one-fourth of E_m. Making the rather rash assumption that the average energies of the beta rays for the *two isotopes* in Problem 4.8 are also one-fourth of the corresponding E_m's, show that the two decay routes do not lead to the same energy state for the final product, if the average energies are used rather than maximum energies. (Actually you can show this would be the case if any reasonable fraction were used instead of the estimated one-fourth.)

4.10 Beryllium-7 ($_4Be^7$) nuclei ordinarily decay by capturing a K-orbit electron, with a half-life of 53.4 days, and changing into lithium-7 ($_3Li^7$). (The end result of a K-capture process is the conversion of a proton inside the nucleus into a neutron and has essentially the same effect as the emission of a positive beta ray from $_4Be^7$ would have had if there had been enough energy for that to have occurred.) When the electron is captured, a neutrino is emitted. A study of the masses of Be^7 and Li^7 indicates that the neutrino must take with it an energy of about 0.86 MeV.

According to the relativity theory, the momentum of a massless particle, such as a neutrino, can be calculated by dividing its energy by the speed of light. Use the conservation of linear momentum to show that the Li^7 recoil energy is about 57 electron volts. (Note: the recoil energy is so small that it can be written as $1/2mv^2$ in which m is the mass of the recoiling atom and v is its velocity. Note also that the mass of a proton multiplied by c^2 is 931 MeV.)

4.11 Assume that the beam of neutrinos that Danby and his collaborators used at Brookhaven had a cross-sectional area S. The beam went through a thickness, L, of aluminum plates. The volume of aluminum traversed by the beam would then be $V = LS$. The mass, M, of aluminum in that volume would be $M = DV = DLS$, if D is the density of aluminum. If we divide this mass by the atomic weight of aluminum, A, we would get the number of moles of aluminum, n, in that volume: $n = DLS/A$.

If we now multiply the number of moles by N_0, Avogadro's number, we should get the number, N, of aluminum atoms (and hence the number of aluminum nuclei) in the volume: $N = DLSN_0/A$. Now let us assume that each of these nuclei presents some very small cross section, σ, to an incoming neutrino. The total area available for reactions would be N times σ. If we divide this area by the cross-sectional area of the beam, we should get the probability, P, that any given neutrino would react with an aluminum nucleus.

$$P = N\sigma/S = DLN_0S\sigma/AS = DLN_0\sigma/A$$

If N_r reactions occur when a total of N_ν neutrinos go through the plates, show that

$$\sigma = \left[\frac{N_r}{N_\nu}\right]\left[\frac{A}{DLN_0}\right]$$

Given the dimensions of the spark chamber, the total number of neutrinos traversing it for a given number of recorded reactions, and looking up the density and atomic number of aluminum, and Avogadro's number, estimate the cross section of the aluminum nuclei for reactions with muon neutrinos.

Why is it permissible to neglect consideration of the neon gas between the plates in doing these calculations?

4.12 Compare the neutrino with constructs in another field, for example with id, ego, and superego in psychology, or the gene, or the atom. What elements do the history of these concepts have in common? What are the important differences?

STUDY GUIDE

Activities

1 Read the Smythe report and *The German Atomic Bomb* (see "Suggestions for Further Reading" at end of Chapter 3). Write an essay contrasting one or more of the most significant differences between the American and German experience.

2 Consider the credibility of the neutrino hypothesis at four stages: (a) when first proposed by Pauli; (b) after Fermi's theory of beta decay; (c) following the discovery of recoils of atoms following electron capture by nuclei, and (d) following the experiment of Reines and Cowan. Suggest criticisms which might have been made of the neutrino hypothesis by philosophers of science and by scientists and see how these criticisms changed from one stage to another. Discuss the appropriateness of these criticisms.

3 Was the costly experiment of Reines and Cowan worth doing? Argue either side of the case (or both sides, if you like). Consider possible outcomes as well as those that did occur, the extent to which the experiment was fruitful of other experiments, as well as the possibility for alternative experiments.

Suggestions for Further Reading

Allen, James S., *The Neutrino*. Princeton University Press, 1958. A comprehensive account of what was known about the neutrino prior to the Reines-Cowan experiments.

Asimov, Isaac, *Heaven*. Garden City: Doubleday and Co., Inc., 1966. The author raises the question of why it took chemists so long to discover that the noble gases can form compounds.

Bernstein, Jeremy, *The Elusive Neutrino*. U.S. Atomic Energy Commission, 1969. A fine introduction to neutrino physics, available free from USAEC, P.O. Box 62, Oak Ridge, Tennessee 37830.

Cohen, I. Bernard, *Science, Servant of Man*. Boston: Little, Brown and Co., 1948. A discussion of the fortunate "accident" in scientific discovery and of the practical application of scientific knowledge.

Conant, James B., *On Understanding Science*. New York: New American Library, Inc., 1947. An analysis of the processes of scientific discoveries, with case histories of research in gases, electricity, and combustion.

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Crane, H. R., "Energy and Momentum Relations in Beta-Decay, and the Search for the Neutrino," *Reviews of Modern Physics*, Vol. 20 (January 1948). An article summarizing the experimental evidence in 1947 for the neutrino.

Holton, Gerald (Ed.) *The Twentieth-Century Sciences: Studies in the Biography of Ideas*. New York: W. W. Norton, 1971. Includes biographical and autobiographical accounts of the discoveries of such scientists as Einstein, Bohr, Linus Pauling, F. Crick, E. Erikson, A. Weinberg, R. R. Wilson, *et al.*

Koestler, Arthur, *The Sleepwalkers*. New York: Grosset and Dunlop, Inc., 1963. Subtitled "a history of man's changing vision of the universe."

Lederman, Leon, "The Two-Neutrino Experiment," *Scientific American*, Vol. 208 (March 1963). An account of the experiment that demonstrated that there are two kinds of neutrinos.

Lederman, Leon M., "Resource Letter on History of the Neutrino, (Neu-l)," American Journal of Physics, 38 (1970), pp. 129 ff. A very valuable guide to the whole literature, obtainable by sending a request with 25c and a stamped return envelope to Department RL, American Association of Physics Teachers, 1785 Massachusetts Ave. N.W., Washington, D.C. 20036.

Morrison, Philip, "Neutrino Astronomy," *Scientific American*, Vol. 207 (August 1962). What we can learn about stars from a study of neutrinos striking the earth.

Reines, Frederick, "Neutrinos, Old and New," *Science*, Vol. 141 (August 30, 1963). A brief article summarizing the evidence that there are four kinds of neutrinos.

Reines, Frederick and Sellschop, J. P. F., "Neutrinos from the Atmosphere and Beyond," *Scientific American*, Vol. 214 (February 1966). Describes the detection of naturally occurring neutrinos.

Romer, A., ed., *The Discovery of Radioactivity and Transmutation*. New York: Dover Publications, Inc., 1964. A reprinting of many fundamental papers in this field, with discussions.

Shamos, Morris H., Editor, *Great Experiments in Physics*. New York: Holt, Rinehart and Winston, Inc., 1960. Reprints of the original papers describing twenty-four important experiments, edited and with marginal notes.

Snow, C. P., *The Search*. New York: Charles Scribner's Sons, 1958. Sections III and V of Chapter 6 give a fictional account of the thoughts of a young scientist in the process of making a discovery.

Townes, Charles H., "Quantum Electronics, and Surprise in the Development of Technology," *Science*, Vol. 159, No. 3816 (February 16, 1968).

Watson, James D., *The Double Helix*. New York: Atheneum Publishers, 1968. One of the discoverers of the DNA molecule gives an account of this important scientific finding.

Wu, C. S., "The Neutrino," a chapter in *Theoretical Physics of the Twentieth Century*, Wiley-Interscience, Inc., New York, 1960. A concise review at an advanced level.

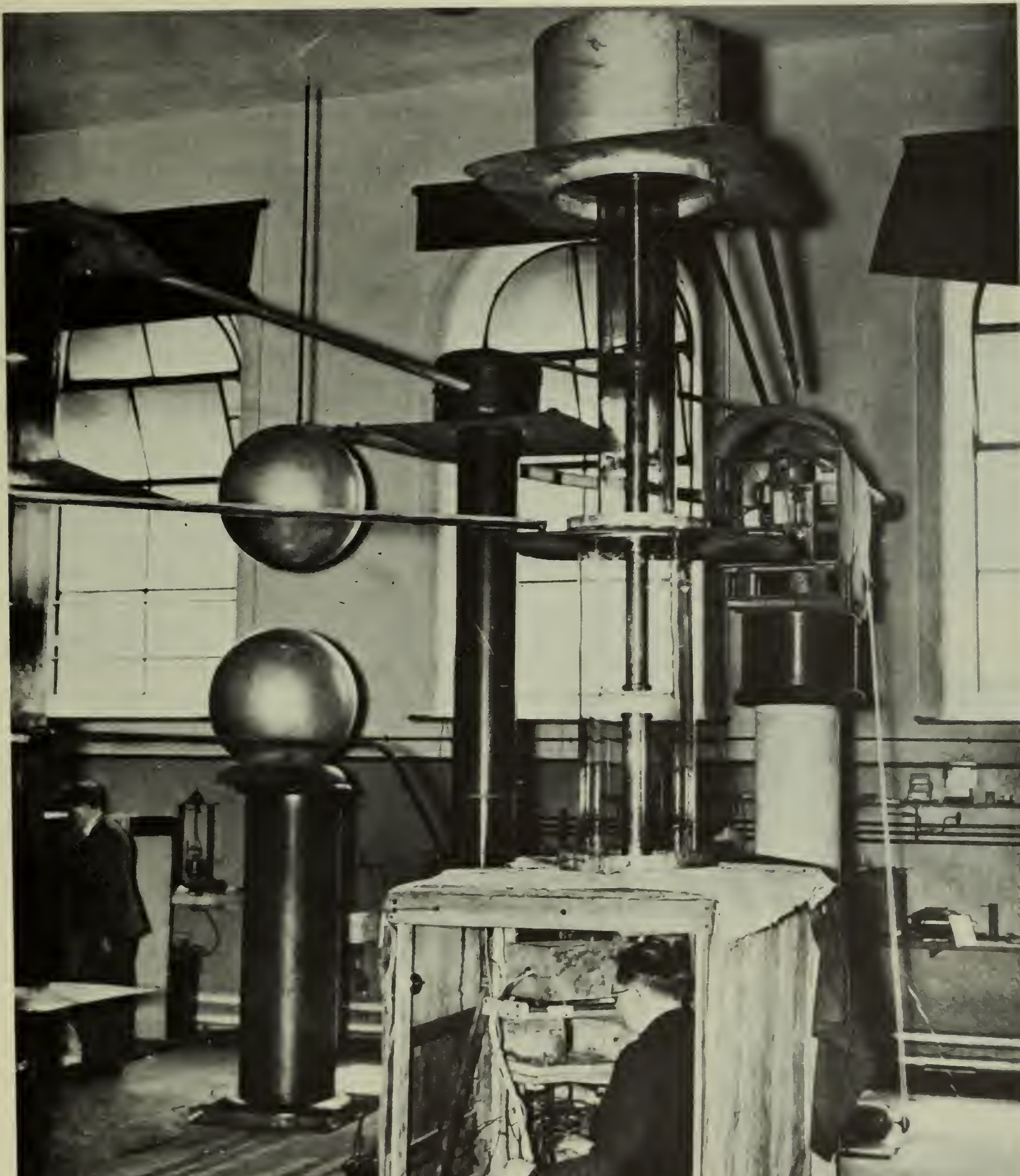


Fig. 4-9 The first successful particle accelerator constructed in 1929 by Cockcroft and Walton at the Cavendish Laboratory.

Epilogue: How Does Science Progress?

In the Prologue we suggested that one might describe the processes of scientific discoveries in terms of various possible models—among them the voyage of discovery model, the army campaign model, the jigsaw puzzle model, and the murder mystery model. Let us see if any one of these models fits all of our four case histories. Most of us would agree that these scientific discoveries cannot all be fitted into any one of these models, but our case histories do show elements of one or another of them.

For example, the initial discovery of the cathode ray beam could be compared to an unexpected event on a voyage of discovery. Likewise, the discovery of the several "transuranic" elements when Fermi first bombarded uranium with neutrons was, in a sense, a product of a "let's try it and see what happens" approach. (Actually, of course, Fermi and his collaborators weren't all that aimless—they had good reason to think that interesting things might turn up in their experiments, just as a voyager to a new country would expect to find new and interesting things.) Herschel's discovery of Uranus might be thought of in the same way, except that Herschel was, in fact, carrying out a well-planned series of observations to map the distribution of stars. He was not on a "voyage of discovery" at all—he was trying to chart in a systematic way the already well-known heavens.

The neutrino, on the other hand, was by no means "found." We have described the process by saying that it was "invented." It was invented on theoretical grounds, in deference to the laws of conservation of energy and angular momentum.

How about the army campaign, the strategy and tactics model? One might certainly describe the attempts to detect the neutrino in terms of such a model. Impressive resources were required, and the cooperation of several men. The probable characteristics of the neutrino had to be worked out in terms of physical theory, so that the experimentalists could plan their experiments within the limitations of space, time, source strengths, detector efficiencies, and the like. Similarly the study of electron pair formation by very high-energy gamma rays, shown in the Project Physics film "People and Particles," would also serve as a good example of scientific research that, in some ways, fits the army campaign model. (But it is also true that much research is not organized on such a scale. A one-man research project also involves much careful planning, strategy and tactics, but not in the way implied by the model.)

Both the cathode ray controversy and the understanding of nuclear fission can be thought of in terms of the jigsaw puzzle model. Various "facts" were found by careful and clever experimentation. The "facts" had to be fitted together, and finally a clear picture emerged.

But the puzzle model suffers from oversimplicity. In a jigsaw puzzle the pieces are all there—you have to sort them out, but presumably you have them all to start with. In real-life science, you have to find the pieces,

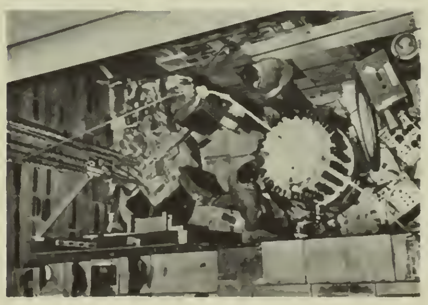
sometimes in the most unlikely places, and you have to interpret them. The existence of some of the experimental "facts," for example, in the cathode ray controversy, depended very much on certain preconceptions. (Lenard's experiments in which he sent the rays through thin foils and Hertz' experiments in which he tried to follow the flow of current are examples.) One might say also that Droste's experimental search for the alpha particles thought to emerge from neutron bombardment of uranium was a case of failure to find a real piece of a puzzle (the ionization pulses due to fission fragments) while he was looking carefully for pieces that didn't really exist (the alpha particles).

The murder mystery model comes closer, perhaps, to describing the process by which Neptune was discovered. There was a genuine mystery: what could be causing the strange behavior or Uranus? There were various possible solutions to the mystery: interaction with a comet, a possible breakdown of the inverse-square law of gravitation, a new planet beyond Uranus, and possibly others. The evidence of continued perturbations continued to accumulate. The two "detectives," Adams and Leverrier, had to use ingenious mathematical techniques and much hard work to derive the solution to the mystery.

The understanding of nuclear fission also involved many of the elements of a puzzling mystery. There were peculiar clues, false scents, an "obvious" solution too strange to believe, and other elements beloved by mystery writers.

If there is no model that can fit even our four case histories, there is certainly none that will work for *all* scientific discoveries. Still our models have been useful, if only to help us see that certain threads are common to two or more discoveries. Moreover, all of them had elements of surprise, of occasional confusion, and of delight. Adams and Leverrier, Fermi, Lise Meitner, Frisch, J. J. Thomson, Hertz, and all the others all had one thing in common—their minds were restless until they had found answers, until they could say, "So *that* is how it works!"

The scientist, or the potential scientist, will probably find familiar this common sequence of surprise, confusion, and delight in discovery—either in his own work, or in the scientific work of those he knows. One young Nobel Prize-winning physicist was asked why he was a physicist, and he is said to have replied, "Well, if I knew of some other work that was more fun, then I'd do that." There is a creative satisfaction, quite apart from whatever usefulness the research may have. An unsolved mystery in science cries out to be solved. Personal fame, financial reward, usefulness to society—all of these and many more motivations may spur the scientist on. He is, after all, an ordinary human being. But there are other paths to fame, fortune, and usefulness, so it is the creative tension of the unsolved puzzle and the delight in the occasional understanding of nature that leads to careers in science.



But all that is from the standpoint of the scientist, looking at his work and at himself. From the viewpoint of the scientific community and society at large, there are questions about science that our case studies may help us answer. What is the value of vast and costly laboratories? How are science and technology related? How do scientists communicate with each other and with the world? What conditions favor scientific discovery? Why do some new discoveries take so long to get accepted?

Let us consider, for example, this last question, about the acceptance of new ideas in science. Why didn't Airy, the Astronomer Royal, rush to his telescope to find Neptune when Adams asked him to do so? Why was Ida Noddack's suggestion (that uranium atoms might undergo fission) ignored by Fermi and almost every one else in 1934? Why did Hahn and Strassmann take so long to believe their own very impressive chemical evidence?

There is no single answer to such questions. In the first place, busy scientists do not have time to consider seriously every idea that comes their way—not even every idea they have themselves, let alone those that turn up from others who are not in the main stream of research. Rontgen was surprised enough by a glowing fluorescent card near his cathode ray apparatus to begin to investigate it carefully, and so he discovered x rays. Other men before him had observed fluorescence from what must have been x rays, but they were busy thinking of other things. One cannot be distracted by every intriguing thing that turns up. Airy had the work of his observatory carefully scheduled, and he did not want to be interrupted by a young man he thought was an upstart with far-fetched ideas. (Admittedly, Airy is an extreme example. His psychological makeup was such that almost *no* interruption of his schedule was tolerable. But any scientist trying to get on with a carefully planned program of research cannot help having a certain sympathy for him.)

But there is a second, and more important, reason why it often takes so long for a new idea to be accepted. If a new discovery—and especially a new theoretical concept—does not seem to fit into the currently accepted patterns of scientific thought, most scientists are not eager to take it very seriously. Some textbook prefaces, in describing "the scientific method," insist that scientists are always very open-minded, always willing to discard an old theory or an old concept the very minute some apparently contrary observation is made. In actual fact, scientists are rather conservative in scientific matters. They have good reason to make use of the ideas that have worked well in the past.

Consider, for example, the current scientific view of the structure of atoms. We think of an atom as having a very small nucleus (with a diameter of about 10^{-12} centimeter), with a certain electrical charge and a certain mass, surrounded by electrons distributed in orbits or "clouds" in certain ways, to make up a total diameter of about 10^{-8} centimeters. Present physical theory can tell us, at least in principle, how the electronic clouds are distributed, what sort of light the atom can emit or absorb, what forces it can exert on nearby atoms, how it will form molecules, and, in certain cases, whether it is likely that the nucleus of the atom will emit an alpha particle or some other radiation. Our theory can also predict how such an atom will be affected by a magnetic field, how much energy will be needed to ionize it, and many other things. In practice, the calculation of some of these properties would be very difficult, but in principle the behavior of atoms and their nuclei is quite well understood. Now suppose someone comes along with an awkward experimental observation, or some new theory, that does not seem to fit into this beautiful, workable and satisfying picture of the atom. Must this picture be then discarded?

The first question scientists probably would ask is, "Who claims to have made this discovery?" Few, if any, scientists will waste much time trying to check or repeat the observations if the claimant does not have some standing in the field. Even if a person has a good reputation in one area of science, any really unusual ideas he may put forth in another field will not be taken very seriously. When Ida Noddack criticized the logic Fermi had used in his original paper in which he claimed to have produced some transuranic elements, no one paid much attention. She was a chemist, and she pointed out flaws in the chemical argument: Fermi and his colleagues had not ruled out all other elements by careful chemical tests. Physicists did not take her argument seriously, because they could not see any likely way for nuclei to split into large fragments. All previous experiments, in fact, had shown just the opposite: only very light particles (alpha particles, neutrons, protons, beta rays, or gamma rays) were emitted by disturbed nuclei. The idea that a nucleus could split into large fragments after the capture of a neutron simply did not fit into the prevailing nuclear theory. One would sooner expect that an iron cannonball would fly apart when hit by a small BB pellet than imagine that a nucleus would undergo fission when hit by a slow-moving neutron, and certainly nobody would be asked to perform lengthy tests to prove that a cannonball hit by a BB will remain intact. So Miss Noddack's argument, though sound from a chemical standpoint, was ignored.

On the other hand, four and a half years later, it was a different story. For one thing, as we have seen, mystery had piled upon mystery as more and more experiments were done with neutron bombardment of heavy nuclei. But Frisch and Meitner did not simply pronounce the magic word, "fission." They showed how it made sense out of all the observations, in a way that was in accordance with contemporary ideas about the nucleus. So the moment the news of Frisch's and Meitner's interpretation of Hahn's and Strassmann's results was made public, physicists quite literally could not get to their laboratories fast enough to check all sorts of implications of the dramatic new idea of nuclear fission.

Otto Frisch has quoted Niels Bohr as having said, when he was told that Frisch and Meitner had suddenly realized how there really could be enough energy available for nuclear fission to occur, "Oh, what fools we have been! We ought to have seen that before!" But Bohr was too hard on himself. It is always easy to look back and see how blind one has been to a simple but new idea.

The moral is not, of course, that scientists must spend all their time considering every unlikely idea that pops up. But clearly they must remain open-minded to *some* degree; they must preserve their sense of curiosity. And yet it must be a disciplined kind of curiosity. If our four case histories have anything in common, aside from the joy in discovery we have already mentioned, perhaps it is that great discoveries and great ideas are most often made by men and women who are thoroughly immersed in the best scientific experimentation and thinking of their day. They are the ones who, in Pasteur's words, are *prepared* for the accidents of discoveries, for the hard work, and for insights that produce creative discoveries. Adams and Leverrier were magnificently trained in classical mechanics. Reines, Cowan, and the other experimentalists who finally "caught" the neutrino, were imaginative and creative experimentalists, well prepared to take advantage of new technological developments to achieve breakthroughs in pure science. Hahn and Strassmann were known to be such impeccably careful radiochemists that Frisch and Meitner were able to trust their incredible results.

Let us go on to consider some of the other questions raised earlier in this chapter that might be asked about scientific creativity, as viewed from that standpoint of society as a whole. What circumstances seem to encourage scientific creativity? One might ask, for example, the rather simple question of whether the most fruitful work is done in large groups or small. Our four case histories provide too small a sampling to give us a clear answer. Herschell, Adams, and Leverrier each worked alone. The men who made the crucial experiments in the cathode ray controversy worked singly or in pairs. Fermi worked with a small group of collaborators in making his initial discoveries with neutron bombardment of nuclei.

When Pauli and Fermi first produced their theoretical ideas concerning the existence and nature of the neutrino, they were working individually. But the actual tracking down of that elusive particle experimentally was quite different—enormously complex equipment was needed, and the cooperation of many men. The later experiments on nuclear fission also involved large teams. A recent issue of the *Physical Review Letters,* a journal containing brief reports of current research, has an average of 3.3 authors per paper, with one paper having ten authors and another fifteen. But one will also still find papers with a single author, and many of the really important contributions are made in such papers. In particular, the kind of "discovery" which is, in fact, a breakthrough achieved by looking at old data in a new and creative way is often the creation of one man. And while many of the exciting experiments in modern science require enormous amounts of equipment and many collaborators, it is also true that many significant experiments are thought up, and often carried out, by one person.

But these scientists, whether they work alone or in groups, do not live in a vacuum. Almost all of them, nowadays, work in college or university laboratories, or in governmental institutes, or in industrial research laboratories. There is what might be called "intellectual cross-fertilization" in any good laboratory in which several scientists are working, even though they are not all working on the same projects. And of course there is the wider interplay of ideas among scientists, an interplay which takes place by means of a very large and growing number of scientific journals and by means of national and international meetings, as well as by personal visits.

Not only does the scientist work in collaboration, or at least in cooperation, with other scientists; he knows he is often quite dependent on engineers and other technologists. The interplay between the science and the technology of any period is a fascinating area of study in itself—an area we have been able to touch upon only briefly in our case histories. In some cases a newly developed technique has made a scientific discovery possible: better vacuum pumps led directly to the discovery of cathode rays. In other cases the gradual development of technological resources made it possible to verify or to check some crucial idea. Thus fission reactors, scintillation counters, and modern electronic circuits made it possible to detect neutrinos experimentally.

In modern scientific research it often takes time before some creative person recognizes that an engineering development whose application has so far been mainly technical might provide a new tool or instrument for scientific research. Photomultiplier tubes were used commercially, and for certain research applications, for quite some time before anyone thought of using them to detect and measure the very faint scintillations caused by single particles in nuclear research. Photographic plates and films were available for years before anyone tried to use them to record particle tracks in cosmic ray or other high-energy particle research.

Of course, the interplay between science and technology occurs on a two-way street. The modern oscilloscope and television tubes are direct descendants of the early tubes used in cathode ray research—tubes which a British statesman in the 19th century described with the words, "How beautiful, and how useless!" Lasers, now finding applications in medicine and in industry, resulted from what was thought to be pure research on the energy levels of the electrons in certain atoms.

To put this issue another way, one might say that no board of directors of a large corporation, or of a national foundation, could have said, in 1850, "Let's subsidize the discovery of cathode rays" or, in 1895, "Let's get someone to discover x rays and radioactivity." The most that any such group can do is to decide to spend some fraction of its resources in supporting research undertaken without specific applications in mind, to allocate that fraction to the sort of men and women who have demonstrated creative abilities, and to rejoice when knowledge and understanding of nature are increased. Finally, they may hope that now and then some useful things will come out of that increased knowledge and understanding. The problem, in other words, faced by a forward-looking nation or a forward-looking corporation, is not *whether* to support pure research, but to decide what fraction of its resources should be used for that purpose—and then to choose the scientists to carry out that research. The decision as to what fraction of a nation's or a corporation's resources should be allocated to pure research is difficult; it must be settled in terms of economic and social goals. The choice of which scientists to support is even more complex. Case histories of the sort we have discussed, are helpful but not determinative. One method of choice is to provide support for those who have already shown themselves to be productive, and to enable them to surround themselves with younger scientists whose abilities will develop.

We have been considering, in these past few pages, some of the questions that our case histories might raise in the minds of outsiders, looking at the work of scientists. But at least some readers, looking forward to a scientific career, may see in these histories of past discoveries a more personal goal. They will see that the scientific process is open-ended, and that there is excitement in taking part in scientific research. There are lots of new experiments to be done, new deductions from old theories to be tested, and new theories to be developed.

Activities

1 Read a biography of an outstanding scientist and categorize his major discoveries according to the scheme suggested in this unit. The following are some suggested readings: *Galileo Galilei* (Ludovico Geymonat); *Sir Isaac Newton* (E. N. Andrade); *Count Rumford, Physicist Extraordinary* (Sanborn C. Brown); *Madame Curie* (Eve Curie); *Einstein, His Life and Times* (Philipp Frank); *Pioneers of Science* (Sir Oliver Lodge); *The Double Helix* (James Watson); *Atoms in the Family* (Laura Fermi).
2 Read a novel in which a scientific discovery plays an important part, such as *The Search* (C. P. Snow). How does the discovery process compare with those described in this unit?
3 Read James Watson's *The Double Helix*, and then read some reviews of the book. What do the book and the reviews tell you about scientists' views of the discovery process? Here are some reviews written by scientists:

Science, March 29, 1968 (Erwin Chargaff)
Nation, March 18, 1968 (Jacob Bronowski)
New York Review of Books, March 28, 1968 (P. B. Medaa)
New Yorker, April 13, 1968 (Jeremy Bernstein)
Nature, May 18, 1968 (John Maddox)

Note on Further Reading

Those who, after finishing this book, wish to pursue further the ideas on Discoveries, may wish to consult the following additional resources:
1 the specific references listed at the end of each chapter in this volume
2 one or more of the following books that are concerned with the process of discovery in the physical sciences as reported in historical cases
3 these articles in the Project Physics Readers.

Andrade, E. N. da C., *Rutherford and the Nature of the Atom;* Anchor Books, Doubleday and Company, Inc., Garden City, New York (1964)

Armitage, Angus, *The World of Copernicus;* A Mentor Book published by The New American Library of World Literature, Inc., New York, New York (1951) Published under an earlier title: *Sun, Stand Thou Still;* Henry Schuman, Inc. (1947)

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Fermi, Laura, *Atoms in the Family;* University of Chicago Press, Chicago (1954)

Frank, Philipp, *Einstein: His Life and Times;* Alfred Knopf, New York, New York (1967)

Geymonat, Ludovico, *Galileo Galilei: A Biography and Inquiry into his Philosophy of Science* (trans. Stillman Drake); McGraw-Hill Book Company, New York (1965)

Hadamard, Jacques, *An Essay on the Psychology of Invention in the Mathematical Field;* Dover Publications, Inc., New York (1945)

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Koestler, Arthur, *The Watershed: A Biography of Johannes Kepler;* Anchor Books, Doubleday and Company, Inc., Garden City, New York (1960)

Kuhn, Thomas S., *The Structure of Scientific Revolutions;* The University of Chicago Press, Chicago (1964)

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Moore, Ruth, *Niels Bohr;* Alfred Knopf, New York, New York (1966)

More, Louis Trenchard, *Isaac Newton;* Dover Publications, Inc., New York, New York (1934)

Roe, Anne, *The Making of a Scientist;* Dodd Mead, New York, New York (1953)

Romer, Alfred, Ed., *The Discovery of Radioactivity and Transmutation* (Classics of Science Series, Volume II); Dover Publications, Inc., New York

Romer, Alfred, Ed., *Radiochemistry and the Discovery of Isotopes* (Classics of Science Series, Volume VI); Dover Publications, Inc., New York, New York, (1970)

Rukeyser, Muriel, *Willard Gibbs;* Doubleday, Doran and Company, Inc., Garden City, New York, (1942)

Segre, Emilio, *Enrico Fermi: Physicist;* University of Chicago Press, Chicago, (1970)

Taton, R., *Reason and Chance in Scientific Discovery* (trans. A. J. Pomerans); Science Editions, Inc., New York (1962)

Thomson, George, *J. J. Thomson and the Cavendish Laboratory in His Day;* Doubleday and Company, Inc., Garden City, New York (1965)

Wertheimer, Max, *Productive Thinking;* Harper and Row, New York (1959)

Williams, L. Pearce, *Michael Faraday;* Basic Books, Inc., New York (1965)

Wood, Alexander, *Thomas Young: Natural Philosopher;* The University Press, Cambridge (1954)

From the Project Physics Readers

Reader 1
- *How to Solve It* G. Polya
- *Representation of Movement* Gyorgy Kepes

Reader 2
- *Kepler on Mars* J. Kepler
- *The Garden of Epicurus* A. France
- *The Boy Who Redeemed His Father's Name* Terry Morris

Reader 3
- *The Law of Disorder* George Gamow
- *Silence, Please* Arthur C. Clarke

Reader 4
- *Popular Applications of Polarized Light* William A. Shurcliff and Stanley Ballard
- *The Invention of the Electric Light* Matthew Josephson
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