N O T E

A Closer Look at the Spectrum of Helium

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A common introductory physics laboratory experiment consists of using a sodium light source to calibrate a diffraction grating and using the grating to observe the spectrum of hydrogen and then calculating the wavelengths. Almost any reference consulted shows the four Balmer lines of the hydrogen spectrum with their accepted wavelengths.[1] The wavelengths can also be calculated from the Balmer formula using the Rydberg constant. The results obtained usually agree with the theoretical values, and some insight into the connection between the observed wavelengths and the structure of the hydrogen atom is usually gained from the experiment. This generally provides a complete and satisfactory laboratory experience.

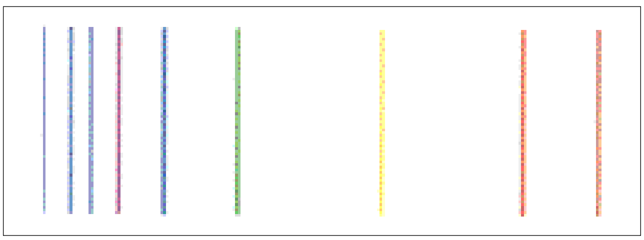

Fig. 1. Nine observed lines of the helium spectrum. In many discharge tubes the yellow and green lines show dimmer lines of the same color right next to them. These "ghost images" are not part of the spectrum and can cause confusion.

He	spectral-line	wavelength nm	from Fig. 2 nm	% difference
			388.9	
1	dim-violet	394	396.5	0.63
2	dim-violet	416	402.6	3.33
3	dim-violet	427	412.1	3.62
4	violet	441	447.1	1.36
5	blue	469	471.3	0.49
6	green	502	501.6	0.08
7	yellow	589	587.6	0.24
8	red	668	667.8	0.03
9	dim-red	710	706.5	0.50
			728.1	

Table I. Calculated wavelengths of nine observed lines of helium spectrum compared with wavelengths of visible transitions found on the helium energy-level diagram.

However, when observing the spectrum of helium, this type of experience is more difficult to achieve. Figure 1 shows nine observed visible lines in the helium spectrum, and Table I shows their calculated wavelengths. The first three violet lines are very dim, but they are there and can be found with a little finesse and darkness. The values of the helium wavelengths are more difficult to find in references than those of hydrogen and if they are found, only six or seven lines are usually shown.[2]

Also, when working with helium in an introductory course there is usually very little insight gained into the structure of the atom. The first theoretical treatment of helium usually seen is the modification of Bohr theory for singly ionized helium.[3] This of course has nothing to do with the lines observed in the laboratory because atoms in the standard helium discharge tubes are not singly ionized. Therefore theoretical values of the observed helium wavelengths cannot be calculated in the same way they are for hydrogen. Often at the introductory level you end up having to tell students that the mathematics necessary to analyze multielectron atoms is extremely complex and "beyond the scope of the course." Leaving a subject hanging like that is less than satisfying both for the students (even those who do not plan to eventually study quantum mechanics) and the instructor. It is, however, possible to investigate the spectrum of helium a little bit more without going beyond the scope of the course; in the process you and your students will join in a laboratory experience that does include some insight into the structure of the helium atom.

To find a detailed explanation of the spectrum of helium, it is necessary to consult works on atomic physics somewhat beyond the introductory level. I have found Herzberg's book *Atomic Spectra and Atomic Structure*[4] very useful and include here the energy-level diagram for helium (see Fig. 2) from this work.

Although the diagram is much more complex than the analogous one for hydrogen,[5] the wavelengths of the transitions are shown. The visible transitions are those on the diagram with wavelengths from about 4000–7000 angstroms. They were converted to nanometers for Table I

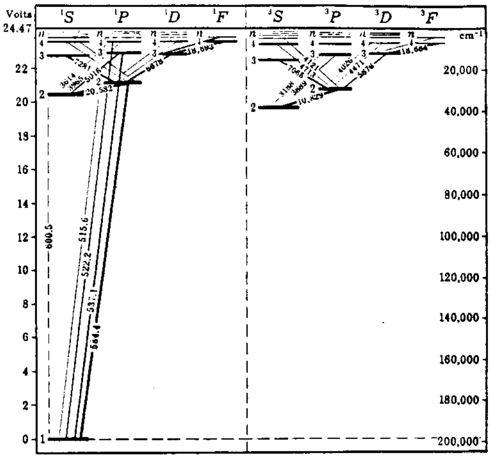

Fig. 2. Energy-level diagram for helium showing wavelengths of transitions measured in angstroms. Reproduced from *Atomic Spectra and Atomic Structure* (Ref. 4) with written permission from the publisher.

by inserting a decimal point before the last digit. After the wavelengths of the observed helium lines are calculated, the visible transitions can be picked out of the diagram and compared with the calculated values. The Table I comparisons are typical of student results.

The energy-level diagram for helium (Fig. 2) is much more complex than that for hydrogen because of the additional electron. In fact, the Bohr model fails when used to analyze helium. Even considering the Coulomb interaction between the two electrons in addition to the interaction between the individual electrons and the nucleus does not give the energies that agree with experiments.[6] This is largely because relativistic effects at the speeds of the orbiting electrons are ignored. Furthermore, the assumption that the electrons actually travel in orbits ignores uncertainties in the position and the momentum of the electrons. The main reason, however, is due to the spin of the electrons.[7]

The spins of two electrons in the same orbital region must be antiparallel. This creates the "singlet" state. In the "triplet" state, the two spins are parallel, but the electrons are necessarily in different orbitals.[8] The array of lines on the left of Fig. 2 represents the singlet states; the array on the right represents triplet states. Allowable transitions are those in which angular momentum is conserved. Including the effect of spin on angular momentum results in there being no transitions between the singlet and triplet states. This is why Fig. 2 is split in two. Note that the triplet array does not have a ground, n = 1, level that corresponds to the one in the singlet array. This is because of Pauli's exclusion principle. If both electrons are in the ground state they must have opposite spin. At higher levels, one electron can be in a higher orbital than the other so the spin can be either opposite or parallel. [9]

Observed visible lines 1, 6, and 8 in Table I (the first dim-violet, the green, and the red lines in Fig. 1) are from the singlet array. All the rest are from the triplet array. All visible transitions are part of n = 2 series.

I have found the introduction and use of the helium energy-level diagram in the above fashion very useful in the classroom. The means to verify the accuracy of the observed spectrum and the calculated wavelengths makes the experiment seem more complete. The diagram also provides an opportunity for discussion of some of the reasons that the analysis of helium and other multi-electron atoms is so complex. This provides much more satisfaction than having to say that it is "beyond the scope of this course."

Acknowledgments

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References

1. For example, R. A. Serway and J. Faughn, *College Physics*, 4th ed. (Saunders, New York, 1995), p. 899.
2. Central Scientific Company, *Spectrum Analysis* poster shows only six lines of the helium spectrum. See also, Serway, Moses, and Mayer, *Modern Physics* (Saunders, New York, 1989); inside front cover shows only seven lines.
3. For example, Ref. 1, pp. 905–907.
4. Gerhard Herzberg, *Atomic Spectra and Atomic Structure,* (Dover, New York, 1944), p. 65. Wolfgang Finkelnburg, *Atomic Physics* (McGraw-Hill, New York, 1950), p. 134 has the same diagram, but without the wavelengths of the transitions.
5. For example, Ref. 1, p. 903 or Ref. 4, p. 24.
6. R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles* (Wiley, New York, 1985), p. 318.
7. C. E. Swartz and T. Miner, *Teaching Introductory Physics–A Sourcebook* (AIP Press, Williston, VT, 1996), pp. 520–521.
8. Ref. 6, p. 316.
9. Ref. 7, p. 520.

Fruitful Physics

To illustrate the concept of forces occuring in pairs, I obtained a wood pear from a gift shop, cut it in half, and painted the word "forces" on each flat surface. I leave it on top of the blackboard and frequently open it up to show that "forces occur in PEARS." I have had students return years later and ask if I still have the pear.

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