

Aula 4

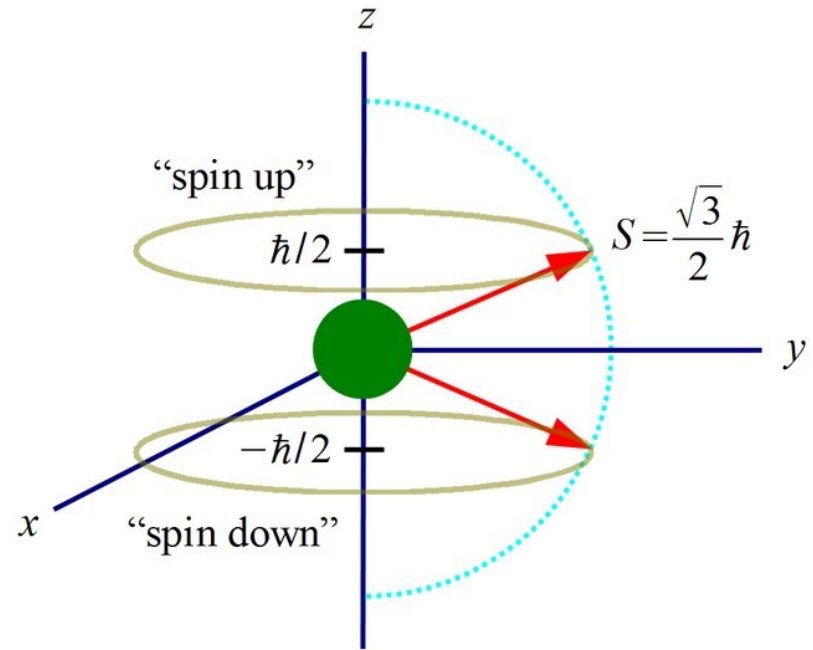
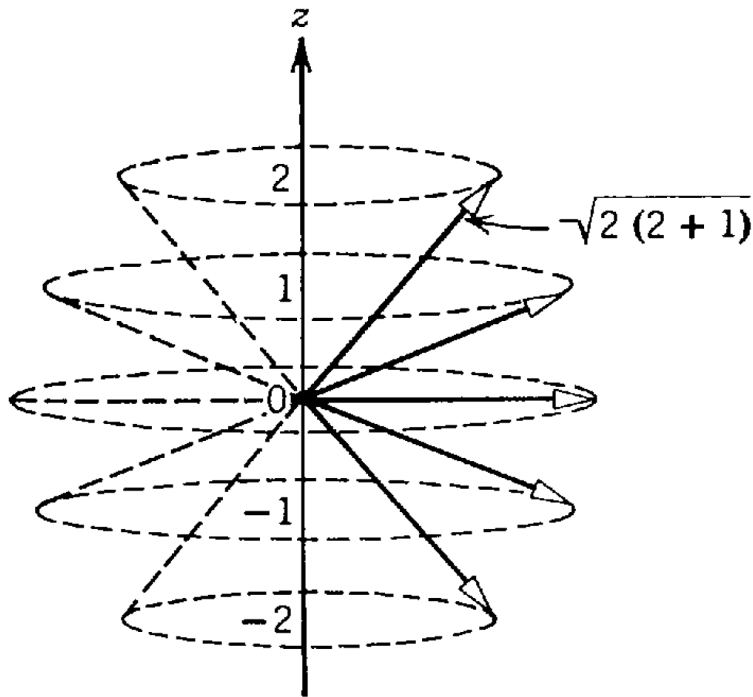
Efeito Zeeman

Interação Spin - Órbita

Momento Angular Total

Spin como Rotação

Copiamos a teoria do momento angular



$$L = \sqrt{l(l+1)} \hbar$$

$$L_z = m_l \hbar$$

$$-l \leq m_l \leq l$$

$$l = 0, 1, 2, \dots$$



$$S = \sqrt{s(s+1)} \hbar$$

$$S_z = m_s \hbar$$

$$m_s = -s, -s+1, \dots, s$$

$$s = \frac{1}{2} \quad m_s = -\frac{1}{2}, +\frac{1}{2}$$

$$\vec{\mu} = \frac{g_l \mu_b}{\hbar} \vec{L}$$



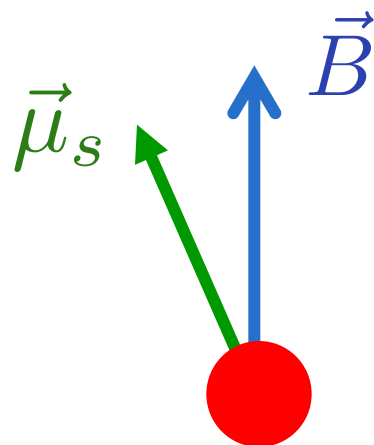
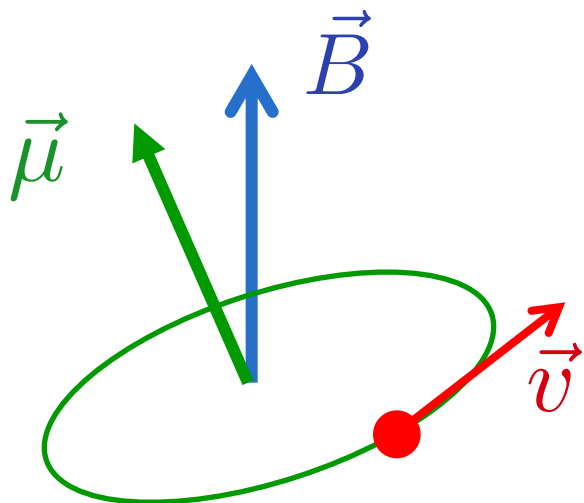
$$\vec{\mu}_s = \frac{g_s \mu_b}{\hbar} \vec{S}$$

$$\mu_{sz} = \frac{g_s \mu_b}{\hbar} S_z$$

$$U = -\vec{\mu} \cdot \vec{B}$$



$$U = -\vec{\mu}_s \cdot \vec{B}$$



$$\vec{B} = B_z \hat{k}$$

$$U = -\vec{\mu}_s \cdot \vec{B} = -\mu_{sz} B_z$$

$$\mu_{sz} = \frac{g_s \mu_b}{\hbar} S_z$$

$$U = -\frac{g_s \mu_b}{\hbar} S_z B_z$$

$$S_z = m_s \hbar$$

$$U = -g_s \mu_b m_s B_z \quad \left\{ \begin{array}{ll} U = -\frac{1}{2} g_s \mu_b B_z & m_s = \frac{1}{2} \\ U = \frac{1}{2} g_s \mu_b B_z & m_s = -\frac{1}{2} \end{array} \right.$$

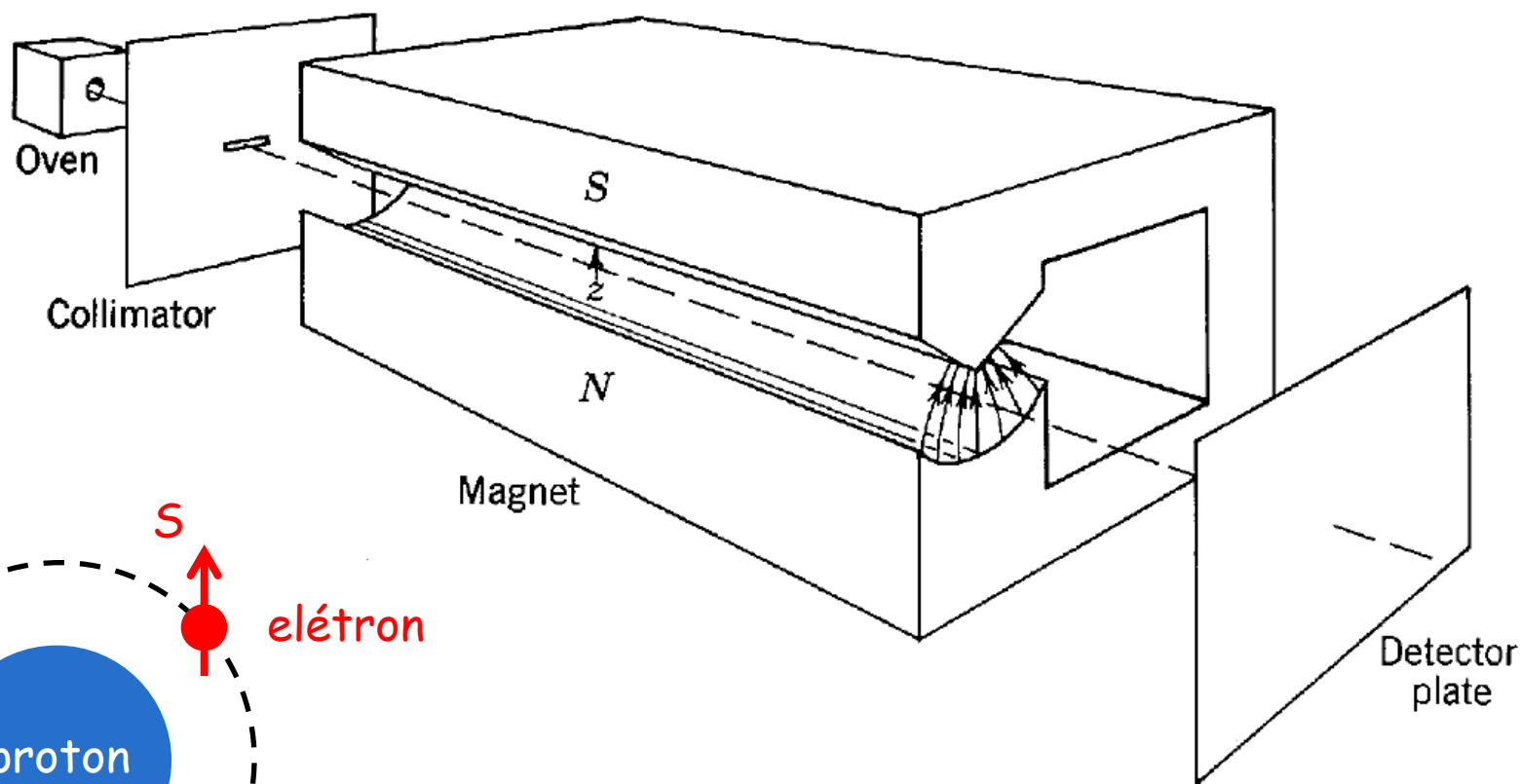
$$\vec{F} = -\hat{k} \frac{\partial}{\partial z} U$$



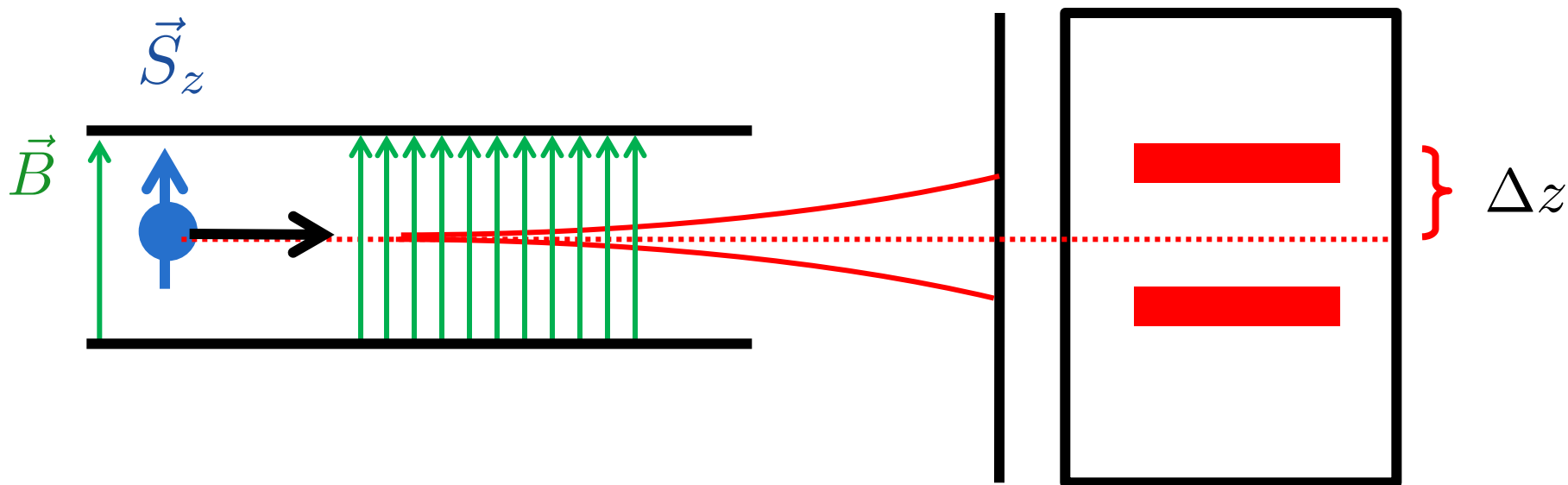
$$F = g_s \mu_b m_s \frac{\partial B_z}{\partial z}$$

Experiência de Phipps-Taylor (1927)

Stern-Gerlach com átomos de hidrogênio **no estado fundamental !!!**



Átomo de hidrogênio $L = 0$ $L_z = 0$



$$F = g_l \mu_b m_l \frac{\partial B_z}{\partial z} \longrightarrow F = g_s \mu_b m_s \frac{\partial B_z}{\partial z}$$

$$\text{Conhecemos } \frac{\partial B_z}{\partial z}, m_s = \pm \frac{1}{2} \quad \text{Medimos } \Delta z$$

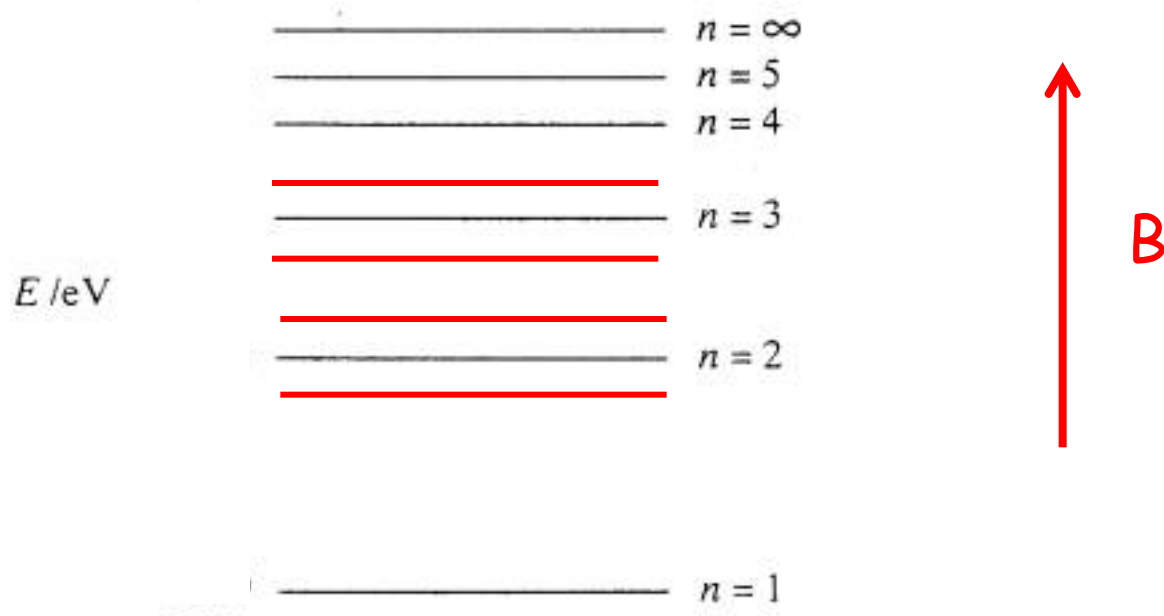
$$\text{Determinamos : } g_s = 2$$

Como sabemos que spin existe ?

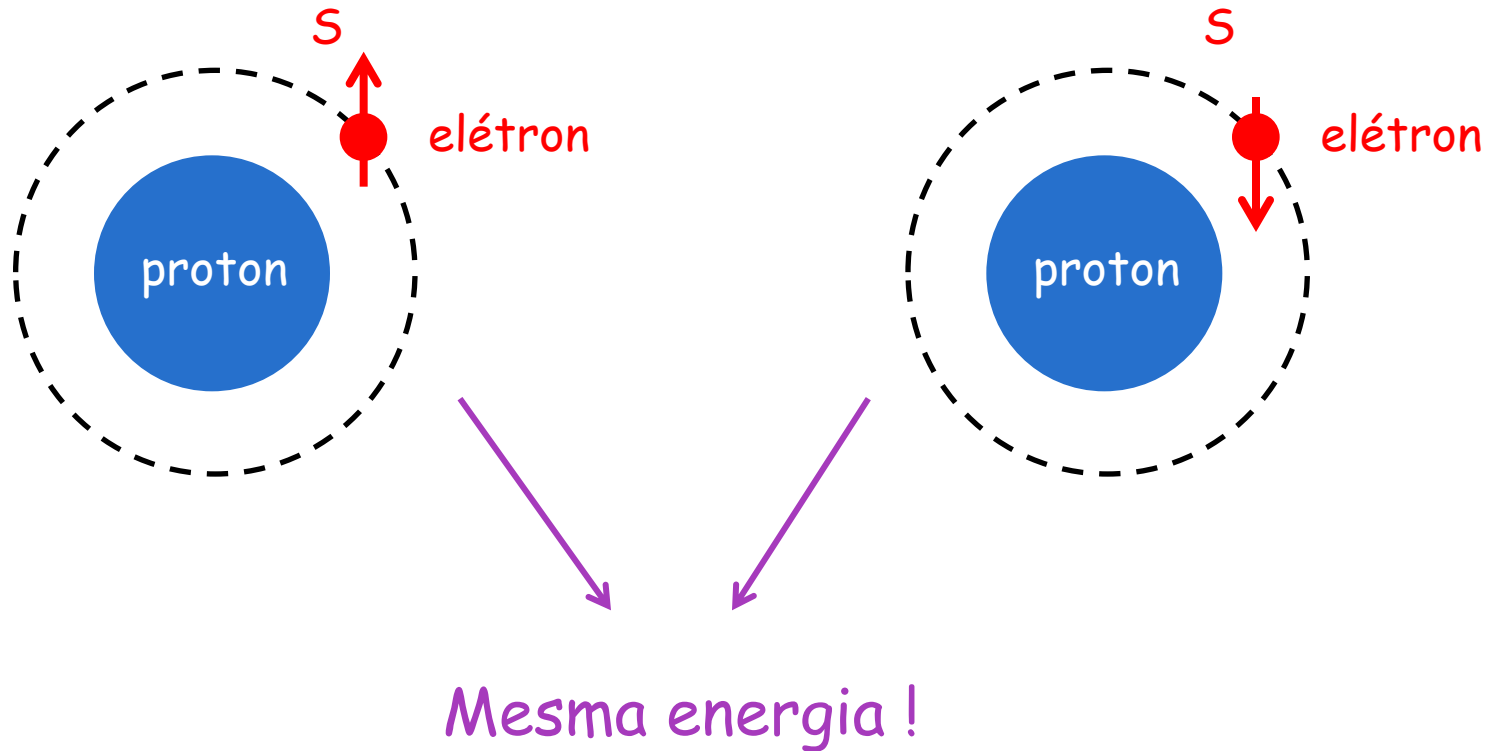
Stern - Gerlach

Phipps - Taylor

Mudanças nas linhas espectrais !!! $U = -g_s \mu_b m_s B_z$

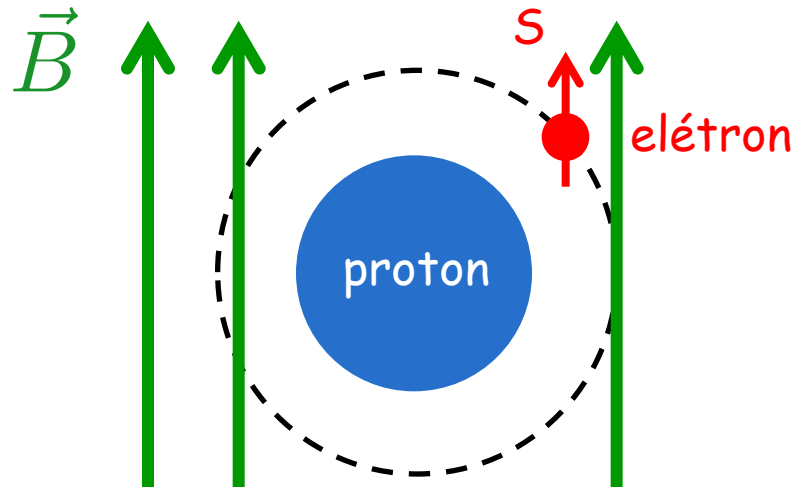


Efeito Zeeman Anômalo

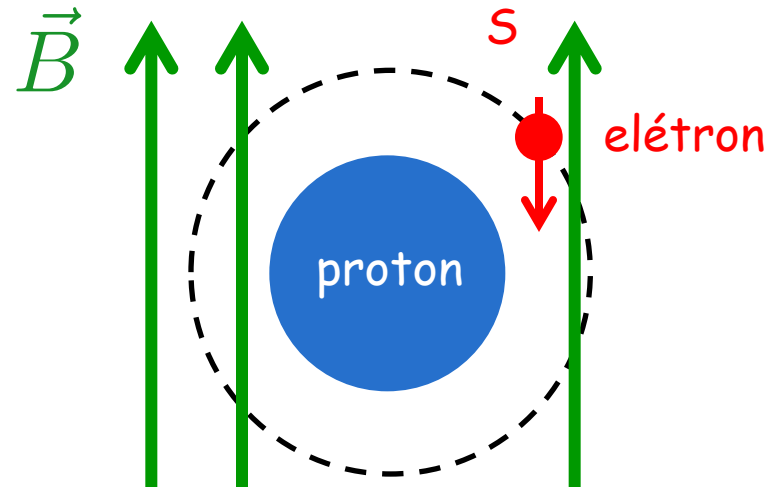


Estado fundamental $n = 1$ $\rightarrow E = -\frac{m}{2} \left(\frac{Z e^2}{4 \pi \epsilon_0 \hbar} \right)^2 \frac{1}{n^2} = E_1$

Efeito Zeeman Anômalo



$$E_1^+ = E_1 + \frac{1}{2} g_s \mu_b B_z$$

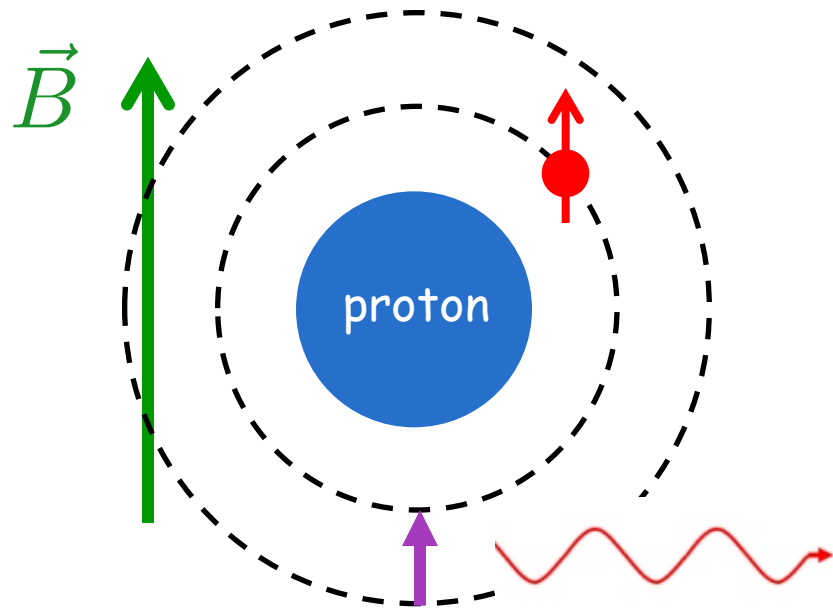


$$E_1^- = E_1 - \frac{1}{2} g_s \mu_b B_z$$

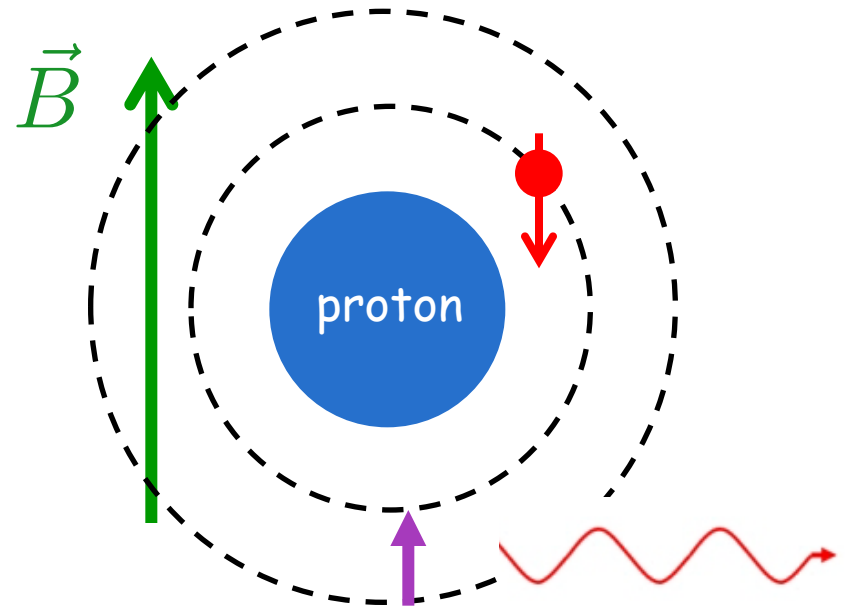
Depois de "ligar" o campo B, injetamos energia no átomo e fazemos o elétron ir para um nível excitado!

Obs: a carga negativa do elétron mudou os sinal das energias acima)

Efeito Zeeman Anômalo

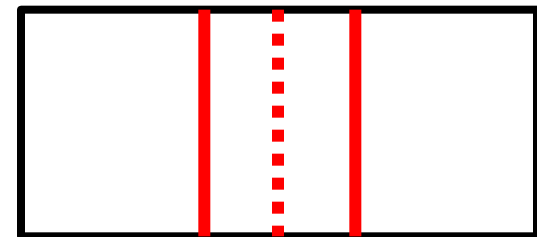
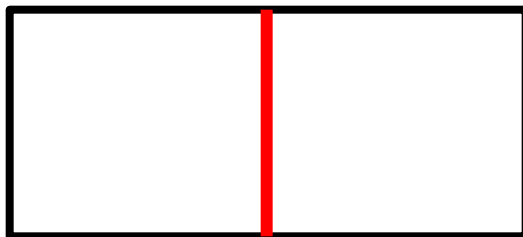


$$E_{\gamma} = E_2 - E_1^{+}$$



$$E_{\gamma} = E_2 - E_1^{-}$$

Desdobramento das linhas espectrais :

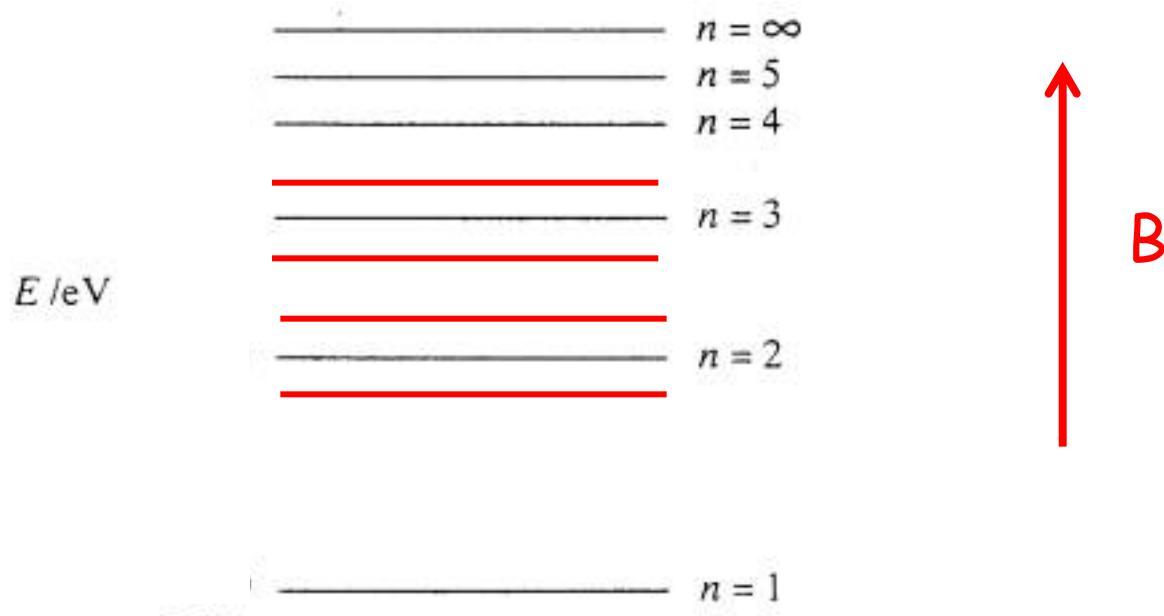


Efeito Zeeman Normal

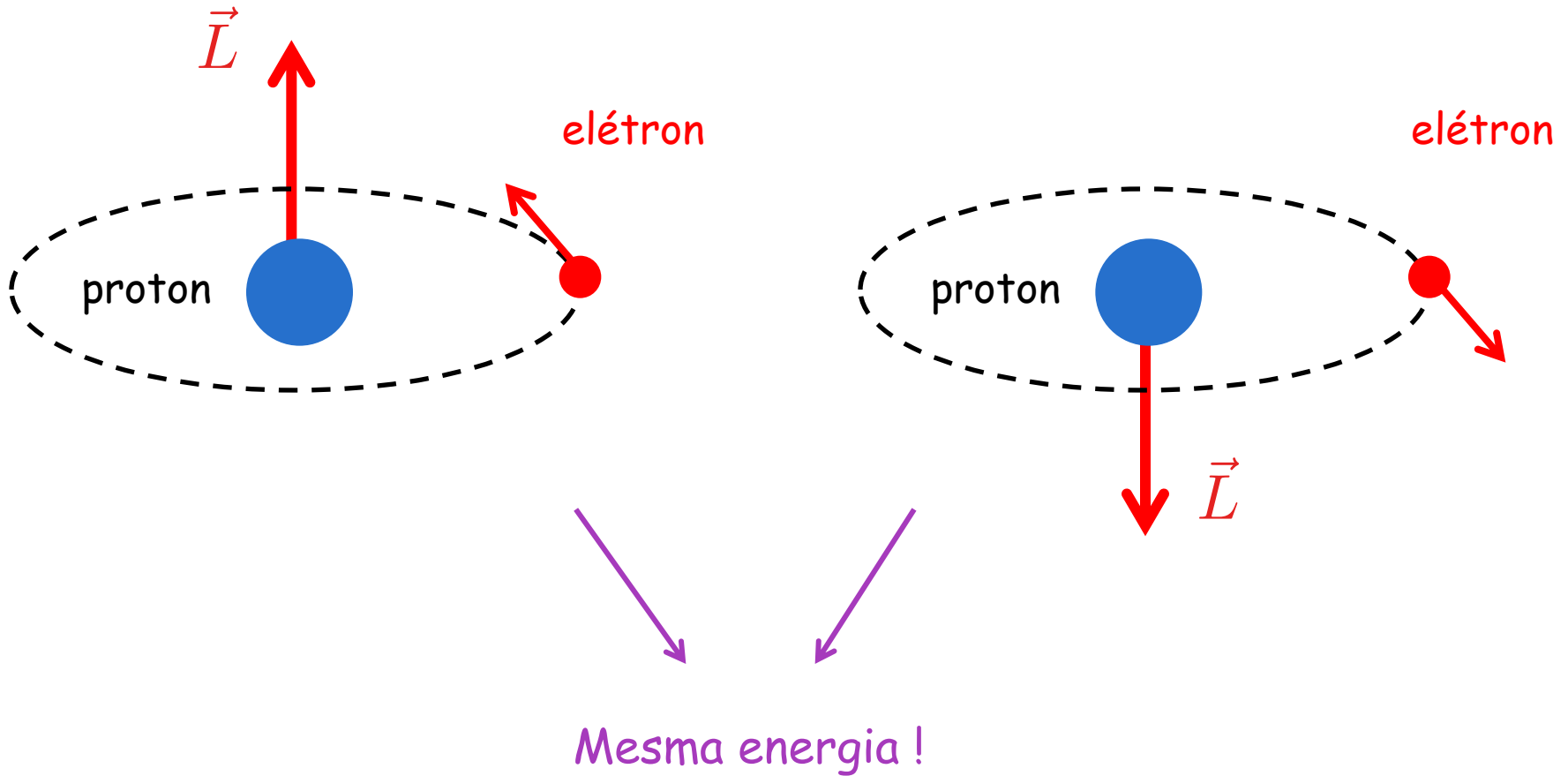
O campo magnético altera o espectro atômico por causa da interação com o momento angular orbital

Mudanças nas linhas espectrais !!!

$$U = -g_l \mu_b m_l B_z$$



Efeito Zeeman Normal



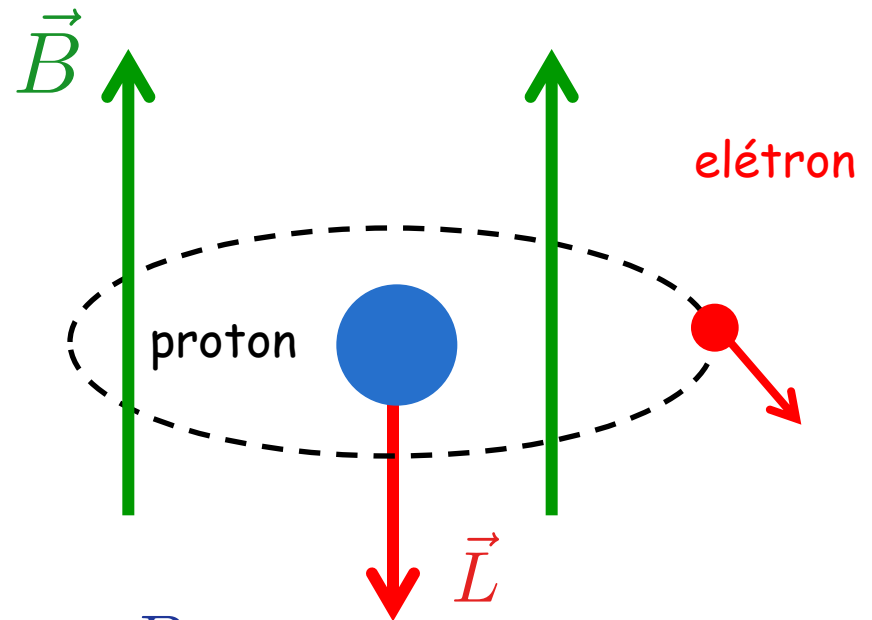
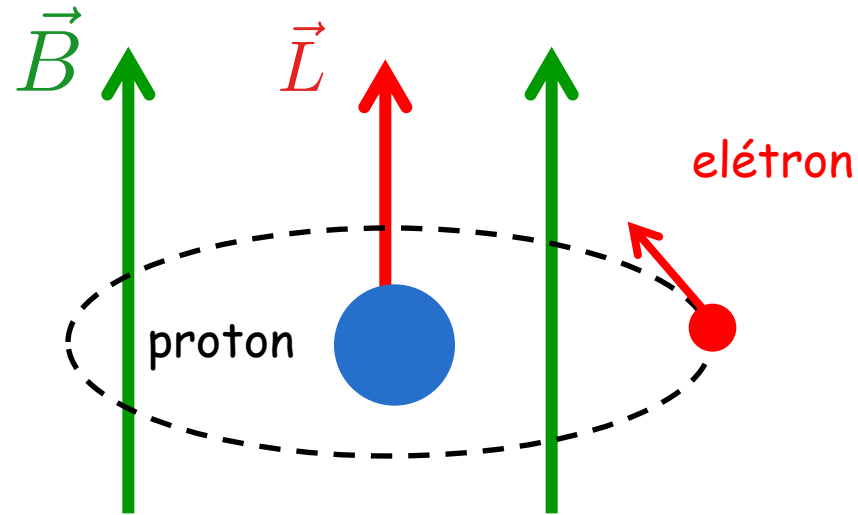
Estado $n = 2$



$$E = -\frac{m}{2} \left(\frac{Z e^2}{4 \pi \epsilon_0 \hbar} \right)^2 \frac{1}{n^2} = E_2$$

($n = 1$ só com $L=0$)

Efeito Zeeman Normal



$$U = +g_l \mu_b m_l B_z$$

$$m_l = +\frac{1}{2}$$

$$E_2^+ = E_2 + U$$

$$E_2^+ = E_2 + g_l \mu_b B_z$$

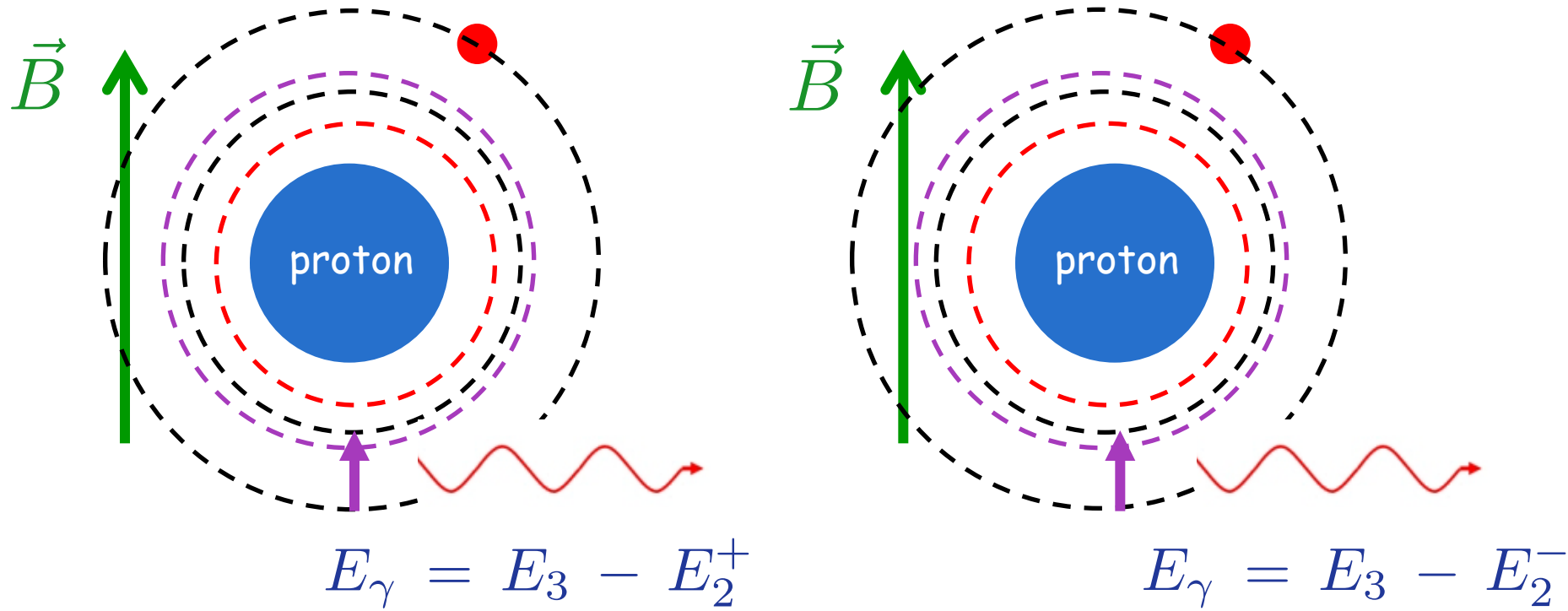
$$m_l = -\frac{1}{2}$$

$$E_2^- = E_2 + U$$

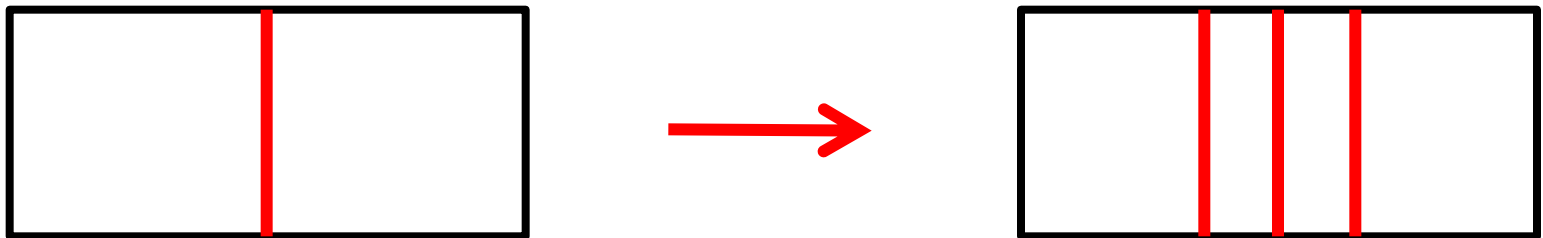
$$E_2^- = E_2 - g_l \mu_b B_z$$

Temos também $E_2^0 = E_2$ quando $m_l = 0$

Efeito Zeeman Normal

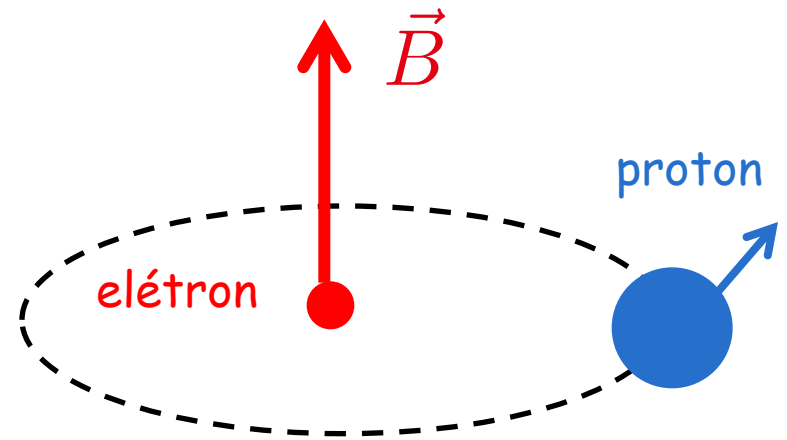
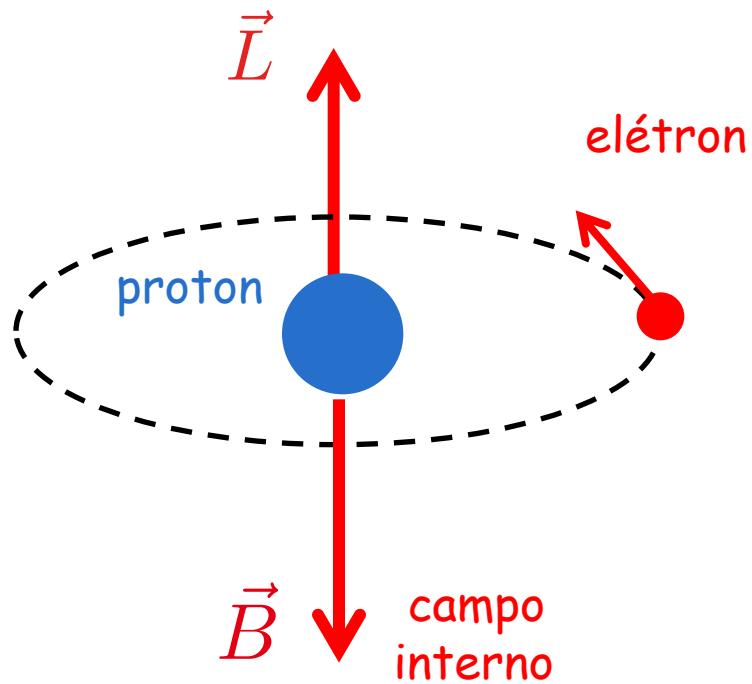


Desdobramento das linhas espectrais :



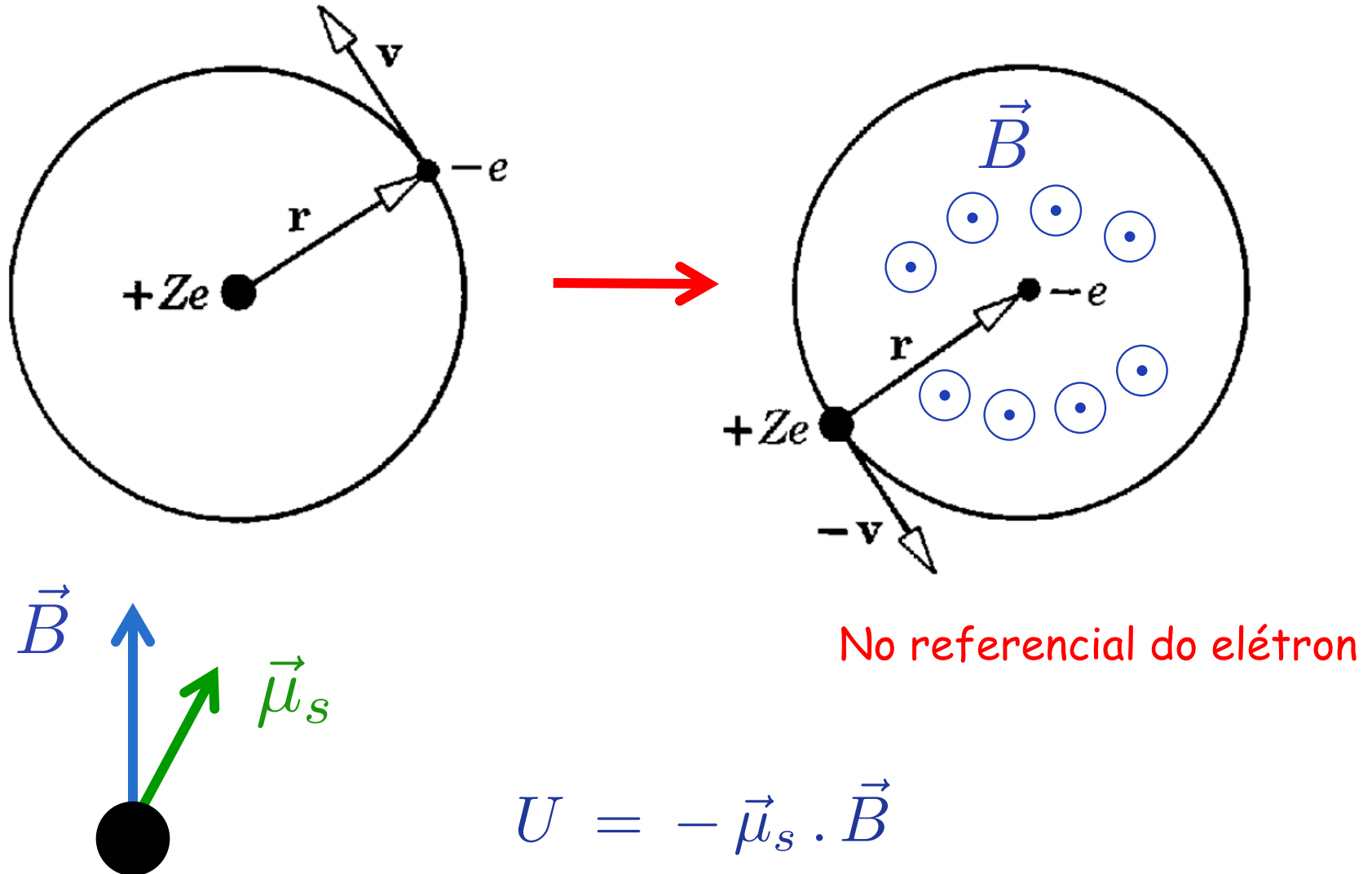
Interação spin-órbita

Campo magnético interno



Interação spin-órbita

Átomo tipo-hidrogênio



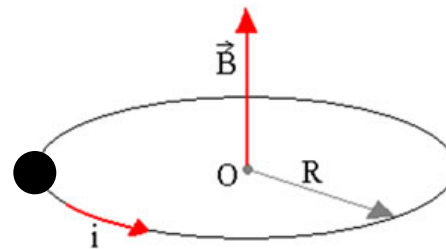
$$U = - \vec{\mu}_s \cdot \vec{B}$$

$$\vec{\mu}_s = - \frac{g_s \mu_b}{\hbar} \vec{S}$$

$$\mu_b = \frac{e \hbar}{2 m}$$

$$\vec{\mu}_s = - \frac{g_s e}{2 m} \vec{S}$$

$$U = -\vec{\mu}_s \cdot \vec{B}$$



$$\vec{B} = B \hat{k}$$

$$L = m v r$$

$$B = \frac{\mu_0 i}{2 r}$$



$$v = \frac{L}{m r}$$

$$i = \frac{e}{T} = \frac{e v}{2 \pi r}$$

$$B = \frac{\mu_0 e}{4 \pi m r^3} L$$

$$B = \frac{\mu_0 e v}{2 r 2 \pi r}$$

$$\vec{B} = \frac{\mu_0 e}{4 \pi m r^3} \vec{L}$$

$$U = -\vec{\mu}_s \cdot \vec{B}$$

$$\vec{\mu}_s = -\frac{g_s e}{2m} \vec{S}$$

$$\vec{B} = \frac{\mu_0 e}{4\pi m r^3} \vec{L}$$

$$U = -\vec{\mu}_s \cdot \vec{B} = \frac{\mu_0 g_s e^2}{8\pi m^2 r^3} \vec{L} \cdot \vec{S}$$

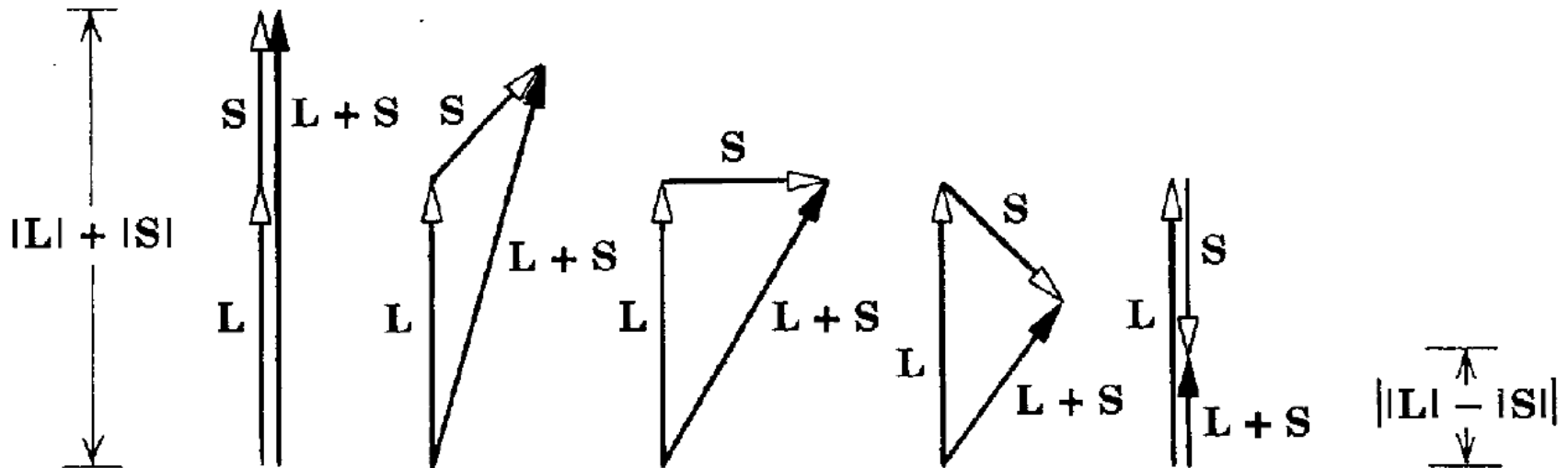
Esta energia potencial também vai mudar os níveis de energia do átomo !

Correções de estrutura fina ! (ver exemplo 8.3)

Momento Angular Total

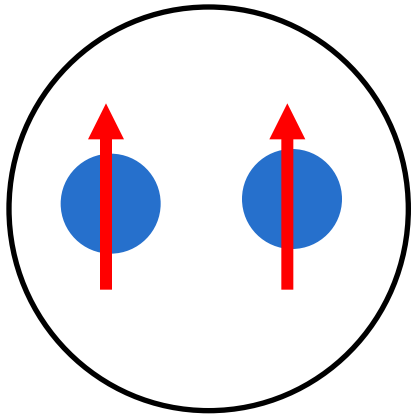
Momento angular orbital e intrínseco **se somam** : "rotação total"

$$\vec{J} = \vec{L} + \vec{S}$$

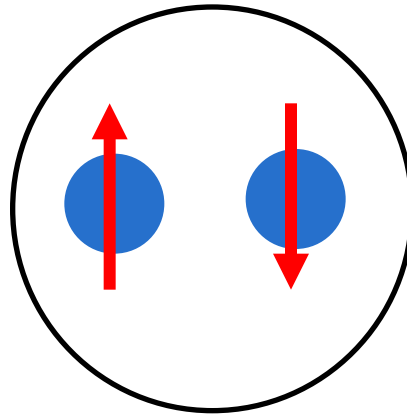


O spin é "parente" do momento angular orbital

$$\rho \rightarrow \pi^{+} + \pi^{-}$$

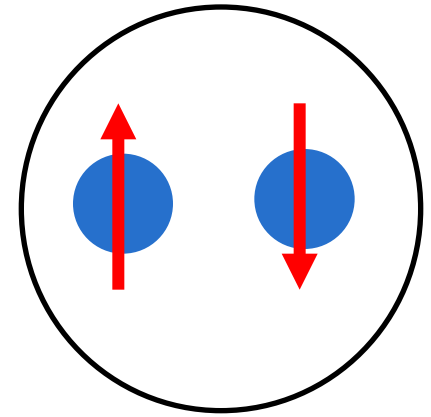


Spin 1



Spin 0

+



Spin 0

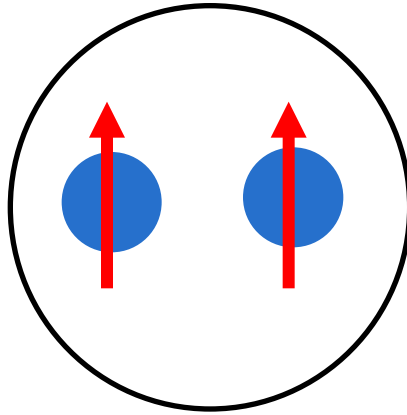
$$\left\{ \begin{array}{l} s = 1 \\ S = \sqrt{s(s+1)} \hbar = \sqrt{2} \hbar \\ S_z = m_s \hbar = \pm \hbar \end{array} \right.$$

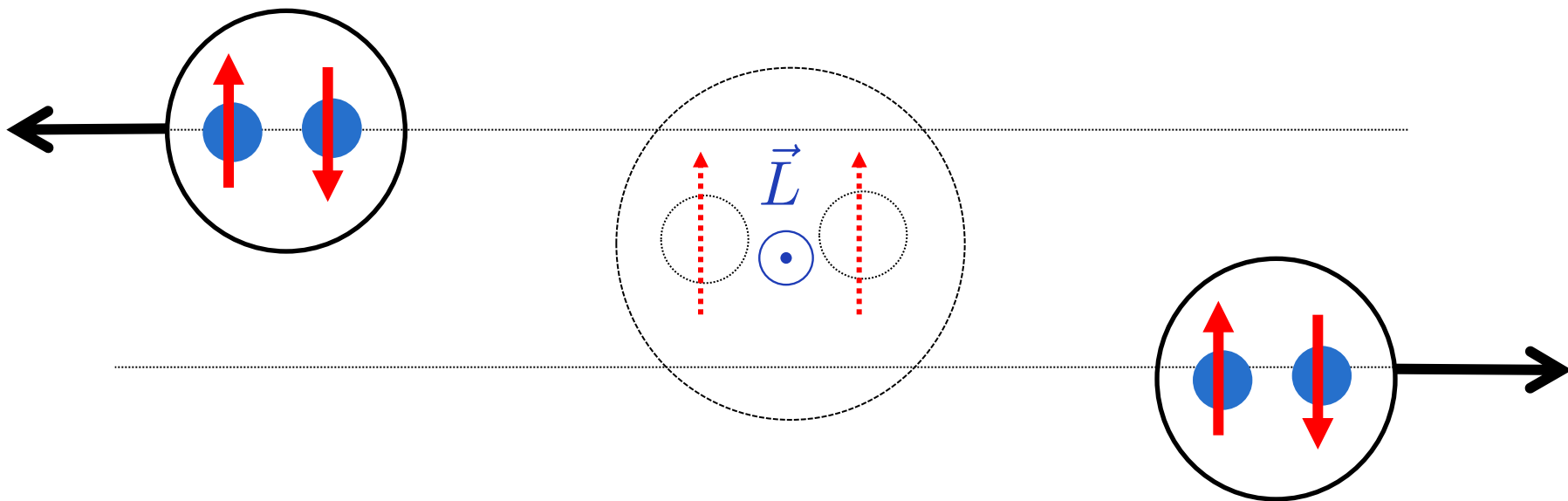
$$s = 0$$

$$s = 0$$

Spin não é conservado !

Antes : $L = 0$





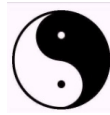
Depois : $L = 1$

Momento angular orbital não é conservado !

Momento angular total é conservado !

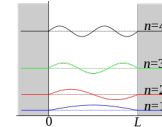
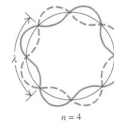
Mapa Lógico (resumão)

Dualidade onda-partícula



Princípio da incerteza

Confinamento gera quantização !



$$L = n \hbar$$

$$E = \frac{h^2 n^2}{8 m L^2}$$

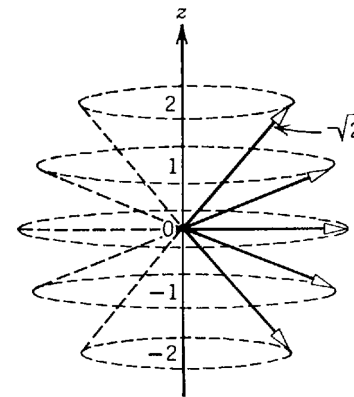
Schrödinger

$$L_z = m_l \hbar$$

$$L^2 = l(l + 1) \hbar^2$$

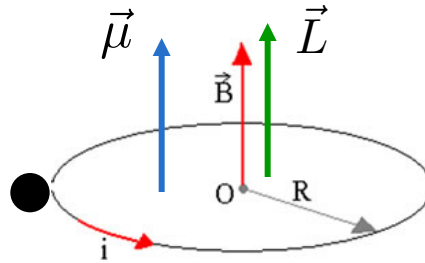
o elétron não cai !

L e L_z nunca paralelos !



Magnetismo microscópico

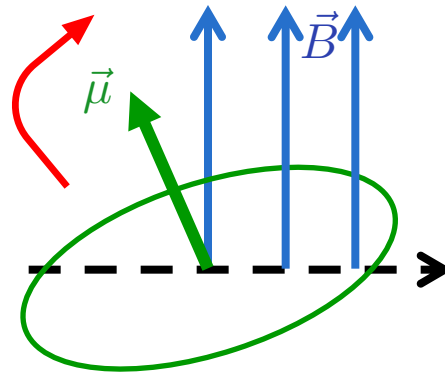
campo B gerado
pela corrente



$$\vec{\mu} = \frac{g_l \mu_b}{\hbar} \vec{L}$$

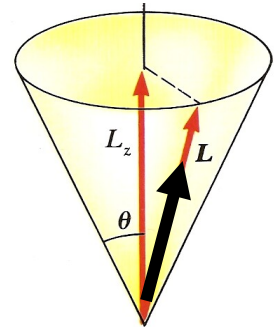
momento de dipolo
magnético

campo B
externo

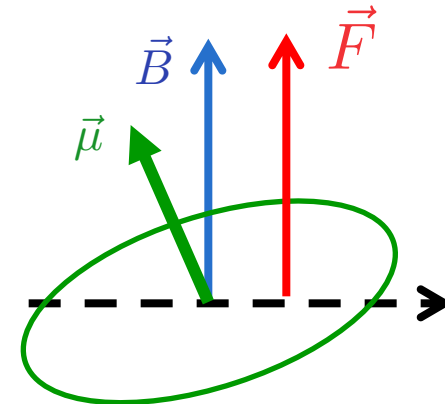


$$U = -\vec{\mu} \cdot \vec{B}$$

energia potencial
de orientação



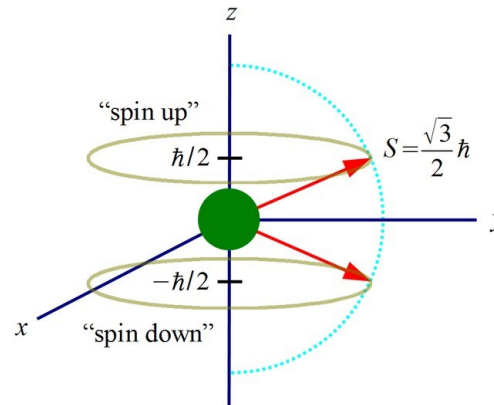
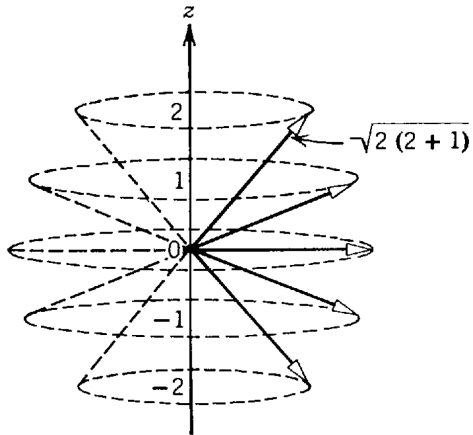
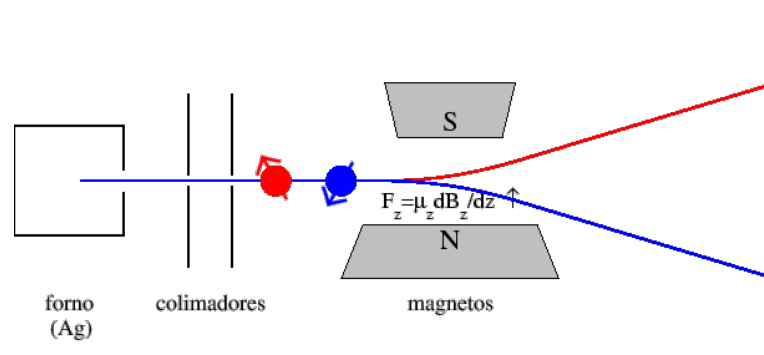
B externo
não uniforme



$$F = \frac{g_l \mu_b L_z}{\hbar} \frac{\partial B_z}{\partial z} \quad \text{clássico}$$

$$F = g_l \mu_b m_l \frac{\partial B_z}{\partial z} \quad \text{quântico}$$

Stern - Gerlach e Phipps-Taylor



$$S = \sqrt{s(s+1)} \hbar$$

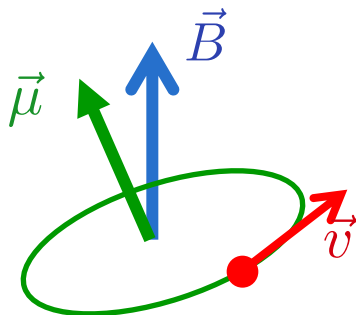
$$S_z = m_s \hbar$$

$$s = \frac{1}{2}$$

$$m_s = -\frac{1}{2}, +\frac{1}{2}$$

Campo magnético muda espectroscopia

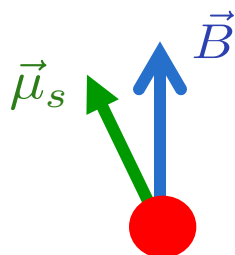
campo B
externo



$$U = -g_l \mu_b m_l B_z$$

Efeito Zeeman
Normal

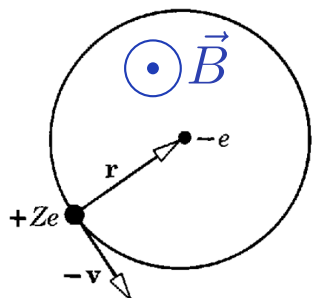
campo B
externo



$$U = -g_s \mu_b m_s B_z$$

Efeito Zeeman
Anômalo

campo B
interno



$$U = \frac{\mu_0 g_s e^2}{8 \pi m^2 r^3} \vec{L} \cdot \vec{S}$$

Spin-Órbita
estrutura fina