

# Física do spin

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(buscar: física do spin)

# Plano do curso

- 13/03 aula 1: Partículas elementares e idéias da física quântica
- 20/03 aula 2: Átomo de Bohr, quantização do momento angular
- 27/03 aula 3: Momento de dipolo magnético, Stern - Gerlach
- 10/04 aula 4: Efeito Zeeman anômalo
- 17/04 1ª Prova
- 24/04 aula 5: Equações de autovalores, matrizes de Pauli
- 08/05 aula 6: Comutadores, medidas SG sequenciais
- 15/05 aula 7: Medidas e valores médios
- 22/05 aula 8: Precessão e adição de spins
- 29/05 aula 9: Adição de spins

05/06 2ª Prova

12/06 aula 10: Princípio da exclusão de Pauli

19/06 aula 11: Interação hiperfina no hidrogênio

26/06 aula 12: Ressonância paramagnética do elétron

03/07 aula 13: Ressonância magnética nuclear

10/07 3ª Prova

## Avaliação

Três provas : P1 P2 P3

Média das duas melhores :  $P = (P_i + P_j)/2$

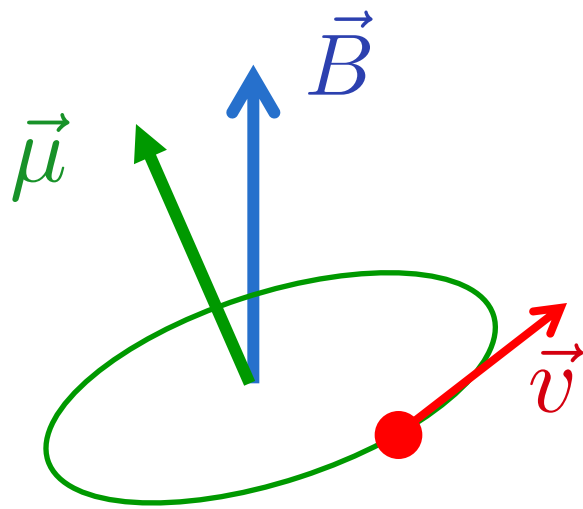
Substitutiva fechada

# Aula 4

Efeito Zeeman

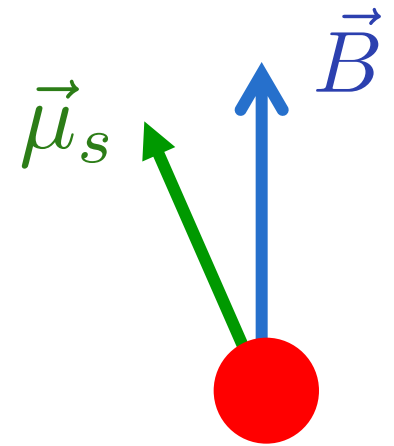
Interação Spin - Órbita

Momento Angular Total



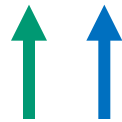
$$\vec{B} = B_z \hat{k}$$

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



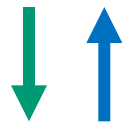
Carga positiva

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



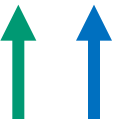
Carga negativa

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



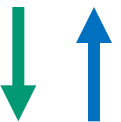
Carga positiva

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



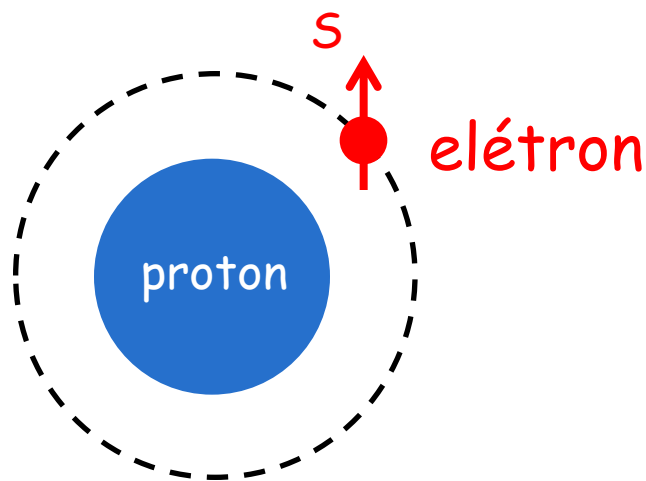
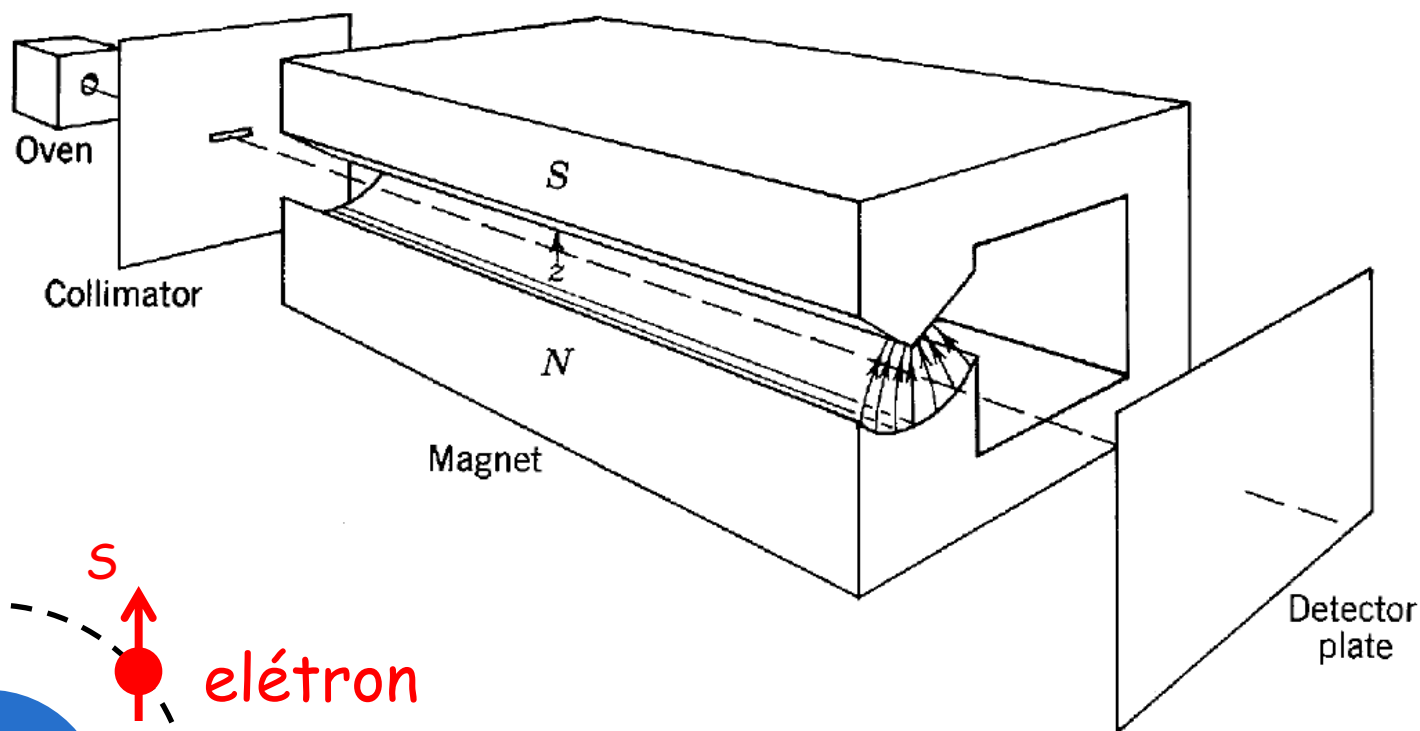
Carga negativa

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



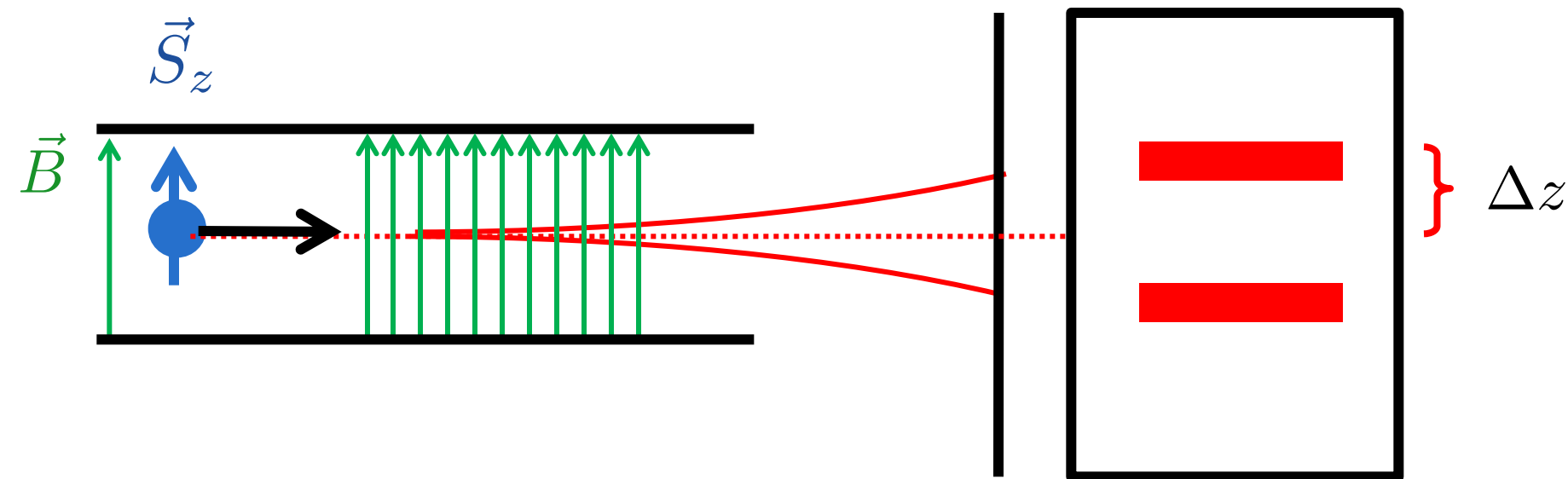
# Experiência de Phipps-Taylor (1927)

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



Átomo de hidrogênio

$$L = 0 \quad L_z = 0$$



$$U = g_s \mu_b m_s B_z$$

$$F = -\frac{\partial U}{\partial z}$$

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

Conhecemos  $\frac{\partial B_z}{\partial z}$ ,  $m_s = \pm \frac{1}{2}$

Medimos  $\Delta z$

Determinamos  $g_s = 2$

# Efeito Zeeman

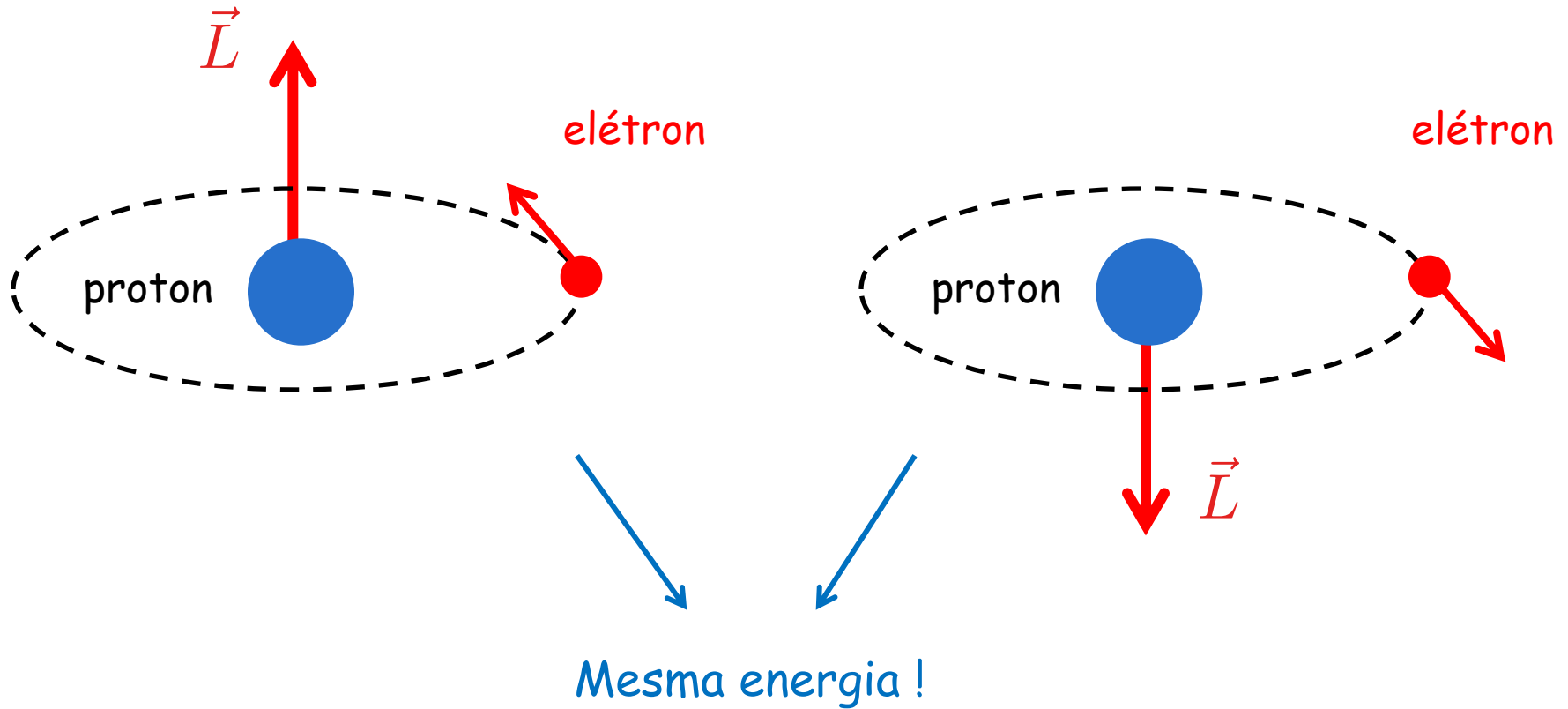
Medida do desdobramento das linhas do sódio  
1896



Pieter Zeeman  
(1865 - 1943)

Prêmio Nobel de Física em 1902

# Efeito Zeeman Normal



Estado  $n = 2$

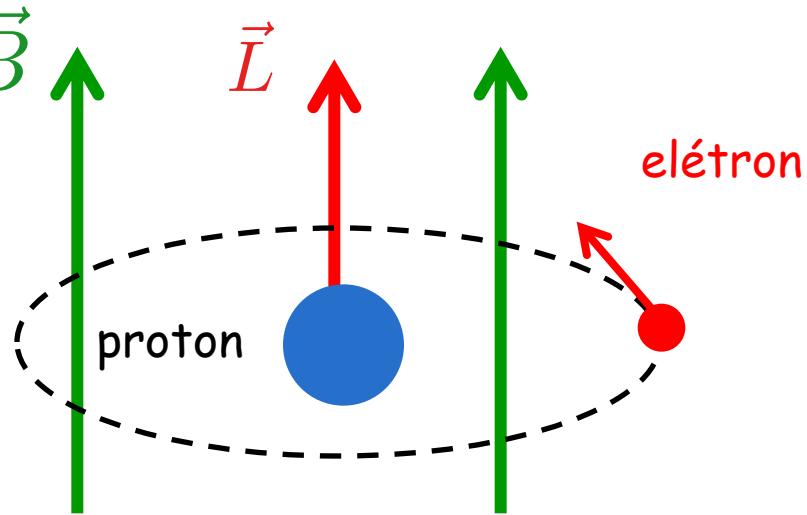


$$E = -\frac{m}{2} \left( \frac{Z e^2}{4 \pi \epsilon_0 \hbar} \right)^2 \frac{1}{n^2} = E_2$$

$n = 2$

(  $n = 1$  só com  $L=0$  )

# Efeito Zeeman Normal

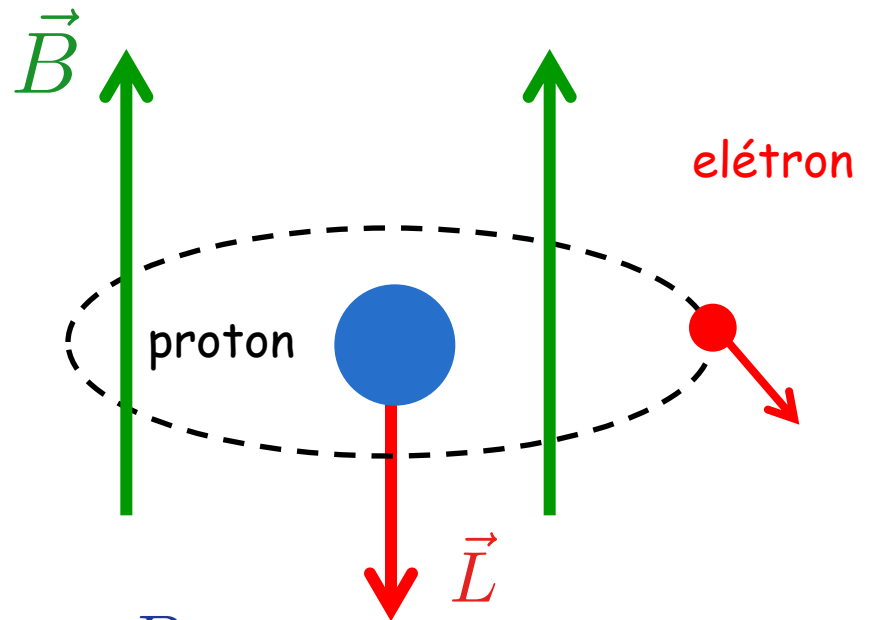


$$U = +g_l \mu_b m_l B_z$$

$$m_l = +1$$

$$E_2^+ = E_2 + U$$

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



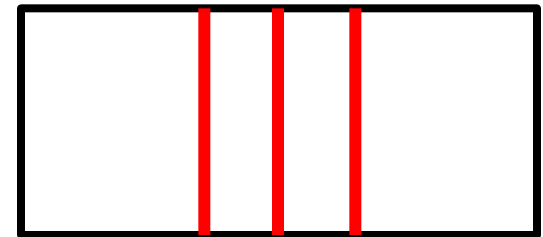
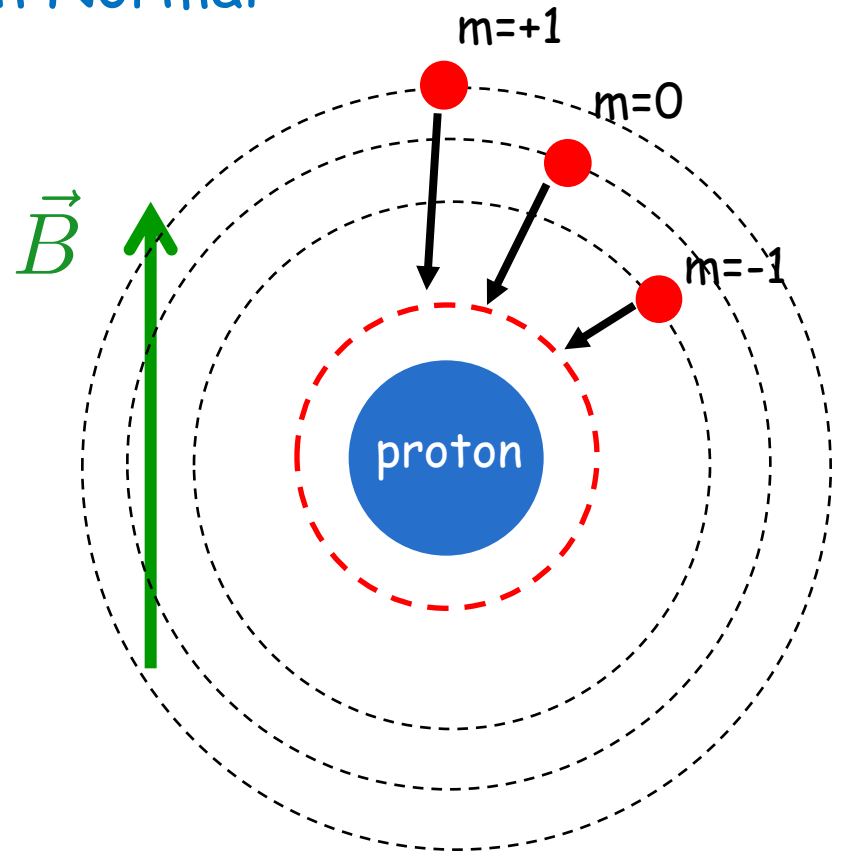
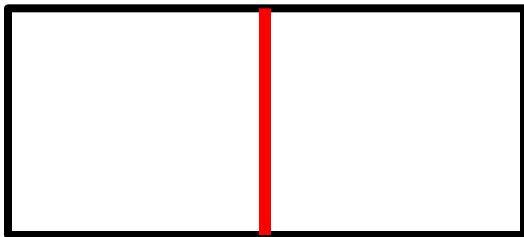
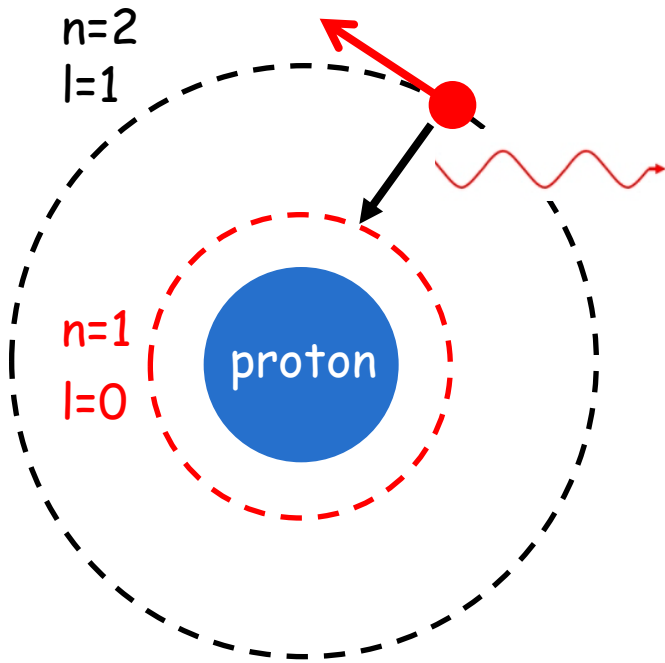
$$m_l = -1$$

$$E_2^- = E_2 + U$$

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

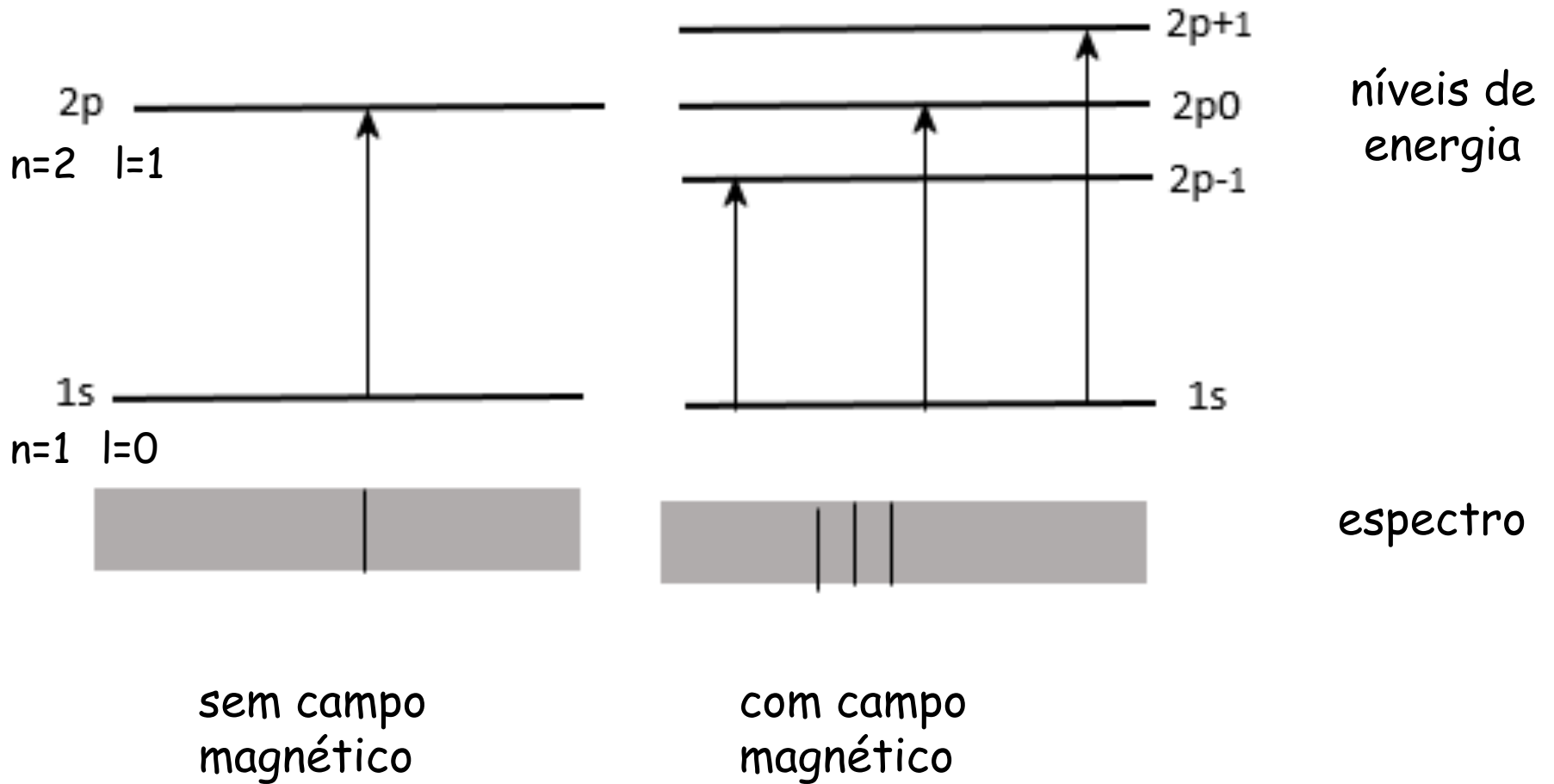
Temos também  $E_2^0 = E_2$  quando  $m_l = 0$

# Efeito Zeeman Normal

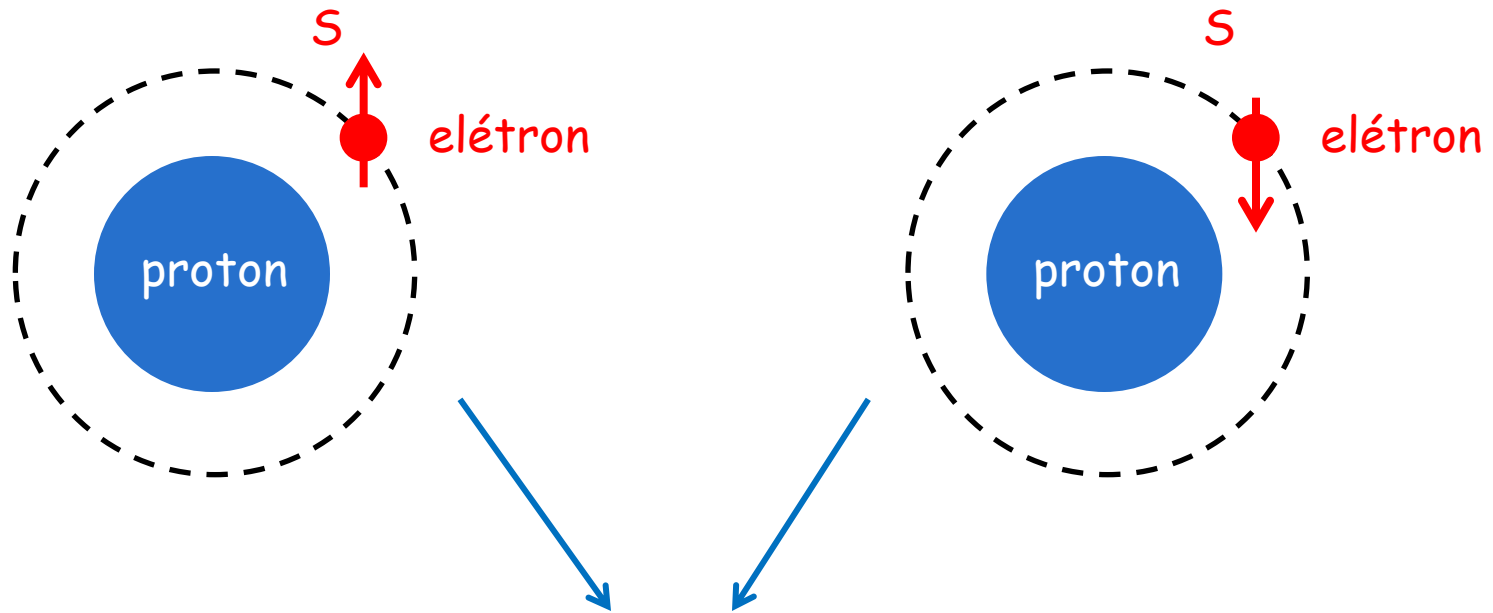


Desdobramento das linhas espectrais !

# Efeito Zeeman Normal



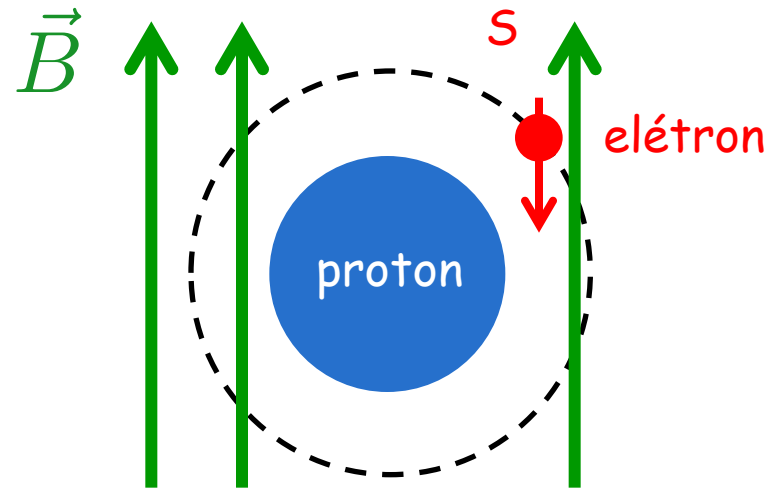
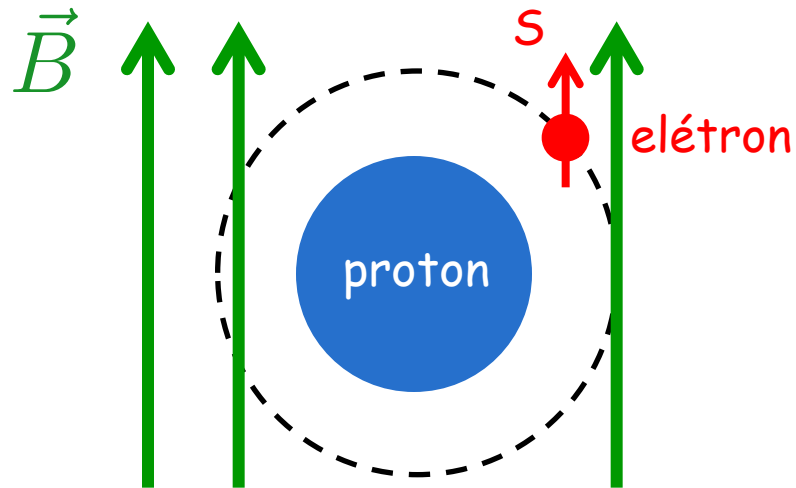
# Efeito Zeeman Anômalo



Mesma energia !

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

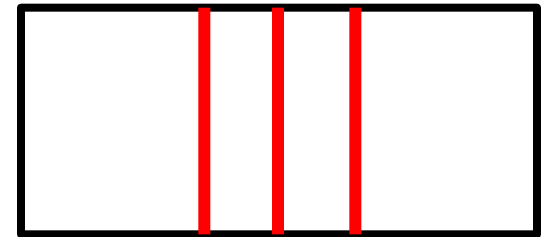
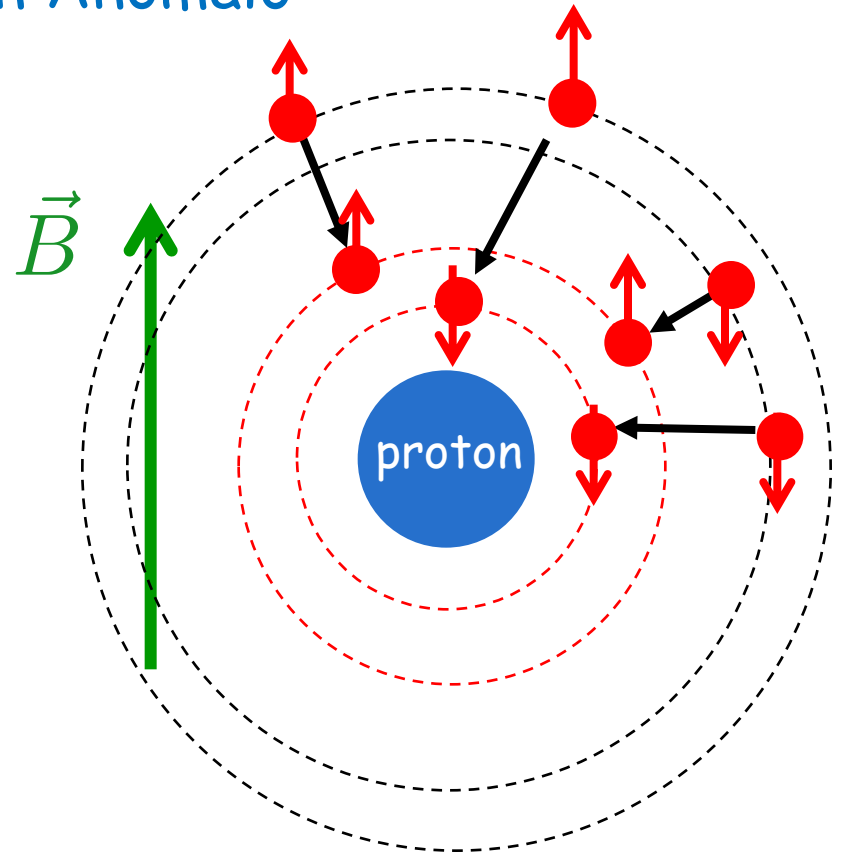
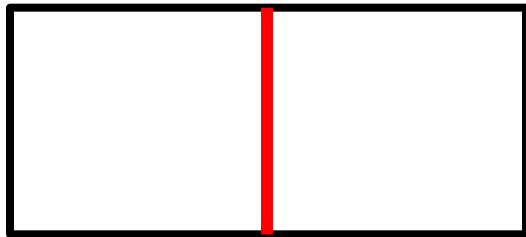
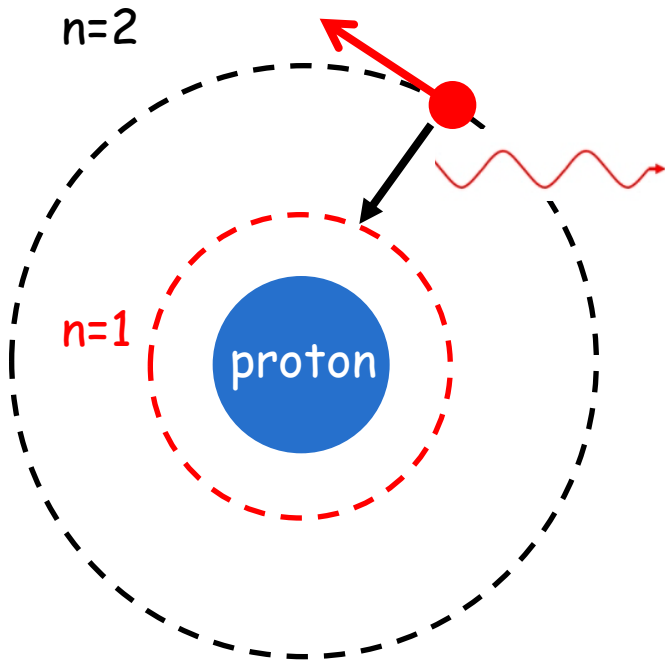


$$U = + g_s \mu_b m_s B_z$$

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

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

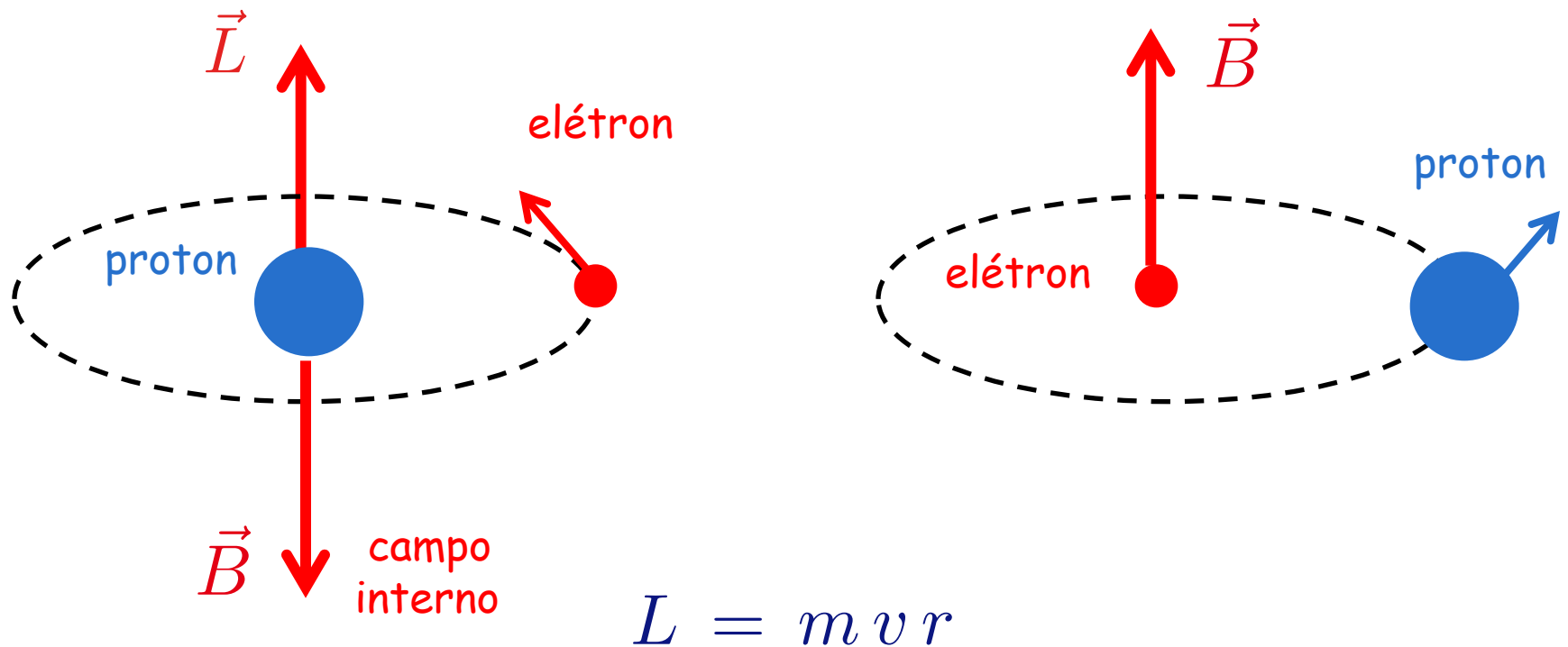
# Efeito Zeeman Anômalo



Desdobramento das linhas espectrais !

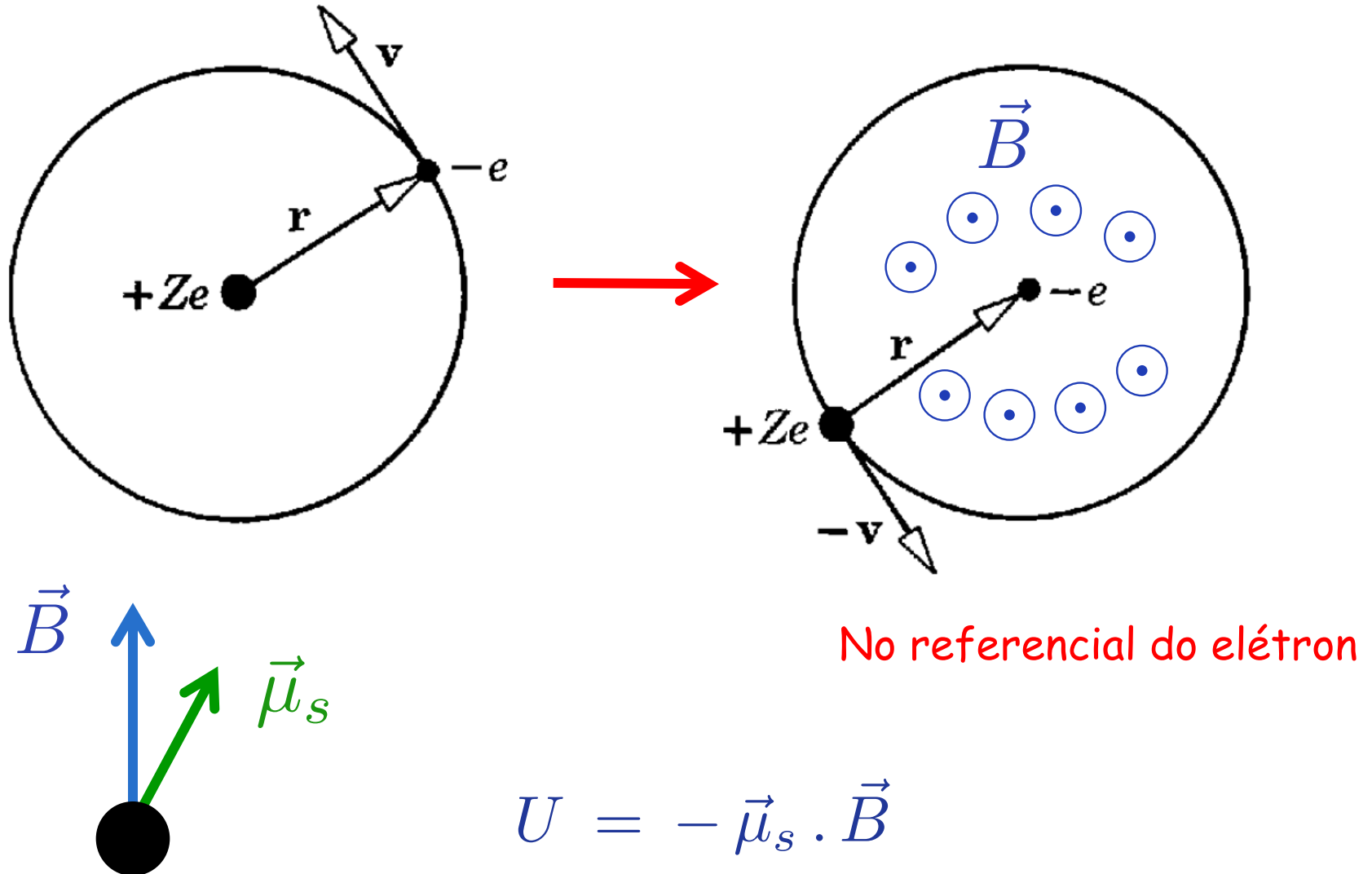
# Interação spin-órbita

## Campo magnético interno



# Interação spin-órbita

## Átomo tipo-hidrogênio



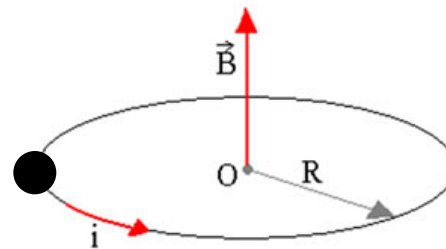
$$U = -\vec{\mu}_s \cdot \vec{B}$$

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

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

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

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



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

$$L = m v r$$

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



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

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

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

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

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

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

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

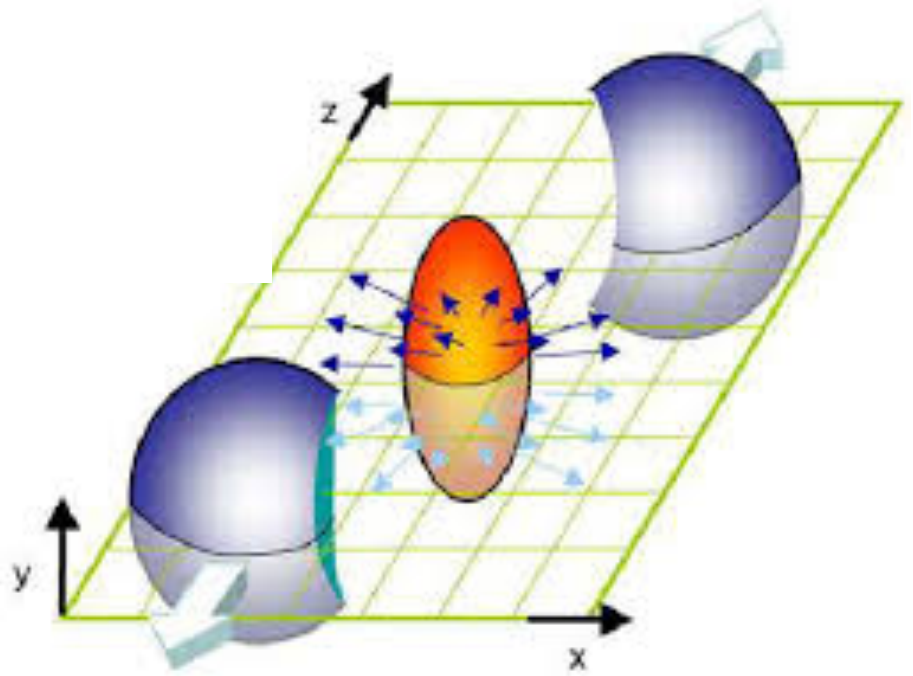
$$\vec{B} = \frac{\mu_0 e}{4\pi m r^3} \vec{L}$$

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

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

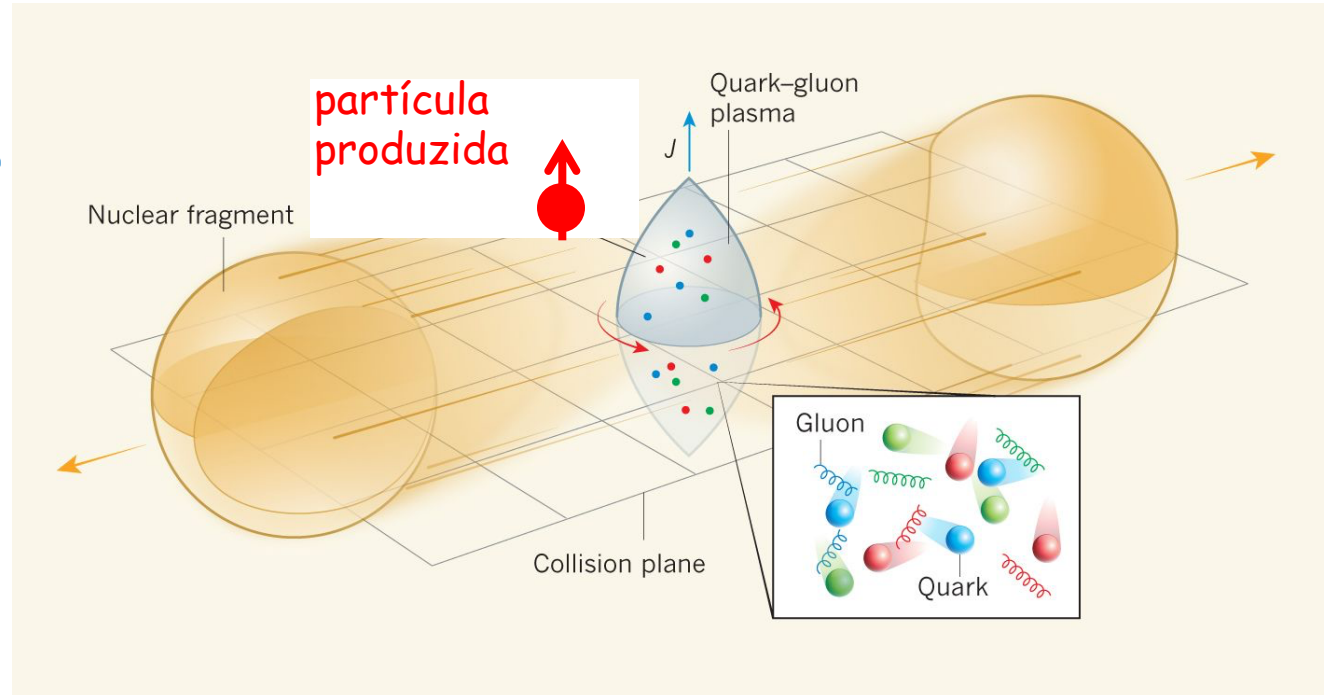
Correções de estrutura fina ! (ver exemplo 8.3)

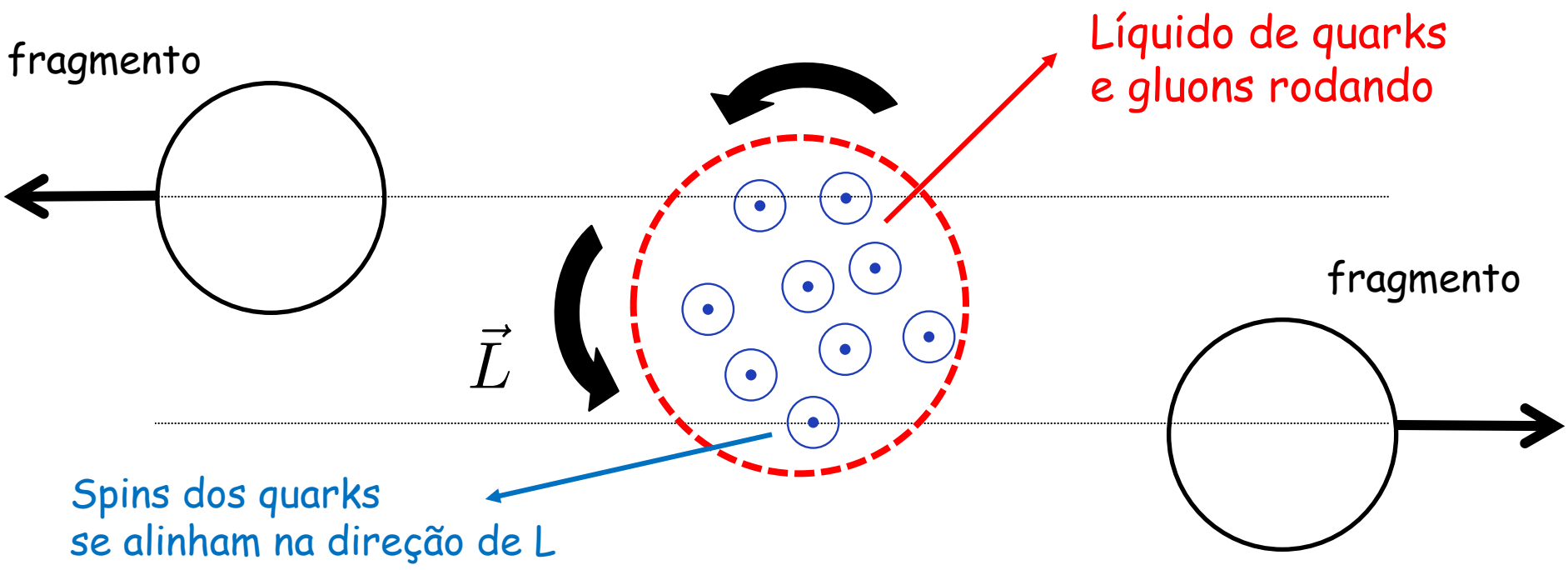
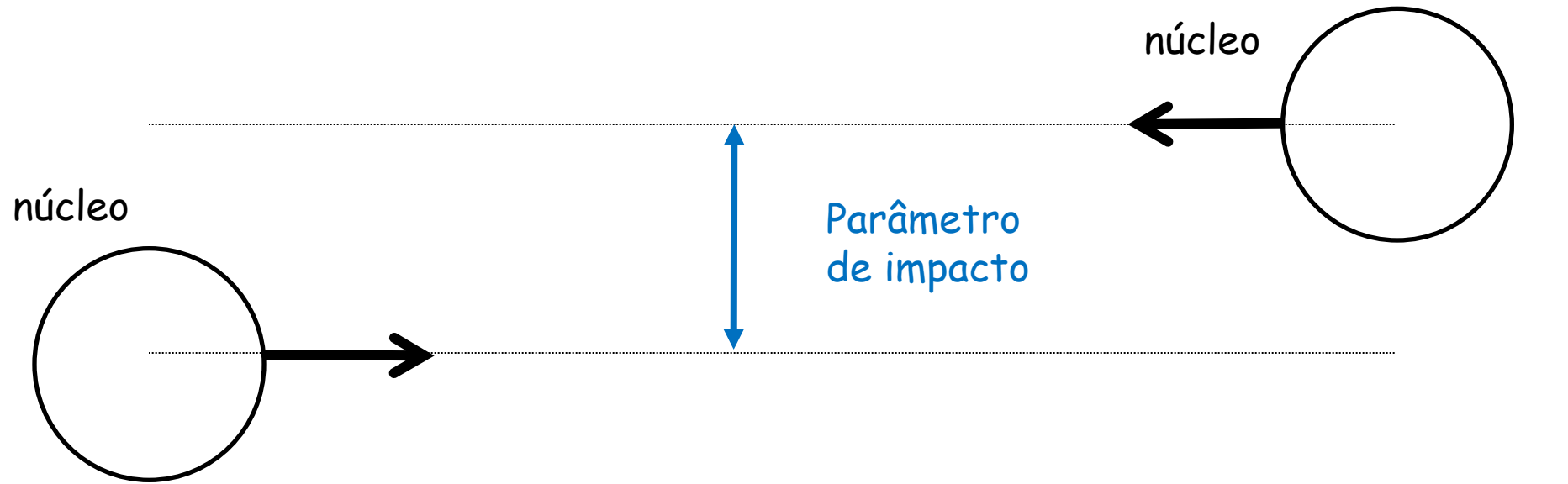
# Colisão de Ions Pesados Relativísticos no LHC



Spin alinhado ao  
Momento Angular

Polarização !

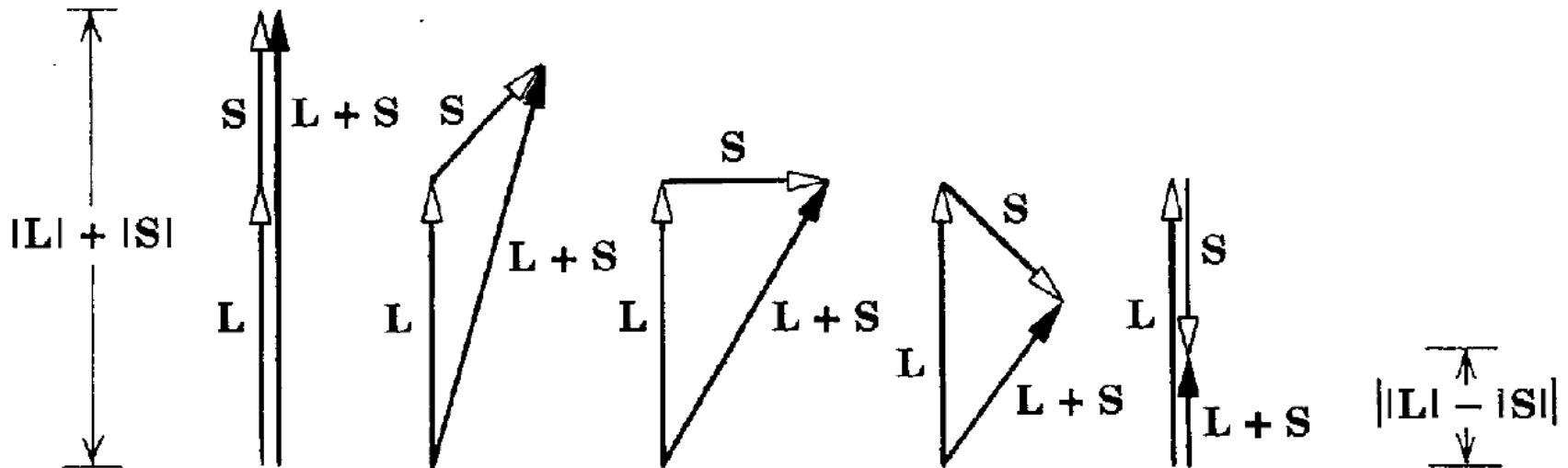




# Momento Angular Total

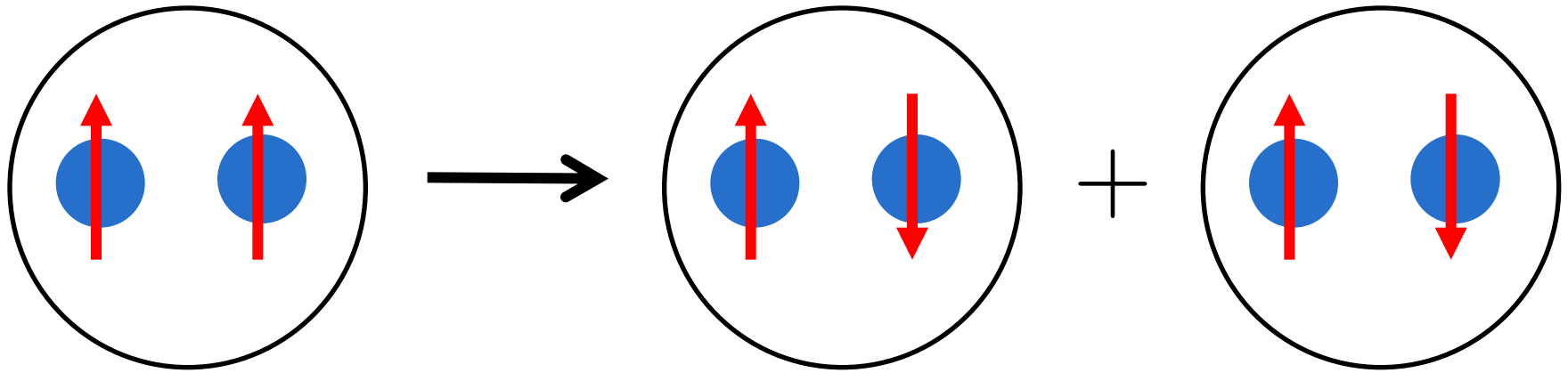
Momento angular orbital e intrínseco **se somam** : "rotação total"

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



O spin é "parente" do momento angular orbital

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



Spin 1

Spin 0

Spin 0

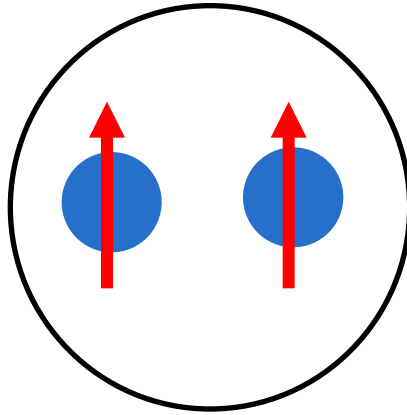
$$\left\{ \begin{array}{l} s = 1 \\ S = \sqrt{s(s+1)} \hbar = \sqrt{2} \hbar \\ S_z = m_s \hbar = \pm \hbar \end{array} \right.$$

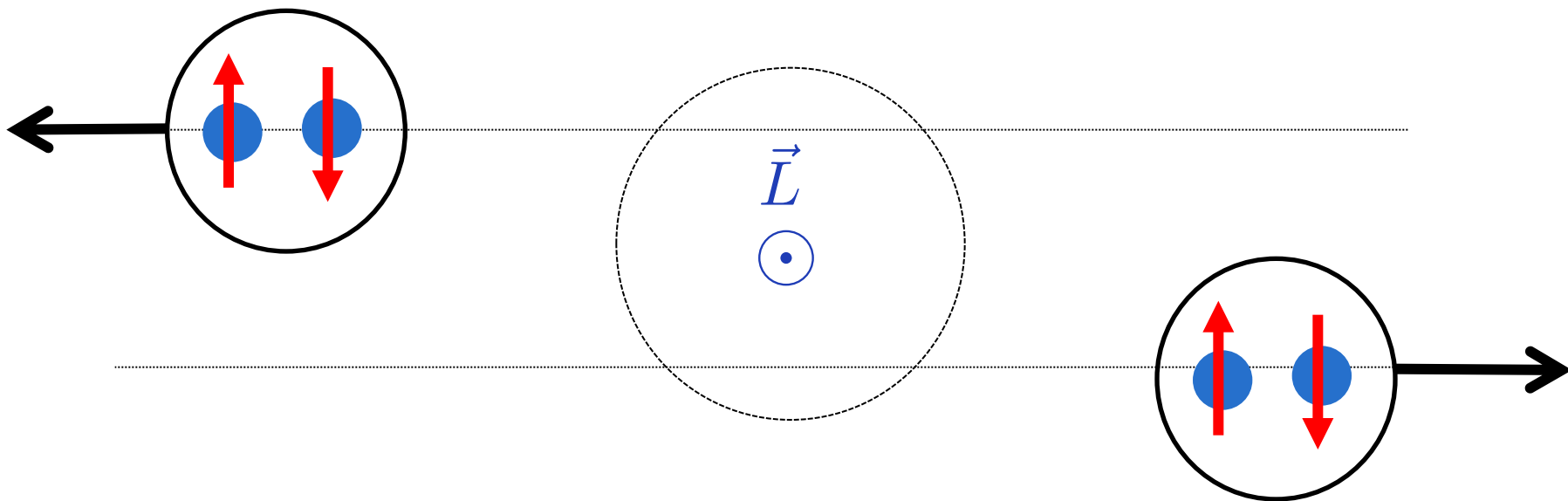
$$s = 0$$

$$s = 0$$

Spin não é conservado !

Antes :  $L = 0$



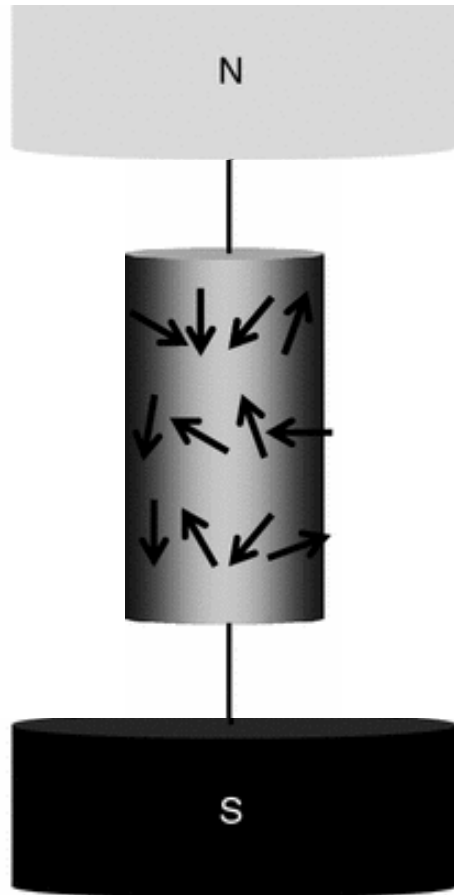


Depois :  $L = 1$

Momento angular orbital não é conservado !

Momento angular total é conservado !

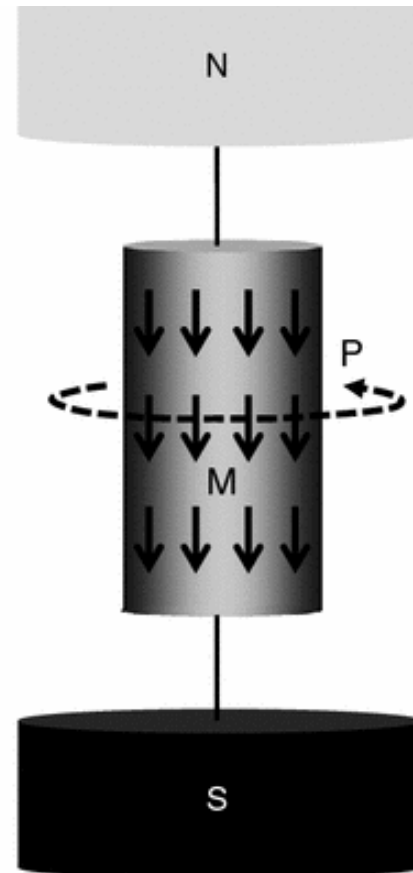
# Efeito Einstein - de Haas



Antes:

$$S = 0 \quad L = 0$$

$$J = L + S = 0$$



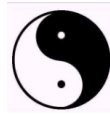
Depois

$$S = A \quad L = -A$$

$$J = L + S = 0$$

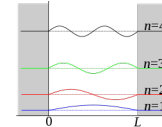
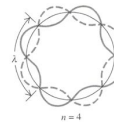
# Mapa Lógico (resumão)

# Dualidade onda-partícula



Princípio da incerteza

Confinamento gera quantização !



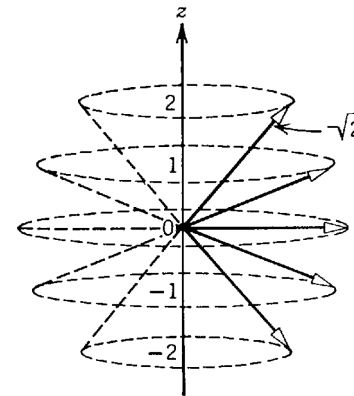
$$L = n \hbar$$

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

Schrödinger

$$L_z = m_l \hbar$$

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

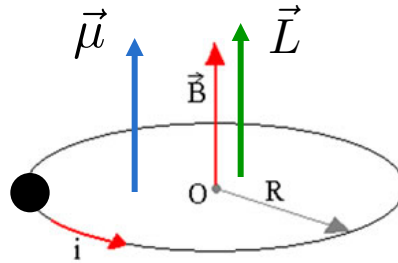


o elétron não cai !

$L$  e  $L_z$  nunca paralelos !

# Magnetismo microscópico

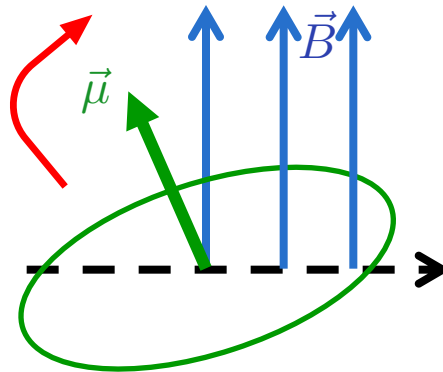
campo B gerado  
pela corrente



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

momento de dipolo  
magnético

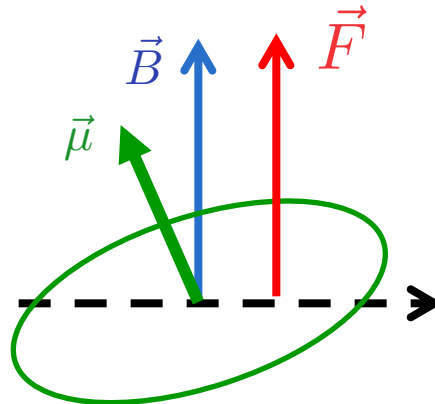
campo B  
externo



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

energia potencial  
de orientação

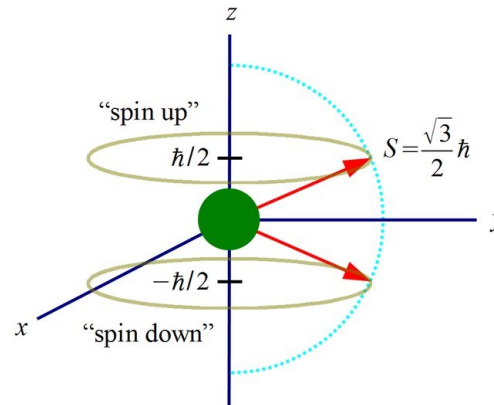
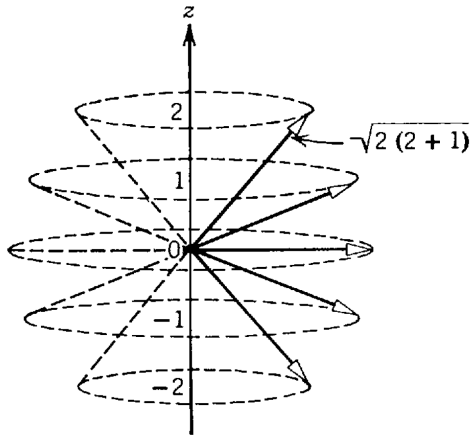
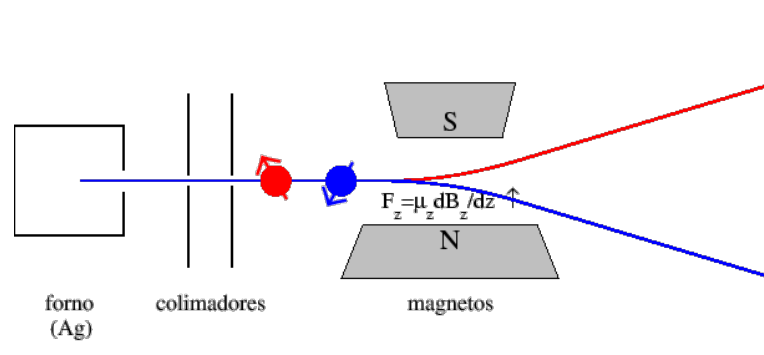
B externo  
não uniforme



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

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

# Stern - Gerlach e Phipps-Taylor



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

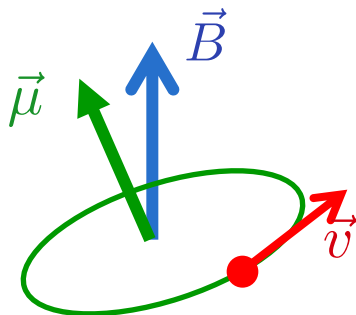
$$S_z = m_s \hbar$$

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

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

# Campo magnético muda espectroscopia

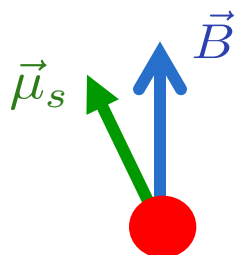
campo B  
externo



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

Efeito Zeeman  
Normal

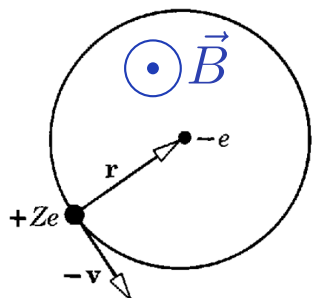
campo B  
externo



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

Efeito Zeeman  
Anômalo

campo B  
interno



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

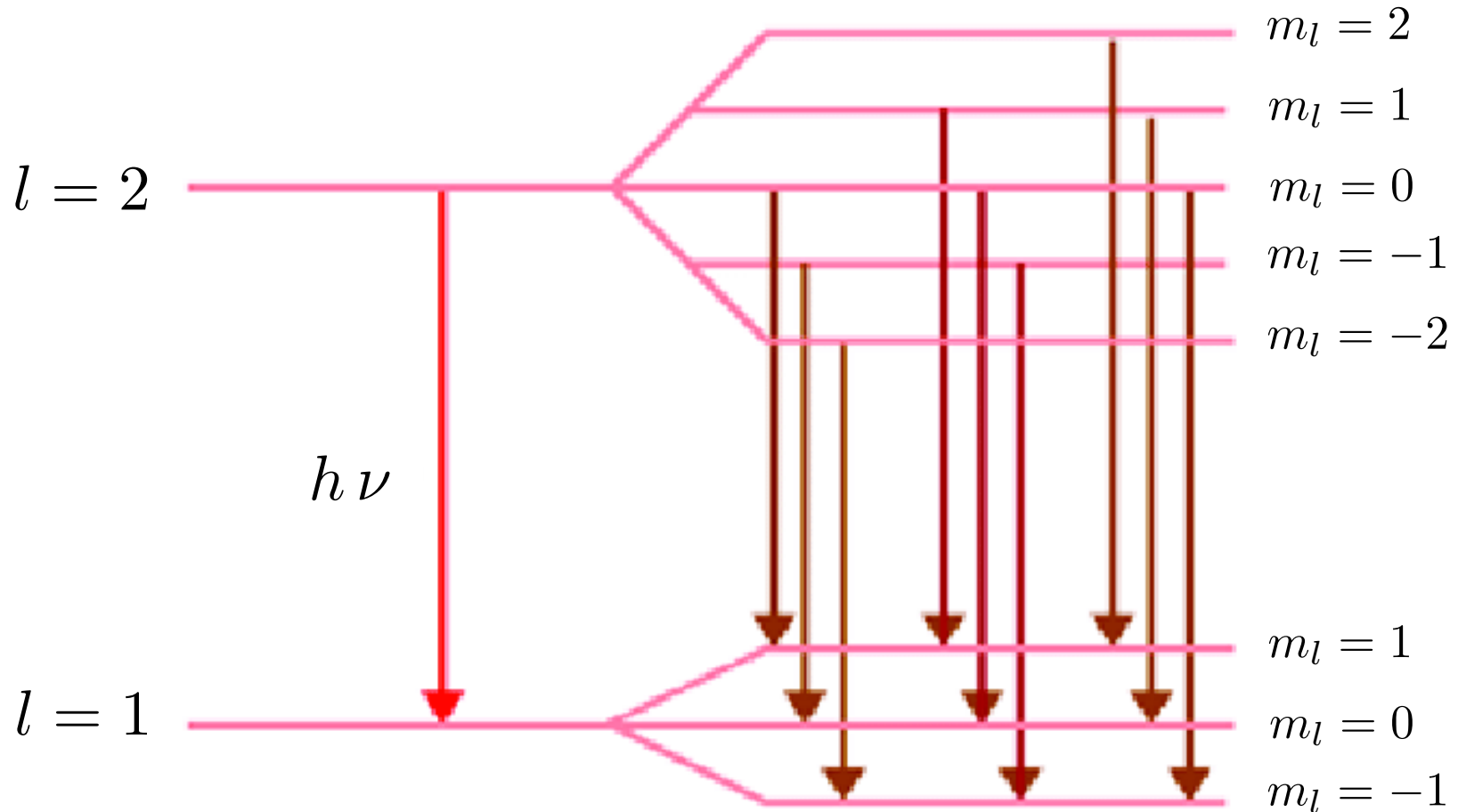
Spin-Órbita  
estrutura fina

FIM

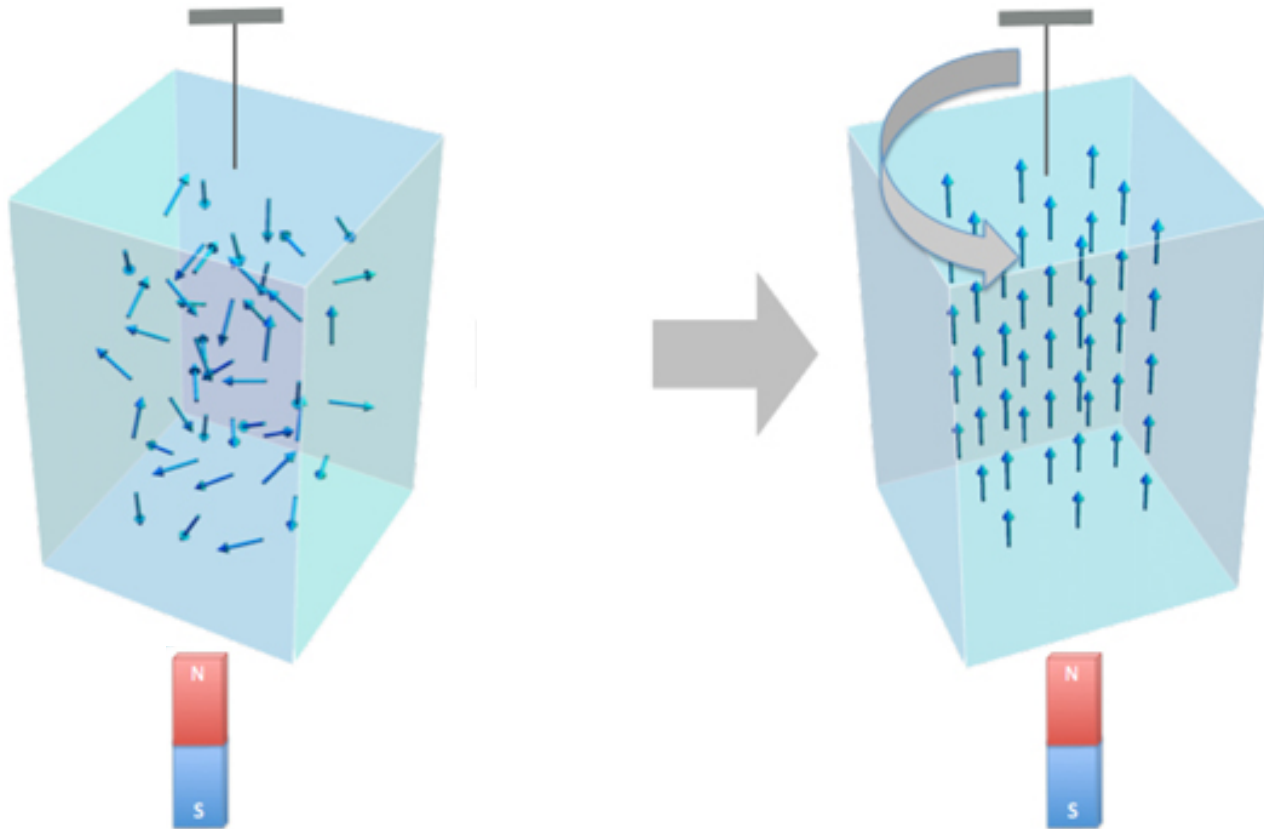
# Efeito Zeeman Normal

Sem campo magnético

Com campo magnético



# Efeito Einstein - de Haas



Antes:

$$S = 0 \quad L = 0$$

$$J = L + S = 0$$

Depois

$$S = A \quad L = -A$$

$$J = L + S = 0$$