Introdução à Física das Partículas Elementares

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(buscar: física das partículas elementares)

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Plano do Curso

14/03	Cap. 1	25/04	Cap. 4	25/05	Cap. 9
16/03	Cap. 1	27/04	Cap. 6	30/05	Cap. 9
21/03	Cap. 2	04/05	Cap. 7	01/06	Cap. 9
23/03	Cap. 2	09/05	Cap. 7	06/06	
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Aula 10

Capítulo 4

Spin

Helicidade

Dirac e o Spin

Pato !

Mecânica Quântica : $$\frac{dO}{dt} = \frac{d}{dt}\langle\hat{O}\rangle = i\langle\psi|[\hat{H},\hat{O}]|\psi\rangle$$

Se o operador comutar com o Hamiltoniano, o observável associado é conservado no tempo !

Partícula livre de Dirac $$\hat{H}_D = \boldsymbol{\alpha}\cdot\hat{\mathbf{p}} + \beta m,$$

$$[\hat{H}_D, \hat{\mathbf{L}}] = [\boldsymbol{\alpha}\cdot\hat{\mathbf{p}} + \beta m, \hat{\mathbf{r}}\times\hat{\mathbf{p}}] = [\boldsymbol{\alpha}\cdot\hat{\mathbf{p}}, \hat{\mathbf{r}}\times\hat{\mathbf{p}}] + [\beta \cancel{m}, \vec{\mathbf{r}}\times\vec{\mathbf{p}}]$$

$$[\hat{H}_D, \hat{L}_x] = [\boldsymbol{\alpha}\cdot\hat{\mathbf{p}}, (\hat{\mathbf{r}}\times\hat{\mathbf{p}})_x] = [\alpha_x\hat{p}_x + \alpha_y\hat{p}_y + \alpha_z\hat{p}_z,\ \hat{y}\hat{p}_z - \hat{z}\hat{p}_y]$$

$$[\hat{x}, \hat{p}_x] = [\hat{y}, \hat{p}_y] = [\hat{z}, \hat{p}_z] = i$$

$$[\hat{H}_D, \hat{L}_x] = \alpha_y[\hat{p}_y, \hat{y}]\hat{p}_z - \alpha_z[\hat{p}_z, \hat{z}]\hat{p}_y = -i(\alpha_y\hat{p}_z - \alpha_z\hat{p}_y) = -i(\boldsymbol{\alpha}\times\hat{\mathbf{p}})_x$$

$$\boxed{[\hat{H}_D, \hat{\mathbf{L}}] = -i\boldsymbol{\alpha}\times\hat{\mathbf{p}}}$$

L não é conservado !!!

Vamos introduzir $$\hat{\mathbf{S}} \equiv \frac{1}{2}\hat{\mathbf{\Sigma}} \equiv \frac{1}{2}\begin{pmatrix} \boldsymbol{\sigma} & 0 \\ 0 & \boldsymbol{\sigma} \end{pmatrix}$$ (candidato a spin)

$$\hat{\Sigma}_x = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \qquad \hat{\Sigma}_y = \begin{pmatrix} 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \end{pmatrix} \qquad \hat{\Sigma}_z = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$[\alpha_i, \hat{\Sigma}_x] = \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix}\begin{pmatrix} \sigma_x & 0 \\ 0 & \sigma_x \end{pmatrix} - \begin{pmatrix} \sigma_x & 0 \\ 0 & \sigma_x \end{pmatrix}\begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix} = \begin{pmatrix} 0 & [\sigma_i, \sigma_x] \\ [\sigma_i, \sigma_x] & 0 \end{pmatrix}$$

Usando $[\sigma_x, \sigma_x] = 0, \quad [\sigma_y, \sigma_x] = -2i\sigma_z \qquad [\sigma_z, \sigma_x] = 2i\sigma_y$

$$[\alpha_x, \Sigma_x] = 0$$

$$[\alpha_y, \Sigma_x] = \begin{pmatrix} 0 & -2i\sigma_z \\ -2i\sigma_z & 0 \end{pmatrix} = -2i\alpha_z$$

$$[\alpha_z, \Sigma_x] = \begin{pmatrix} 0 & 2i\sigma_y \\ 2i\sigma_y & 0 \end{pmatrix} = 2i\alpha_y$$

$$[\hat{H}_D, \Sigma_x] = [\boldsymbol{\alpha} \cdot \hat{\mathbf{p}} + \beta m, \Sigma_x]$$

$$[\beta, \hat{\Sigma}_x] = 0$$

$$[\hat{H}_D, \hat{\Sigma}_x] = [\boldsymbol{\alpha} \cdot \hat{\mathbf{p}}, \hat{\Sigma}_x] = [\alpha_x \hat{p}_x + \alpha_y \hat{p}_y + \alpha_z \hat{p}_z, \hat{\Sigma}_x]$$

$$= \hat{p}_x \cancel{[\alpha_x, \hat{\Sigma}_x]} + \hat{p}_y [\alpha_y, \hat{\Sigma}_x] + \hat{p}_z [\alpha_z, \hat{\Sigma}_x]$$

$$[\hat{H}_D, \hat{\Sigma}_x] = -2i\hat{p}_y \alpha_z + 2i\hat{p}_z \alpha_y \quad = 2i(\boldsymbol{\alpha} \times \hat{\mathbf{p}})_x$$

Incluindo a coordenada y e z e usando $\hat{\mathbf{S}} = \frac{1}{2}\hat{\boldsymbol{\Sigma}}$ → $\boxed{[\hat{H}_D, \hat{\mathbf{S}}] = i\,\boldsymbol{\alpha} \times \hat{\mathbf{p}}}$

"spin" não é conservado !

$$\hat{\mathbf{J}} = \hat{\mathbf{L}} + \hat{\mathbf{S}}$$

$$\boxed{\left[\hat{H}_D, \hat{\mathbf{J}}\right] \equiv \left[\hat{H}_D, \hat{\mathbf{L}} + \hat{\mathbf{S}}\right] = 0}$$

"Momento angular total" é conservado !

$$\hat{\mathbf{S}} = \tfrac{1}{2}\hat{\boldsymbol{\Sigma}} = \frac{1}{2}\begin{pmatrix} \boldsymbol{\sigma} & 0 \\ 0 & \boldsymbol{\sigma} \end{pmatrix} \longrightarrow [\hat{S}_x, \hat{S}_y] = i\hat{S}_z$$

Mesma relação de comutação que o momento angular : $[\hat{L}_x, \hat{L}_y] = i\hat{L}_z$

Tem a mesma regra de quantização !

$$\hat{L}^2 = \hat{L}_x^2 + \hat{L}_y^2 + \hat{L}_z^2$$

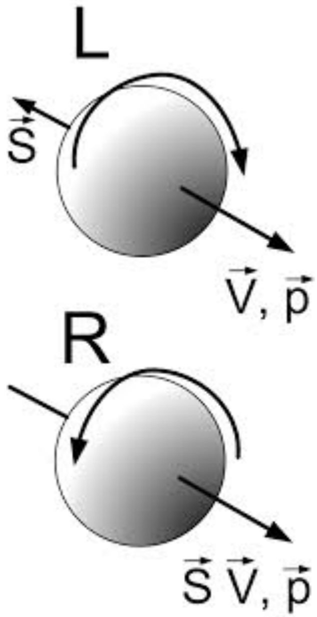
$$\hat{\mathbf{S}}^2 = \frac{1}{4}(\hat{\Sigma}_x^2 + \hat{\Sigma}_y^2 + \hat{\Sigma}_z^2) = \frac{3}{4}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\hat{\mathbf{S}}^2|s, m_s\rangle = s(s+1)|s, m_s\rangle$$

$$\hat{\mathbf{S}}^2\psi = s(s+1)\psi = \tfrac{3}{4}\psi \longrightarrow s = \frac{1}{2}$$

Spin "sai" da equação de Dirac !!!

Helicidade



Partícula de mão esquerda

Partícula de mão direita

Soluções da Eq. de Dirac com momento constante $\psi_i = u_i(E,\mathbf{p})e^{i(\mathbf{p}\cdot\mathbf{x}-Et)}$

$$u_1 = N_1\begin{pmatrix}1\\0\\\frac{p_z}{E+m}\\\frac{p_x+ip_y}{E+m}\end{pmatrix}\quad u_2 = N_2\begin{pmatrix}0\\1\\\frac{p_x-ip_y}{E+m}\\\frac{-p_z}{E+m}\end{pmatrix}\qquad u_3 = N_3\begin{pmatrix}\frac{p_z}{E-m}\\\frac{p_x+ip_y}{E-m}\\1\\0\end{pmatrix}\quad u_4 = N_4\begin{pmatrix}\frac{p_x-ip_y}{E-m}\\\frac{-p_z}{E-m}\\0\\1\end{pmatrix}$$

$$E = +\left|\sqrt{\mathrm{p}^2+m^2}\right| \qquad\qquad E = -\left|\sqrt{\mathrm{p}^2+m^2}\right|$$

Em repouso $\psi = u(E,0)e^{-iEt}$

$$\psi_1 = N\begin{pmatrix}1\\0\\0\\0\end{pmatrix}e^{-imt},\ \psi_2 = N\begin{pmatrix}0\\1\\0\\0\end{pmatrix}e^{-imt},\ \psi_3 = N\begin{pmatrix}0\\0\\1\\0\end{pmatrix}e^{+imt}\ \psi_4 = N\begin{pmatrix}0\\0\\0\\1\end{pmatrix}e^{+imt}$$

São auto-estados de spin ?

Partículas em repouso com $u_1(E,0)$ $u_2(E,0)$ são autoestados de $\hat{S}_z$

$$\hat{S}_z = \tfrac{1}{2}\Sigma_z = \tfrac{1}{2}\begin{pmatrix} \sigma_z & 0 \\ 0 & \sigma_z \end{pmatrix} = \tfrac{1}{2}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$u_1(E,0) = N\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\hat{S}_z u_1 = \frac{1}{2} u_1$$

Partículas em movimento com

$$u_1(p) = \sqrt{E+m}\begin{pmatrix} 1 \\ 0 \\ \frac{p_z}{E+m} \\ \frac{p_x+ip_y}{E+m} \end{pmatrix}$$

não são autoestados de $\hat{S}_z$

Partículas viajando na direção z são autoestados de $\hat{S}_z$

$$u_1 = N\begin{pmatrix} 1 \\ 0 \\ \frac{\pm p}{E+m} \\ 0 \end{pmatrix}, \quad u_2 = N\begin{pmatrix} 0 \\ 1 \\ 0 \\ \frac{\mp p}{E+m} \end{pmatrix}, \quad v_1 = N\begin{pmatrix} 0 \\ \frac{\mp p}{E+m} \\ 0 \\ 1 \end{pmatrix} \text{ and } v_2 = N\begin{pmatrix} \frac{\pm p}{E+m} \\ 0 \\ 1 \\ 0 \end{pmatrix},$$

$$\hat{S}_z\, u_1(E,0,0,\pm\mathrm{p}) = +\tfrac{1}{2} u_1(E,0,0,\pm\mathrm{p}),$$
$$\hat{S}_z\, u_2(E,0,0,\pm\mathrm{p}) = -\tfrac{1}{2} u_2(E,0,0,\pm\mathrm{p}).$$

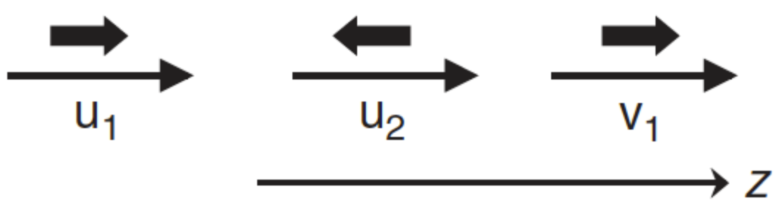
Porque o sinal menos ?

Lebowski

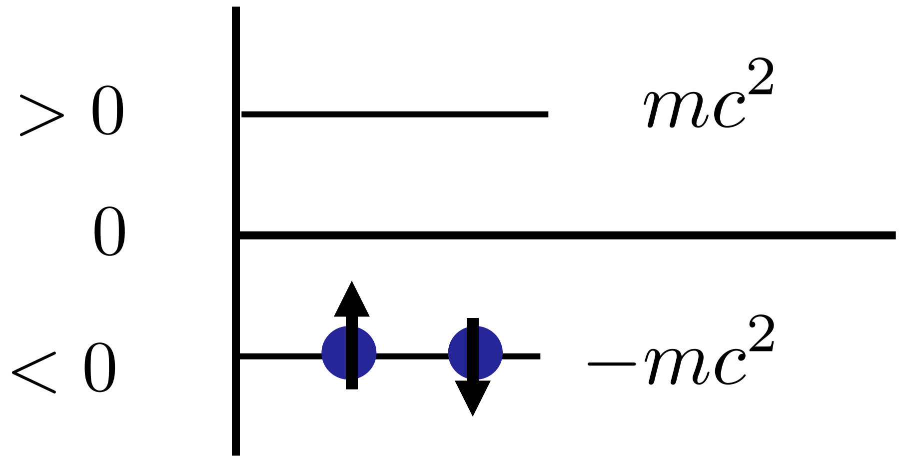
Para as antipartículas $\hat{S}_z^{(v)} = -\,\hat{S}_z$

$$\hat{S}_z^{(v)} v_1(E,0,0,\pm\mathrm{p}) \equiv -\hat{S}_z v_1(E,0,0,\pm\mathrm{p}) = +\tfrac{1}{2} v_1(E,0,0,\pm\mathrm{p}),$$
$$\hat{S}_z^{(v)} v_2(E,0,0,\pm\mathrm{p}) \equiv -\hat{S}_z v_2(E,0,0,\pm\mathrm{p}) = -\tfrac{1}{2} v_2(E,0,0,\pm\mathrm{p}).$$

Escolhemos momento + p :

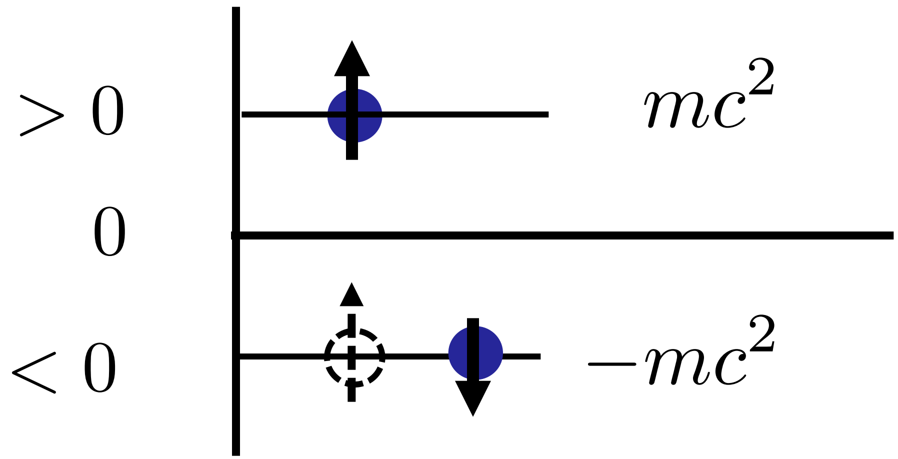


Energia



A falta do spin prá cima é vista como excesso de spin prá baixo !

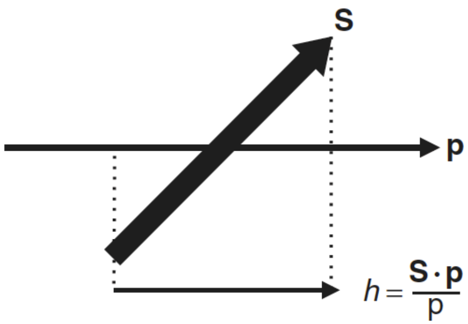
Energia



Se você tá dizendo...

Helicidade

Componente do spin na direção de vôo $$h \equiv \frac{\mathbf{S}\cdot\mathbf{p}}{p}$$



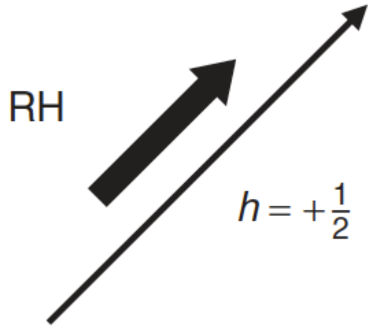
$$\hat{h} = \frac{\hat{\boldsymbol{\Sigma}}\cdot\hat{\mathbf{p}}}{2p} = \frac{1}{2p}\begin{pmatrix} \boldsymbol{\sigma}\cdot\hat{\mathbf{p}} & 0 \\ 0 & \boldsymbol{\sigma}\cdot\hat{\mathbf{p}} \end{pmatrix}$$

$$\hat{H}_D = \boldsymbol{\alpha}\cdot\hat{\mathbf{p}} + \beta m,$$

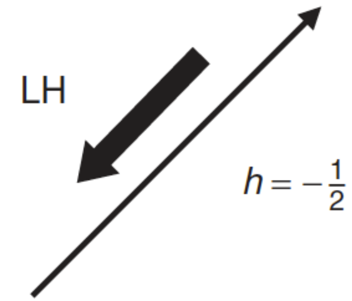
Helicidade é conservada $[\hat{H}_D, \hat{\boldsymbol{\Sigma}}\cdot\hat{\mathbf{p}}] = 0$

$$\alpha_i = \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix}$$

Dois autoestados de helicidade :



Mão direita



Mão esquerda

Autovalores de Helicidade

$$\hat{h}u = \lambda u$$

$$\frac{1}{2\mathrm{p}}\begin{pmatrix} \boldsymbol{\sigma}\cdot\mathbf{p} & 0 \\ 0 & \boldsymbol{\sigma}\cdot\mathbf{p} \end{pmatrix}\begin{pmatrix} u_A \\ u_B \end{pmatrix} = \lambda\begin{pmatrix} u_A \\ u_B \end{pmatrix}$$

$$\begin{cases} (\boldsymbol{\sigma}\cdot\mathbf{p})u_A = 2\mathrm{p}\,\lambda u_A \\ (\boldsymbol{\sigma}\cdot\mathbf{p})u_B = 2\mathrm{p}\,\lambda u_B \end{cases} \longrightarrow$$

Multiplicamos à esquerda por $\boldsymbol{\sigma}\cdot\mathbf{p}$ X

Lembrando que $(\boldsymbol{\sigma}\cdot\mathbf{p})^2 = \mathrm{p}^2$ a primeira equação fica

$$\mathrm{p}^2 u_A = 2\mathrm{p}\lambda(\boldsymbol{\sigma}\cdot\mathbf{p})u_A = 4\mathrm{p}^2\lambda^2 u_A \longrightarrow \boxed{\lambda = \pm 1/2}$$

Lembrando que $(\boldsymbol{\sigma}\cdot\mathbf{p})u_A = (E+m)u_B \longrightarrow u_B = 2\lambda\left(\frac{\mathrm{p}}{E+m}\right)u_A$

Encontrando u_A logo encontramos u_B !

Autoestados de Helicidade

$$(\boldsymbol{\sigma}\cdot\mathbf{p})u_A = 2\mathrm{p}\,\lambda u_A$$

$$\mathbf{p} = (\mathrm{p}\sin\theta\cos\phi,\ \mathrm{p}\sin\theta\sin\phi,\ \mathrm{p}\cos\theta)$$ (esféricas)

$$\left\{\begin{aligned} &\frac{1}{2\mathrm{p}}(\boldsymbol{\sigma}\cdot\mathbf{p}) = \frac{1}{2\mathrm{p}}\begin{pmatrix} p_z & p_x - ip_y \\ p_x + ip_y & -p_z \end{pmatrix} = \frac{1}{2}\begin{pmatrix} \cos\theta & \sin\theta e^{-i\phi} \\ \sin\theta e^{i\phi} & -\cos\theta \end{pmatrix} \\ &u_A = \begin{pmatrix} a \\ b \end{pmatrix} \end{aligned}\right.$$

$$\begin{pmatrix} \cos\theta & \sin\theta e^{-i\phi} \\ \sin\theta e^{i\phi} & -\cos\theta \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix} = 2\lambda\begin{pmatrix} a \\ b \end{pmatrix}$$

Escolhemos $\lambda = +1/2$ e descobrimos $u_\uparrow$

Resolvemos o sistema de duas equações com duas incógnitas

O espinor de mão direita $u_\uparrow = N \begin{pmatrix} \cos\left(\frac{\theta}{2}\right) \\ e^{i\phi}\sin\left(\frac{\theta}{2}\right) \\ \frac{\mathrm{p}}{E+m}\cos\left(\frac{\theta}{2}\right) \\ \frac{\mathrm{p}}{E+m}e^{i\phi}\sin\left(\frac{\theta}{2}\right) \end{pmatrix}$ $N = \sqrt{E+m}$

Depois escolhemos $\lambda = -1/2$ e repetimos os passos para encontrar $u_\downarrow$

$$u_\uparrow = \sqrt{E+m}\begin{pmatrix} c \\ se^{i\phi} \\ \frac{\mathrm{p}}{E+m}c \\ \frac{\mathrm{p}}{E+m}se^{i\phi} \end{pmatrix} \qquad u_\downarrow = \sqrt{E+m}\begin{pmatrix} -s \\ ce^{i\phi} \\ \frac{\mathrm{p}}{E+m}s \\ -\frac{\mathrm{p}}{E+m}ce^{i\phi} \end{pmatrix}$$

$$s = \sin\left(\frac{\theta}{2}\right) \qquad c = \cos\left(\frac{\theta}{2}\right)$$

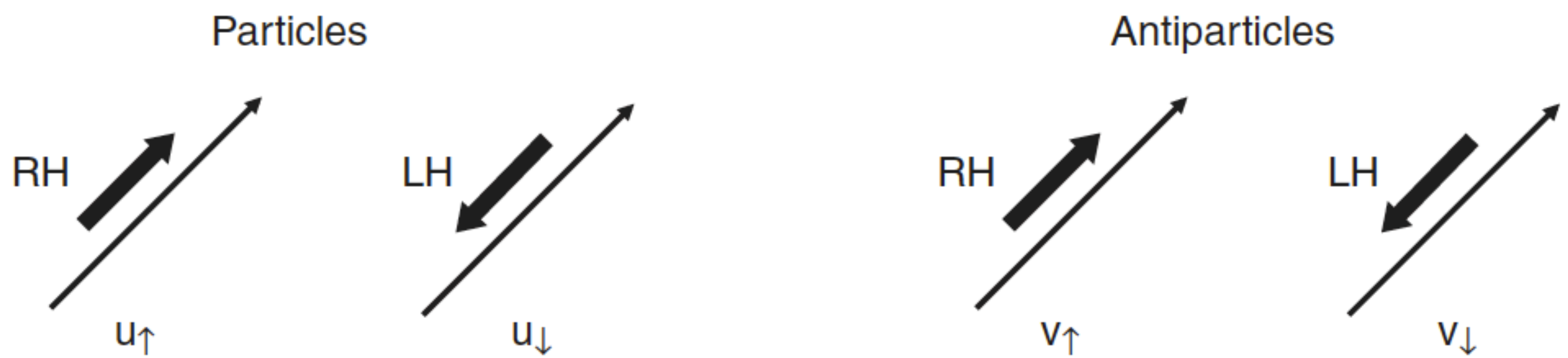
Antipartículas $\hat{\mathbf{S}}^{(v)} = -\hat{\mathbf{S}}$

$$\hat{h}u = \lambda u \qquad \lambda = +1/2 \longrightarrow \left(\frac{\boldsymbol{\Sigma}\cdot\mathbf{p}}{2\mathrm{p}}\right)v_\uparrow = -\tfrac{1}{2}v_\uparrow$$

$$v_\uparrow = \sqrt{E+m}\begin{pmatrix} \frac{p}{E+m}s \\ -\frac{p}{E+m}ce^{i\phi} \\ -s \\ ce^{i\phi} \end{pmatrix} \qquad v_\downarrow = \sqrt{E+m}\begin{pmatrix} \frac{p}{E+m}c \\ \frac{p}{E+m}se^{i\phi} \\ c \\ se^{i\phi} \end{pmatrix}$$

Quando $E \gg m$

$$u_\uparrow \approx \sqrt{E}\begin{pmatrix} c \\ se^{i\phi} \\ c \\ se^{i\phi} \end{pmatrix}, \; u_\downarrow \approx \sqrt{E}\begin{pmatrix} -s \\ ce^{i\phi} \\ s \\ -ce^{i\phi} \end{pmatrix}, \; v_\uparrow \approx \sqrt{E}\begin{pmatrix} s \\ -ce^{i\phi} \\ -s \\ ce^{i\phi} \end{pmatrix} \text{ and } v_\downarrow \approx \sqrt{E}\begin{pmatrix} c \\ se^{i\phi} \\ c \\ se^{i\phi} \end{pmatrix}$$



Capítulo 5

Propagador

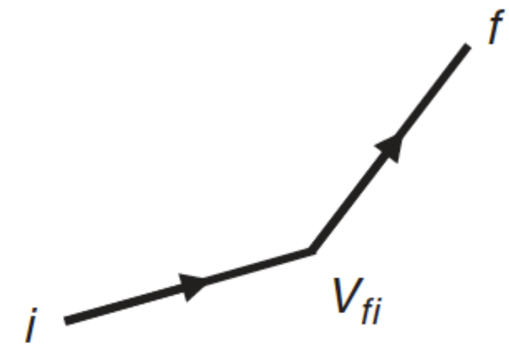
Regras de Feynman

Regra de ouro de Fermi

$$\Gamma_{fi} = 2\pi |T_{fi}|^2 \rho(E_f)$$

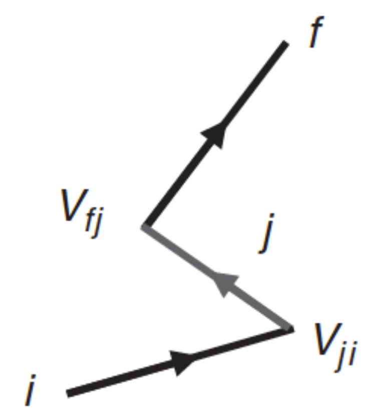
$$T_{fi} = \langle f|V|i\rangle$$

$V = H'$ Hamiltoniano de interação



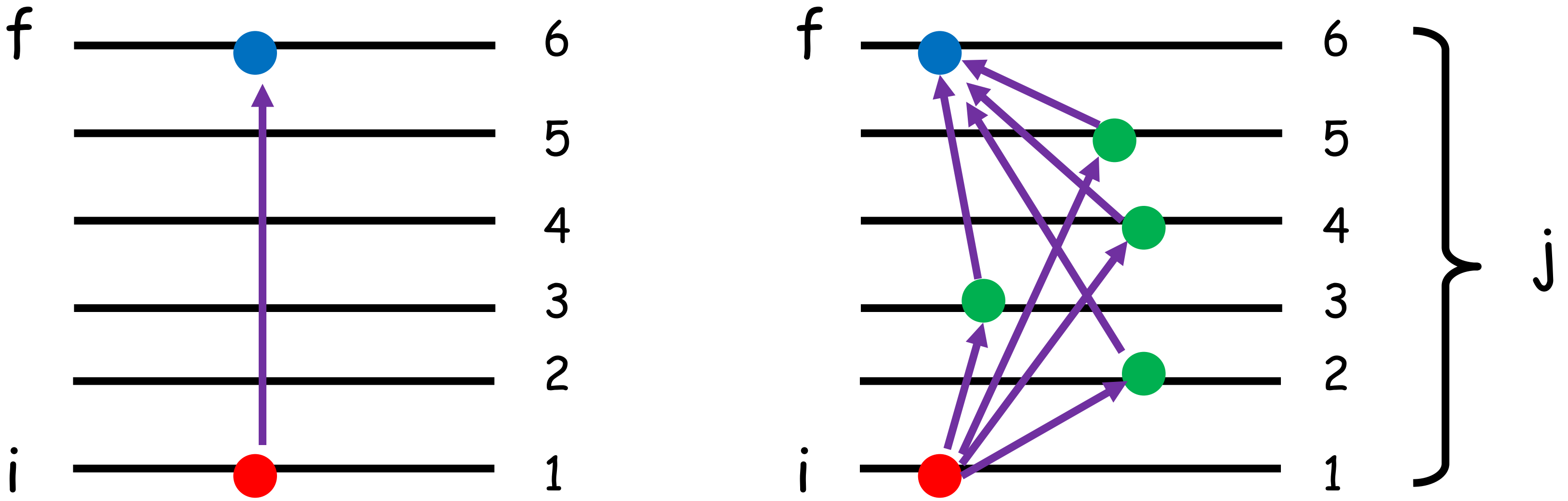
Correção de segunda ordem

$$T_{fi} = \langle f|V|i\rangle + \sum_{j\neq i} \frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j} + \cdots$$



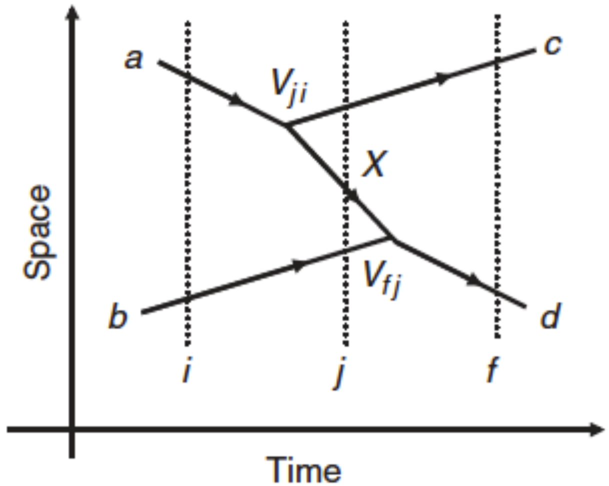
Correção de segunda ordem

Ilustração: níveis de energia



Primeira ordem

Segunda ordem



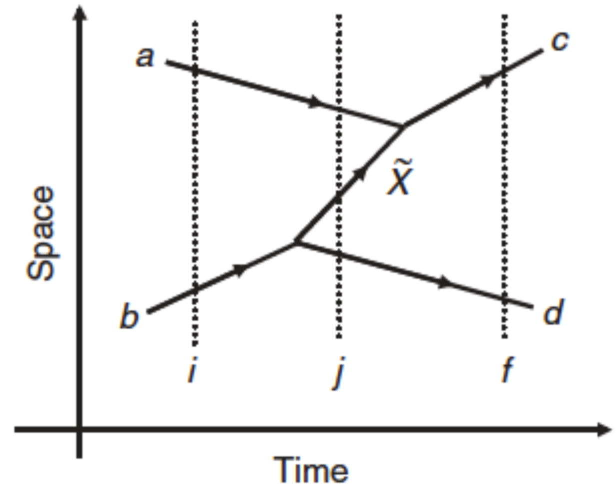


Diagrama da esquerda :

$$T_{fi}^{ab} = \frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j} = \frac{\langle d|V|X+b\rangle\langle c+X|V|a\rangle}{(E_a+E_b)-(E_c+E_X+E_b)}$$

$$V_{ji} = \langle c+X|V|a\rangle$$

$$V_{fj} = \langle d|V|X+b\rangle$$

$$V_{ji} = \mathcal{M}_{ji}\prod_k (2E_k)^{-1/2} \longrightarrow V_{ji} = \langle c+X|V|a\rangle = \frac{\mathcal{M}_{a\to c+X}}{(2E_a 2E_c 2E_X)^{1/2}}$$

$$\mathcal{M}_{a\to c+X} = g_a \longrightarrow V_{ji} = \langle c+X|V|a\rangle = \frac{g_a}{(2E_a 2E_c 2E_X)^{1/2}}$$

(hipótese)

Analogamente :

$$V_{fj} = \langle d|V|X+b\rangle = \frac{g_b}{(2E_b 2E_d 2E_X)^{1/2}}$$

$$T_{fi}^{ab} = \frac{\langle d|V|X+b\rangle\langle c+X|V|a\rangle}{(E_a+E_b)-(E_c+E_X+E_b)} = \frac{1}{2E_X}\cdot\frac{1}{(2E_a 2E_b 2E_c 2E_d)^{1/2}}\cdot\frac{g_a g_b}{(E_a-E_c-E_X)}$$

$$\mathcal{M}_{fi}^{ab} = (2E_a 2E_b 2E_c 2E_d)^{1/2} T_{fi}^{ab} \quad \longrightarrow \quad \mathcal{M}_{fi}^{ab} = \frac{1}{2E_X}\cdot\frac{g_a g_b}{(E_a-E_c-E_X)}$$

Diagrama da direita :

$$\mathcal{M}_{fi}^{ba} = \frac{1}{2E_X}\cdot\frac{g_a g_b}{(E_b-E_d-E_X)}$$

Estado inicial e final são iguais. Então somamos as amplitudes :

$$\mathcal{M}_{fi} = \mathcal{M}_{fi}^{ab} + \mathcal{M}_{fi}^{ba} = \frac{g_a g_b}{2E_X}\cdot\left(\frac{1}{E_a-E_c-E_X}+\frac{1}{E_b-E_d-E_X}\right)$$

Usando conservação da energia :

$$E_b - E_d = E_c - E_a$$

$$\mathcal{M}_{fi} = \frac{g_a g_b}{2E_X}\cdot\left(\frac{1}{E_a-E_c-E_X}-\frac{1}{E_a-E_c+E_X}\right) = \frac{g_a g_b}{(E_a-E_c)^2-E_X^2}$$

$$\mathcal{M}_{fi} = \frac{g_a g_b}{2E_X} \cdot \left(\frac{1}{E_a - E_c - E_X} - \frac{1}{E_a - E_c + E_X} \right) = \frac{g_a g_b}{(E_a - E_c)^2 - E_X^2}$$

Usamos as definição de energia de X :

$$E_X^2 = \mathbf{p}_X^2 + m_X^2 \qquad \mathbf{p}_X = (\mathbf{p}_a - \mathbf{p}_c) \longrightarrow E_X^2 = \mathbf{p}_X^2 + m_X^2 = (\mathbf{p}_a - \mathbf{p}_c)^2 + m_X^2$$

$$\mathcal{M}_{fi} = \frac{g_a g_b}{(E_a - E_c)^2 - (\mathbf{p}_a - \mathbf{p}_c)^2 - m_X^2} = \frac{g_a g_b}{(p_a - p_c)^2 - m_X^2}$$

p_a e p_c são quadrivetores ! $\longrightarrow$ $q = p_a - p_c$

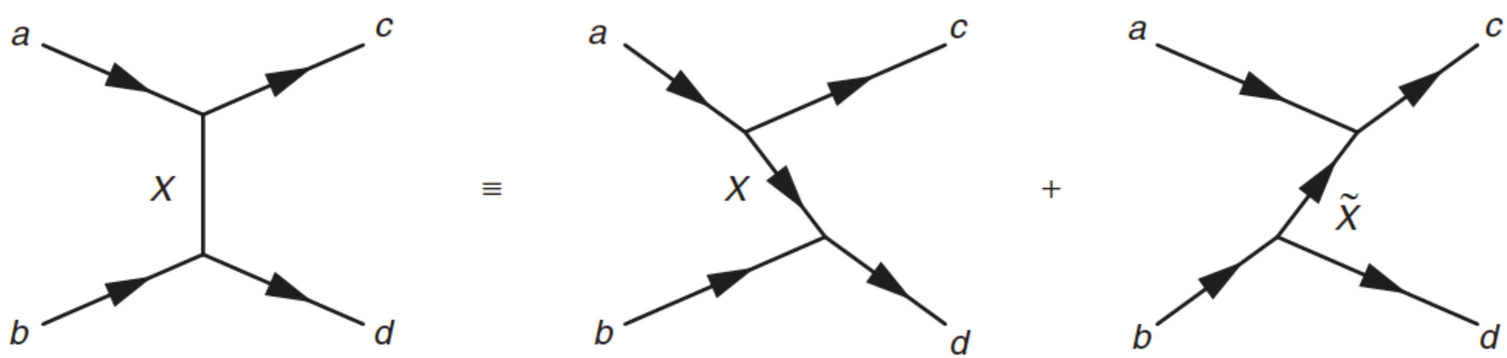
$$\mathcal{M}_{fi} = \frac{g_a g_b}{q^2 - m_X^2}$$

$$\boxed{\frac{1}{q^2 - m_X^2}}$$

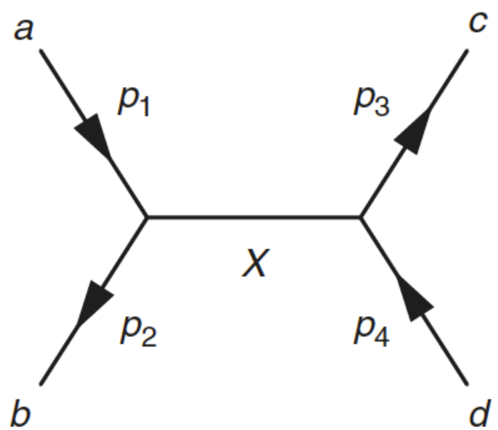
é o propagador !

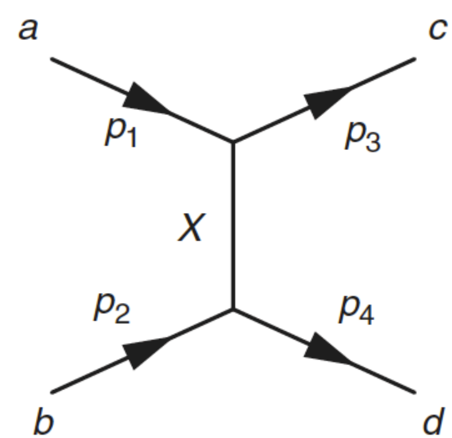
Diagrama de Feynman e partículas virtuais

Soma de todos os ordenamentos temporais = diagrama de Feynman



X é uma partícula virtual : $q = p_a - p_c = p_d - p_b$ $q^2 \neq m_X^2$





$$q = p_1 + p_2 = p_3 + p_4$$

$$q = p_1 - p_3 = p_4 - p_2$$

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