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UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN

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FACULTAD DE CIENCIAS FÍSICO MATEMÁTICAS



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**Mécaninca Cuántica Relativista**  
**Ejercicios propuestos**  
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## Ejercicio 1

Mostrar que:

$$U_{\perp} = \frac{u_i}{\gamma_v \left[ 1 + \frac{v \cdot v}{c^2} \right]}$$

De las transformaciones:

$$\begin{aligned} r_{\parallel} &= \gamma_v [r'_{\parallel} + vt'] \\ r_{\perp} &= r'_{\perp} \\ t &= \gamma_v \left[ t' + \frac{v \cdot v}{c^2} \right] \end{aligned}$$

tomando los diferenciales:

$$\begin{aligned} dr_{\parallel} &= \gamma_v [dr'_{\parallel} + vdt] \\ dr_{\perp} &= dr'_{\perp} \\ dt &= \gamma_v \left[ dt + \frac{vdr}{c^2} \right] \end{aligned}$$

entonces:

$$\begin{aligned} \frac{dr_{\perp}}{dt} &= \frac{dr'_{\perp}}{\gamma_v dt' \left[ 1 + \frac{v}{c^2} \frac{dr'}{dt'} \right]} \\ u_{\perp} &= \frac{dr'_{\perp}}{\gamma_v dt' \left[ 1 + \frac{v}{c^2} \frac{dr'}{dt'} \right]} \\ &= \frac{u'_{\perp}}{\gamma_v \left[ 1 + \frac{v \cdot u'}{c^2} \right]} \end{aligned}$$

por lo tanto:

$$u_{\perp} = \frac{u'_{\perp}}{\gamma_v \left[ 1 + \frac{v \cdot u'}{c^2} \right]} \quad (1)$$

## Ejercicio 2

Mostrar que

$$\begin{aligned} (U_d)_x &= \frac{-c\beta \sin(\theta')}{\gamma_v(1 - \beta^2 \cos(\theta'))} \\ (U_d)_z &= \frac{c\beta(1 - \cos(\theta'))}{1 - \beta^2 \cos(\theta')} \end{aligned}$$

Se sabe que por convención:

$$\begin{aligned} (U_d)_{\perp} &= (U_d)_x = \frac{(U'_d)_{\perp}}{\gamma_v \left( 1 + \frac{v \cdot u'_d}{c^2} \right)} \\ (U_d)_{\parallel} &= (U_c)_z = \frac{(U'_d)_{\parallel} + v}{1 + \frac{v \cdot u'_d}{c^2}} \end{aligned}$$

pero, del diagrama

$$\begin{aligned}(U'_d)_\perp &= U'_d \sin(\theta') \\ (U'_d)_\parallel &= U'_d \cos(\theta')\end{aligned}$$

por lo tanto:

$$\begin{aligned}(U_d)_x &= \frac{U'_d \sin(\theta')}{\gamma_v \left(1 + \frac{|v||u_d| \cos(\theta)}{c^2}\right)} \\ (U_d)_z &= \frac{U'_d \cos(\theta') + v}{\gamma_v \left(1 + \frac{|v||u_d| \cos(\theta)}{c^2}\right)}\end{aligned}$$

pero  $U'_d = -v$

$$\begin{aligned}(U_d)_x &= \frac{-v \sin(\theta')}{\gamma_v \left(1 - \frac{v^2}{c^2} \cos(\theta')\right)} \\ &= \frac{-c\beta \sin(\theta')}{\gamma_v (1 - \beta^2 \cos(\theta'))} \\ (U_d)_z &= \frac{c\beta(1 - \cos(\theta'))}{1 - \beta^2 \cos(\theta')}\end{aligned}$$

### Ejercicio 3

Mostrar que

$$u_c^2 = u_a^2 - \frac{\eta}{\gamma_a} \quad (2)$$

$$\begin{aligned}(U_c)_x &= \frac{c\beta \sin(\theta')}{\gamma_v [1 + \beta^2 \cos(\theta')]} \\ &\approx \frac{c\beta \theta}{\gamma_v [1 + \beta^2 (1 - \frac{\theta^2}{2})]} \\ (U_c)_z &\approx \frac{c\beta(1 + (1 - \frac{\theta^2}{2}))}{1 + \beta^2 (1 - \frac{\theta^2}{2})}\end{aligned}$$

realizando el calculo para ángulos pequeños, tomando en cuenta que  $\cos(\theta) = 1 - \theta^2/2$  y  $\sin(\theta) = \theta$

$$\begin{aligned}
(U_c)_z^2 &= \frac{c^2 \beta^2 \left(4 - 2\theta^2 + \frac{\theta^4}{4}\right)}{(1 + \beta^2) \left(1 - \frac{\beta^2 \theta^2}{2(1 + \beta^2)}\right)^2} \\
&= \frac{c^2 \beta^2 (4 - 2\theta^2)}{(1 + \beta^2)^2 \left(1 - \frac{\beta^2 \theta^2}{2(1 + \beta^2)}\right)^2} \\
&\approx \frac{c^2 \beta^2 (4 - 2\theta^2)}{(1 + \beta^2)^2} \left(1 + \frac{\beta^2}{1 + \beta^2} \theta^2\right) \\
&\approx \frac{4c^2 \beta^2}{(1 + \beta^2)^2} - \frac{2c^2 \beta^2 \theta^2}{(1 + \beta^2)^2} + \frac{4c^2 \beta^4 \theta^2}{(1 + \beta^2)^3} \\
&\approx u_a^2 - \frac{2c^2 \beta^2 \theta^2}{(1 + \beta^2)^2} + \frac{4c^2 \beta^4 \theta^2}{(1 + \beta^2)^3}
\end{aligned}$$

$$\begin{aligned}
(U_c)_x^2 &= \frac{c^2 \beta^2 \theta^2}{\gamma_v^2 (1 + \beta^2)^2 \left(1 - \frac{\beta^2 \theta^2}{2(1 + \beta^2)}\right)^2} \\
&\approx \frac{c^2 \beta^2 \theta^2}{\gamma_v^2 (1 + \beta^2)} \left(1 + \frac{\beta}{1 + \beta^2} \theta^2\right) \\
&\approx \frac{c^2 \beta^2 \theta^2}{\gamma^2 (1 + \beta^2)^2} + \frac{c^2 \beta^4 \theta^4}{\gamma^2 (1 + \beta^2)^3} \\
&\approx \frac{c^2 \beta^2 \theta^2}{\gamma^2 (1 + \beta^2)^2}
\end{aligned}$$

se tiene que:

$$u_a = \frac{2\beta c}{1 + \beta^2} \qquad \gamma_a = \frac{1 + \beta^2}{1 - \beta^2}$$

por lo tanto:

$$\begin{aligned}
u_c^2 &= (u_c)_x^2 + (u_c)_z^2 \\
&= u_a^2 - \frac{2c^2 \beta^2 \theta^2}{(1 + \beta^2)^2} + \frac{4c^2 \beta^4 \theta^2}{(1 + \beta^2)^3} + \frac{c^2 \beta^2 \theta^2}{\gamma^2 (1 + \beta^2)^2} \\
&= u_a^2 + \frac{c^2 \beta^2 \theta^2}{(1 + \beta^2)^2} \left(1 - \beta^2 - 2 + \frac{4\beta^2}{1 + \beta^2}\right) \\
&= u_a^2 + \frac{c^2 \beta^2 \theta^2}{(1 + \beta^2)^2} \left(\frac{1 - 2\beta^2 - \beta^4}{1 + \beta^2}\right) \\
&= u_a^2 - \frac{c^2 \beta^2 \theta^2}{(1 + \beta^2)^2} \left(\frac{(1 - \beta^2)^2}{1 + \beta^2}\right) \\
&= u_a^2 - \frac{c^2 \beta^2 \theta^2}{1 - \beta^2} \left(\frac{(1 - \beta^2)^3}{(1 + \beta^2)^3}\right) \\
&= u_a^2 - \eta \frac{1}{\gamma_a^3}
\end{aligned}$$

## Ejercicio 4

Muestre que:

$$\partial_\alpha A^\alpha = \partial^\alpha A_\alpha$$

Se tiene que:

$$x_\alpha = g_{\alpha\beta} x^\beta$$

$$x^\alpha = g^{\alpha\beta} x_\beta$$

por lo tanto:

$$g^{\alpha\beta} \partial_\alpha = \partial^\beta$$

$$g_{\alpha\beta} \partial^\alpha = \partial_\beta$$

calculando  $\partial^\alpha A_\alpha$

$$\begin{aligned}\partial^\alpha A_\alpha &= \left( \frac{\partial A_0}{\partial x_0} \right) - \left( \frac{\partial A_1}{\partial x_1} \right) - \left( \frac{\partial A_2}{\partial x_2} \right) - \left( \frac{\partial A_3}{\partial x_3} \right) \\ &= \frac{\partial A_0}{\partial x_0} - \nabla A\end{aligned}$$

por lo que se encuentra que:

$$A_0 = A^0$$

$$A_1 = -A^1$$

$$A_2 = -A^2$$

$$A_3 = -A^3$$

$$\begin{aligned}\partial^\alpha A_\alpha &= (g^{\alpha\beta} \partial_\beta)(g_{\alpha\gamma} A^\gamma) \\ \delta_\gamma^\beta &= \partial_\beta A^\gamma\end{aligned}$$

## Ejercicio 5

Por verificar que:

$$\partial^\alpha = \left( \frac{\partial}{\partial x_0}, -\nabla \right)$$

Sea  $A^\alpha$  un tensor covariante, entonces:

$$\begin{aligned}\partial^\alpha A_\alpha &= \left( \frac{\partial A_0}{\partial x_0} \right) - \left( \frac{\partial A_1}{\partial x_1} \right) - \left( \frac{\partial A_2}{\partial x_2} \right) - \left( \frac{\partial A_3}{\partial x_3} \right) \\ &= \left( \frac{\partial}{\partial x_0}, -\frac{\partial}{\partial x_1}, -\frac{\partial}{\partial x_2}, -\frac{\partial}{\partial x_3} \right) \cdot (A_0, A_1, A_2, A_3) \\ &= \left( \frac{\partial}{\partial x_0}, -\nabla \right) \cdot A_\alpha\end{aligned}$$

por lo tanto:

$$\partial^\alpha = \left( \frac{\partial}{\partial x_0}, -\nabla \right)$$

## Ejercicio 6

Probar que las matrices  $S_1^2, S_2^2, S_3^2$  son diagonales con -1 y que las matrices  $K_1^2, K_2^2, K_3^2$  son diagonales con 1: Se tiene la matriz  $S_1$  igual a:

$$S_1 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

entonces, calculando  $S_1^2$ , se tiene que:

$$\begin{aligned} S_1^2 &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}^2 \\ &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \end{aligned}$$

Se tiene la matriz  $S_2$  igual a:

$$S_2 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

entonces, calculando  $S_2^2$ , se tiene que:

$$\begin{aligned} S_2^2 &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}^2 \\ &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \end{aligned}$$

Se tiene la matriz  $S_3$  igual a:

$$S_3 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & -0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

entonces, calculando  $S_3^2$ , se tiene que:

$$\begin{aligned} S_3^2 &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}^2 \\ &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{aligned}$$

por lo tanto las matrices  $S_\mu^2$  son diagonales con -1 Se tiene la matriz  $K_1$  igual a:

$$S_1 = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

entonces, calculando  $K_1^2$ , se tiene que:

$$\begin{aligned} K_1^2 &= \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}^2 \\ &= \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{aligned}$$

Se tiene la matriz  $K_2$  igual a:

$$K_2 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

entonces, calculando  $k_2^2$ , se tiene que:

$$\begin{aligned} K_2^2 &= \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}^2 \\ &= \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{aligned}$$

Se tiene la matriz  $K_3$  igual a:

$$K_3 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

entonces, calculando  $K_3^2$ , se tiene que:

$$\begin{aligned} K_3^2 &= \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}^2 \\ &= \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{aligned}$$

por lo tanto las matrices  $K_\mu^2$  son diagonales con 1

## Ejercicio 7

Mostrar que  $F_{\alpha\gamma} = g_{\alpha\gamma} F^{\gamma\delta} g_{\delta\beta}$

Se sabe que:

$$F^{\gamma\delta} = \begin{pmatrix} 0 & -Ex & -Ey & -Ez \\ Ex & 0 & -Bz & By \\ Ey & Bz & 0 & -Bx \\ Ez & -By & Bx & 0 \end{pmatrix} \quad g_{\alpha\gamma} = g_{\delta\beta} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$



realizando la multiplicacion  $F^{\gamma\delta}g_{\delta\beta}$

$$\begin{aligned} F^{\gamma\delta}g_{\delta\beta} &= \begin{pmatrix} 0 & -Ex & -Ey & -Ez \\ Ex & 0 & -Bz & By \\ Ey & Bz & 0 & -Bx \\ Ez & -By & Bx & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \\ &= \begin{pmatrix} 0 & Ex & Ey & Ez \\ Ex & 0 & Bz & -By \\ Ey & -Bz & 0 & Bx \\ Ez & By & -Bx & 0 \end{pmatrix} \end{aligned}$$

por lo tanto:

$$F_{\beta}^{\gamma} = \begin{pmatrix} 0 & Ex & Ey & Ez \\ Ex & 0 & Bz & -By \\ Ey & -Bz & 0 & Bx \\ Ez & By & -Bx & 0 \end{pmatrix}$$

realizando la multiplicacion  $g_{\alpha\gamma}F_{\beta}^{\gamma}$  se obtiene que:

$$\begin{aligned} g_{\alpha\gamma}F_{\beta}^{\gamma} &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 0 & Ex & Ey & Ez \\ Ex & 0 & Bz & -By \\ Ey & -Bz & 0 & Bx \\ Ez & By & -Bx & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & Ex & Ey & Ez \\ -Ex & 0 & -Bz & By \\ -Ey & Bz & 0 & -Bx \\ -Ez & -By & Bx & 0 \end{pmatrix} \end{aligned}$$

por lo tanto:

$$F_{\alpha\beta} = \begin{pmatrix} 0 & Ex & Ey & Ez \\ -Ex & 0 & -Bz & By \\ -Ey & Bz & 0 & -Bx \\ -Ez & -By & Bx & 0 \end{pmatrix}$$

## Ejercicio 8

Compruebe la forma de L, que cumple  $L^T g = -gL$  donde L tiene diagonal de ceros y g es la representación matricial de  $g_{\mu\nu\rho}$  Se tiene que:

$$g = \text{diag}(1, -1, -1, -1)$$

y que

$$g^T = g = g^{-1}$$

por lo tanto:

$$\begin{aligned} c^T &= (gL)^T \\ &= L^T g \\ &= -gL \\ &= -c \end{aligned}$$

por lo tanto:

$$c_{ij} = -c_{ji}$$

si  $i = j$ , entonces  $c_{ii} = 0$ , por lo tanto:

$$gL = C = \begin{pmatrix} 0 & C_{12} & C_{13} & C_{14} \\ -C_{12} & 0 & C_{23} & C_{24} \\ -C_{13} & -C_{23} & 0 & C_{34} \\ -C_{14} & -C_{24} & -C_{34} & 0 \end{pmatrix}$$

realizando la operación  $gc = ggL$ , se tiene que:

$$\begin{aligned} gc &= g(gL) \\ &= (gg)L \\ &= L \end{aligned}$$

por lo tanto  $gc = L$

## Ejercicio 9

Formule la matriz de rotación respecto a  $\hat{z}$  por medio de la transformación de Lorentz partiendo de la invarianza de  $S^2$  se obtiene la forma (dependiente de 6 parámetros) de  $L$ , tal que  $A = e^L$  es la transformación de Lorentz.

Se tiene la base,  $S_\mu, K_\mu$ , donde  $L = -\vec{\omega} \cdot \vec{s} - \vec{\xi} \cdot \vec{k}$ , para rotar con respecto  $\hat{z}$ , se tiene que cumplir que:  $\vec{\xi} = 0, \vec{\omega} = \omega_z \hat{z}$ , entonces:

$$L = -\vec{\omega} \cdot \vec{s} = -\omega_z s_3$$

por lo tanto:

$$\begin{aligned} A &= e^L \\ &= e^{-\omega s_3} \\ &= \sum_{i=0}^{\infty} \frac{(-1)^i (\omega s_3)^i}{i!} \end{aligned}$$

donde se cumple que:

$$\begin{aligned} s_3^3 &= -s_3 \\ s_3^4 &= -s_3^2 \\ s_3^5 &= s_3 \end{aligned}$$

entonces:

$$\begin{aligned} A &= 1 - \omega s_3 + \frac{\omega^2}{2!} s_3^2 + \frac{\omega^3}{3!} s_3 - \frac{\omega^4}{4!} s_3^2 \\ &= (1 + s_3^2) - s_3^2 \left[ 1 - \frac{\omega^2}{2!} + \frac{\omega^4}{4!} - \dots \right] - s_3 \left[ \omega - \frac{\omega^3}{3!} + \frac{\omega^5}{5!} - \dots \right] \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cos(\omega) - \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \sin(\omega) \end{aligned}$$

entonces:

$$A = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\omega) & \sin(\omega) & 0 \\ 0 & -\sin(\omega) & \cos(\omega) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

## Ejercicio 10

Determina la energía threshold para las siguientes reacciones, asumiendo que el proton blanco está en reposo. Consulta en la página de Partice Data Group las masas de las partículas.

- $p + p \rightarrow p + p + \pi^0$
- $p + p \rightarrow p + p + \pi^+ + \pi^-$
- $\pi^- + p \rightarrow p + \bar{p} + n$
- $\pi^- + p \rightarrow K^0 + \Sigma^0$

## Ejercicio 11

Una partícula A en reposo, decae en 2 partículas B y C ( $A \rightarrow B + C$ ). Mostrar que la energía de la partícula que emergió es

$$E_B = \frac{m_A^2 + m_B^2 - m_C^2}{2m_A} c^2$$

De la conservación de la energía se tiene que:

$$m_a = m_b \gamma_b + m_c \gamma_c$$

y de la conservación del momento lineal:

$$0 = p_b + p_c$$

por lo tanto  $p_b = -p_c$ , entonces:

$$\begin{aligned} 0 &= p_b + p_c \\ 0 &= m_b \gamma_b v_b - m_c \gamma_c v_c \\ 0 &= m_b \sqrt{\gamma_b^2 - 1} - m_c \sqrt{\gamma_c^2 - 1} \\ m_b^2 \gamma_b^2 - m_c^2 \gamma_c^2 &= m_b^2 - m_c^2 \end{aligned}$$

nombando a  $\chi_b \equiv m_b \gamma_b$  y a  $\chi_c \equiv m_c \gamma_c$ , entonces se tiene el siguiente sistema de ecuaciones

$$\chi_b^2 - \chi_c^2 = m_b^2 - m_c^2 \quad \chi_b + \chi_c = m_a$$

resolviendo ese sistema se obtiene que  $\chi_b$  es igual a

$$\chi_b = \frac{m_a^2 + m_b^2 - m_c^2}{2m_a}$$

pero  $E_b = c^2\chi_b$ , por lo tanto:

$$E_b = \frac{m_a^2 + m_b^2 - m_c^2}{2m_a}c^2$$

## Ejercicio 12

En una dispersión de 2 cuerpos  $A + B \rightarrow C + D$ , es conveniente introducir las variables de Mandelstam

$$s = (p_A + p_B)^2/c^2$$

$$t = (p_A - p_C)^2/c^2$$

$$u = (p_A - p_D)^2/c^2$$

1. Mostrar que  $s + t + u = m_A^2 + m_B^2 + m_C^2 + m_D^2$

Realizando la suma de  $s + t + u$ , se tiene que:

$$\begin{aligned} s + t + u &= \frac{(p_A + p_B)^2 + (p_A - p_C)^2 + (p_A - p_D)^2}{c^2} \\ &= \frac{p_A^2 + 2p_A p_B + p_B^2 + p_A^2 - 2p_A p_C + p_C^2 + p_A^2 - 2p_A p_D + p_D^2}{c^2} \\ &= \frac{3p_A^2 + 2p_A(p_B - p_C - p_D) + p_B^2 + p_C^2 + p_D^2}{c^2} \\ &= \frac{3p_A^2 - 2p_A^2 + p_B^2 + p_C^2 + p_D^2}{c^2} \\ &= \frac{p_A^2 + p_B^2 + p_C^2 + p_D^2}{c^2} \\ &= m_A^2 + m_B^2 + m_C^2 + m_D^2 \end{aligned}$$

2. Mostrar que la energía de centro de masa de A es  $E_A^{CM} = (s + m_A^2 - m_B^2)c^2/2\sqrt{s}$

3. Mostrar que la energía de A en el sistema de laboratorio (B en reposo) es  $E_A^{LAB} = (s - m_A^2 - m_B^2)c^2/2m_B$

## Ejercicio 13

Mostrar que:

$$\rho'_+ = \frac{e|E_p|}{m_0 c^2} \psi_+^* \psi_+$$

$$\rho'_- = \frac{e|E_p|}{m_0 c^2} \psi_-^* \psi_-$$

considerando que:

$$\begin{aligned}\psi_+ &= A_+ \exp \left[ \frac{i}{\hbar} (\vec{p} \cdot \vec{x} - |E_p t|) \right] \\ \psi_- &= A_- \exp \left[ \frac{i}{\hbar} (\vec{p} \cdot \vec{x} + |E_p t|) \right]\end{aligned}$$

Sea

$$\rho' = \frac{i\hbar e}{2m_0 c^2} \left[ \psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* \right]$$

Usando a  $\psi_+$  se calcularan las derivadas parciales

$$\begin{aligned}\frac{\partial}{\partial t} \psi_+ &= -\frac{|E_p| i}{\hbar} \psi_+ & \frac{\partial}{\partial t} \psi_+^* &= \frac{|E_p| i}{\hbar} \psi_+^* \\ \psi_+^* \frac{\partial}{\partial t} \psi_+ &= -\frac{|E_p| i}{\hbar} \psi_+ \psi_+^* & \psi_+ \frac{\partial}{\partial t} \psi_+^* &= \frac{|E_p| i}{\hbar} \psi_+^* \psi_+\end{aligned}$$

entonces:

$$\begin{aligned}\psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* &= -\frac{2|E_p| i}{\hbar} \psi_+^* \psi_+ \\ \frac{i\hbar e}{2m_0 c^2} \left[ \psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* \right] &= \frac{e|E_p|}{m_0 c^2} \psi_+^* \psi_+\end{aligned}$$

por lo tanto:

$$\rho'_+ = \frac{e|E_p|}{m_0 c^2} \psi_+^* \psi_+$$

Usando a  $\psi_-$  se calcularan las derivadas parciales

$$\begin{aligned}\frac{\partial}{\partial t} \psi_- &= \frac{|E_p| i}{\hbar} \psi_- & \frac{\partial}{\partial t} \psi_-^* &= -\frac{|E_p| i}{\hbar} \psi_-^* \\ \psi_-^* \frac{\partial}{\partial t} \psi_- &= \frac{|E_p| i}{\hbar} \psi_- \psi_-^* & \psi_- \frac{\partial}{\partial t} \psi_-^* &= -\frac{|E_p| i}{\hbar} \psi_-^* \psi_-\end{aligned}$$

entonces:

$$\begin{aligned}\psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* &= \frac{2|E_p| i}{\hbar} \psi_-^* \psi_- \\ \frac{i\hbar e}{2m_0 c^2} \left[ \psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* \right] &= -\frac{e|E_p|}{m_0 c^2} \psi_-^* \psi_-\end{aligned}$$

por lo tanto:

$$\rho'_- = -\frac{e|E_p|}{m_0 c^2} \psi_-^* \psi_-$$

## Ejercicio 14

Usar la ecuación de Euler-Lagrange para  $\psi^*$  y obtener la ecuación de Klein Gordon para  $\psi$ .

Sea

$$\frac{\mathcal{L}}{\partial\psi_0} - \frac{\partial}{\partial x_\beta} \left[ \frac{\partial\mathcal{L}}{\partial\left(\frac{\partial\psi_\sigma}{\partial x_\mu}\right)} \right] = 0$$

y la densidad lagrangiana

$$\mathcal{L}\left(\psi, \psi^*, \frac{\partial\psi}{\partial x^\beta}, \frac{\partial\psi^*}{\partial x^\beta}\right) = \frac{\hbar^2}{2m_0} \left[ g^{\beta\nu} \frac{\partial\psi^*}{\partial x^\mu} \frac{\partial\psi}{\partial x^\nu} - \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right]$$

Para el campo  $\psi_\sigma = \psi^*$ , calculando  $\frac{\mathcal{L}}{\partial\psi^*}$

$$\frac{\partial\mathcal{L}}{\partial\psi^*} = \frac{\hbar^2}{2m_0} \left[ -\frac{m_0^2 c^2}{\hbar} \psi \right]$$

calculando  $\frac{\partial\mathcal{L}}{\partial\left(\frac{\partial\psi^*}{\partial x_\mu}\right)}$

$$\begin{aligned} \frac{\partial\mathcal{L}}{\partial\left(\frac{\partial\psi^*}{\partial x_\mu}\right)} &= \frac{\hbar^2}{2m_0} \frac{\partial}{\partial\left(\frac{\partial\psi^*}{\partial x_\mu}\right)} \left( g^{\mu\nu} \frac{\partial\psi}{\partial x^\nu} \frac{\partial\psi^*}{\partial x^\mu} \right) \\ &= \frac{\hbar^2}{2m_0} \left( g^{\mu\nu} \frac{\partial\psi}{\partial x^\nu} \delta_\beta^\mu \right) \\ &= \frac{\hbar^2}{2m_0} \left( g_{\mu\nu} \frac{\partial\psi}{\partial x_\nu} \delta_\beta^\mu \right) \\ &= \frac{\hbar^2}{2m_0} \left( g_{\beta\nu} \frac{\partial\psi}{\partial x_\nu} \right) \end{aligned}$$

calculando  $\frac{\partial}{\partial x_\beta} \left( \frac{\partial\mathcal{L}}{\partial\left(\frac{\partial\psi^*}{\partial x_\mu}\right)} \right)$ :

$$\begin{aligned} \frac{\partial}{\partial x_\beta} \left( \frac{\partial\mathcal{L}}{\partial\left(\frac{\partial\psi^*}{\partial x_\mu}\right)} \right) &= \frac{\partial}{\partial x_\beta} \left( \frac{\hbar^2}{2m_0} \left( g_{\beta\nu} \frac{\partial\psi}{\partial x_\nu} \right) \right) \\ &= \frac{\hbar^2}{2m_0} \left( \partial^\beta \left( g_{\beta\nu} \frac{\partial\psi}{\partial x_\nu} \right) \right) \\ &= \frac{\hbar^2}{2m_0} \partial^\beta (g_{\beta\nu} \partial^\mu \psi) \\ &= \frac{\hbar^2}{2m_0} \partial_\mu \partial^\mu \psi \end{aligned}$$

por lo tanto:

$$\left[ \frac{m_0^2 c^2}{\hbar^2} + \partial_\mu \partial^\mu \right] \psi = 0$$

## Ejercicio 15

Mostrar que el tensor de energía momento para la densidad lagrangiana es

$$T_{\mu}^{\nu} = \frac{\hbar^2}{2m_0} \left[ g^{\sigma\nu} \frac{\partial\psi^*}{\partial x^{\sigma}} \frac{\partial\psi}{\partial x^{\mu}} + g^{\sigma\nu} \frac{\partial\psi}{\partial x^{\sigma}} \frac{\partial\psi^*}{\partial x^{\mu}} - \left( g^{\sigma\rho} \frac{\partial\psi^*}{\partial x^{\sigma}} \frac{\partial\psi}{\partial x^{\rho}} - \frac{m_0^2 c^2}{\hbar} \psi^* \psi \right) g_{\mu}^{\nu} \right]$$

Sea el tensor energía momento definido por:

$$T_{\mu}^{\nu} = \sum_{\sigma} \frac{\partial\psi_{\sigma}}{\partial x^{\mu}} \frac{\partial\mathcal{L}}{\partial[\partial\psi_{\sigma}/\partial x^{\nu}]} - \mathcal{L}g_{\mu}^{\nu}$$

Utilizando la siguiente densidad lagrangiana

$$\mathcal{L} \left( \psi, \psi^*, \frac{\partial\psi}{\partial x^{\beta}}, \frac{\partial\psi^*}{\partial x^{\alpha}} \right) = \frac{\hbar^2}{2m_0} \left[ g^{\beta\nu} \frac{\partial\psi^*}{\partial x^{\alpha}} \frac{\partial\psi}{\partial x^{\beta}} - \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right]$$

Calculando  $\partial\mathcal{L}/\partial(\partial\psi/\partial x^{\mu})$

$$\begin{aligned} \frac{\partial\mathcal{L}}{\partial(\partial\psi/\partial x^{\mu})} &= \frac{\hbar^2}{2m_0} \left( g^{\sigma\beta} \frac{\partial\psi^*}{\partial x^{\sigma}} \delta_{\nu}^{\beta} \right) \\ &= \frac{\hbar^2}{2m_0} \left( g^{\sigma\nu} \frac{\partial\psi^*}{\partial x^{\sigma}} \right) \end{aligned}$$

Calculando  $\partial\mathcal{L}/\partial(\partial\psi^*/\partial x^{\mu})$

$$\begin{aligned} \frac{\partial\mathcal{L}}{\partial(\partial\psi^*/\partial x^{\mu})} &= \frac{\hbar^2}{2m_0} \left( g^{\sigma\beta} \frac{\partial\psi}{\partial x^{\sigma}} \delta_{\nu}^{\beta} \right) \\ &= \frac{\hbar^2}{2m_0} \left( g^{\sigma\nu} \frac{\partial\psi}{\partial x^{\sigma}} \right) \end{aligned}$$

$$T_{\mu}^{\nu} = \frac{\hbar^2}{2m_0} \left[ g^{\sigma\nu} \frac{\partial\psi^*}{\partial x^{\sigma}} \frac{\partial\psi}{\partial x^{\mu}} + g^{\sigma\nu} \frac{\partial\psi}{\partial x^{\sigma}} \frac{\partial\psi^*}{\partial x^{\mu}} - \left( g^{\sigma\rho} \frac{\partial\psi^*}{\partial x^{\sigma}} \frac{\partial\psi}{\partial x^{\rho}} - \frac{m_0^2 c^2}{\hbar} \psi^* \psi \right) g_{\mu}^{\nu} \right]$$

## Ejercicio 16

Mostrar que:

$$T_0^0 = \frac{\hbar^2}{2m_0} \left[ \frac{1}{c^2} \frac{\partial\psi^*}{\partial t} \frac{\partial\psi}{\partial t} + (\nabla\psi^*) \cdot (\nabla\psi) + \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right]$$

Sea el tensor energía momento:

$$T_{\mu}^{\nu} = \frac{\hbar^2}{2m_0} \left[ g^{\sigma\nu} \frac{\partial\psi^*}{\partial x^{\sigma}} \frac{\partial\psi}{\partial x^{\mu}} + g^{\sigma\nu} \frac{\partial\psi}{\partial x^{\sigma}} \frac{\partial\psi^*}{\partial x^{\mu}} - \left( g^{\sigma\rho} \frac{\partial\psi^*}{\partial x^{\sigma}} \frac{\partial\psi}{\partial x^{\rho}} - \frac{m_0^2 c^2}{\hbar} \psi^* \psi \right) g_{\mu}^{\nu} \right]$$

Tomando el caso de  $\mu = 0, \nu = 0$  y el tensor metrico  $g_{\mu\nu}$  tal que

$$g^{\mu\nu} = \begin{bmatrix} \frac{1}{c^2} & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

entonces:

$$\begin{aligned} T_0^0 &= \frac{\hbar^2}{2m_0} \left[ \frac{1}{c^2} \frac{\partial \psi^*}{\partial t} \frac{\partial \psi}{\partial t} + \frac{1}{c^2} \frac{\partial \psi^*}{\partial t} \frac{\partial \psi}{\partial t} - \frac{1}{c^2} \frac{\partial \psi^*}{\partial t} \frac{\partial \psi}{\partial t} + \frac{\partial \psi^*}{\partial x^1} \frac{\partial \psi}{\partial x^1} + \frac{\partial \psi^*}{\partial x^2} \frac{\partial \psi}{\partial x^2} + \frac{\partial \psi^*}{\partial x^3} \frac{\partial \psi}{\partial x^3} + \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right] \\ &= \frac{\hbar^2}{2m_0} \left[ \frac{1}{c^2} \frac{\partial \psi^*}{\partial t} \frac{\partial \psi}{\partial t}, \left( \frac{\partial \psi^*}{\partial x^1}, \frac{\partial \psi^*}{\partial x^2}, \frac{\partial \psi^*}{\partial x^3} \right) \cdot \left( \frac{\partial \psi}{\partial x^1}, \frac{\partial \psi}{\partial x^2}, \frac{\partial \psi}{\partial x^3} \right), \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right] \\ &= \frac{\hbar^2}{2m_0} \left[ \frac{1}{c^2} \frac{\partial \psi^*}{\partial t} \frac{\partial \psi}{\partial t} + (\nabla \psi^*) \cdot (\nabla \psi) + \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right] \end{aligned}$$

por lo tanto:

$$T_0^0 = \frac{\hbar^2}{2m_0} \left[ \frac{1}{c^2} \frac{\partial \psi^*}{\partial t} \frac{\partial \psi}{\partial t} + (\nabla \psi^*) \cdot (\nabla \psi) + \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right]$$

## Ejercicio 17

Mostras que

- $H(+) = E_{pn}$
- $H(-) = E_{pn}$

Se tiene que:

$$\psi_n(\pm) = \sqrt{\frac{m_0 c^2}{L^3 E_{pn}}} \exp \left[ \frac{i}{\hbar} (\vec{p} \cdot \vec{x} \mp E_{pn} t) \right]$$

y la operación H es definida como:

$$H = \int_{L^B} T_0^0(n, \pm) dx^3$$

donde

$$T_0^0 = \frac{\hbar^2}{2m_0} \left[ \frac{1}{c^2} \frac{\partial \psi^*}{\partial t} \frac{\partial \psi}{\partial t} + (\nabla \psi^*) \cdot (\nabla \psi) + \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right]$$

Para  $H(+)$ , calculando  $\frac{\partial \psi^*}{\partial t}$  y  $\frac{\partial \psi}{\partial t}$ :

$$\begin{aligned} \frac{\partial \psi^*}{\partial t} &= \frac{i}{\hbar} E_{pn} \psi^* & \frac{\partial \psi}{\partial t} &= \frac{-i}{\hbar} E_{pn} \psi \\ \frac{1}{c^2} \frac{\partial \psi^*}{\partial t} \frac{\partial \psi}{\partial t} &= \frac{E_{pn}^2}{\hbar^2 c^2} \psi^* \psi \\ &= \frac{E_{pn} m_0}{\hbar^2 L^3} \end{aligned}$$



Calculando  $\nabla\psi^*$  y  $\nabla\psi$

$$\begin{aligned}
\nabla\psi^* &= \frac{-i\vec{P}}{\hbar}\psi^* & \nabla\psi &= \frac{i\vec{P}}{\hbar}\psi \\
(\nabla\psi^*) \cdot (\nabla\psi) &= \frac{\vec{P} \cdot \vec{P}}{\hbar^2}\psi^*\psi \\
&= \frac{P^2}{\hbar^2} \left( \frac{m_0 c^2}{L^3 E_{\rho n}} \right) \\
&= \frac{1}{c^2 \hbar^2} \left( \frac{m_0 c^2}{L^3 E_{\rho n}} \right) (E_{\rho n}^2 - m_0^2 c^4) \\
&= \left( \frac{m_0}{L^3 E_{\rho n} \hbar^2} \right) (E_{\rho n}^2 - m^2 c^4)
\end{aligned}$$

por lo tanto

$$\begin{aligned}
T_0^0 &= \frac{\hbar^2}{2m_0} \left[ \frac{1}{c^2} \frac{\partial\psi^*}{\partial t} \frac{\partial\psi}{\partial t} + (\nabla\psi^*) \cdot (\nabla\psi) + \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right] \\
&= \frac{\hbar^2}{2m_0} \left[ \frac{E_{\rho n} m_0}{\hbar^2 L^3} + \left( \frac{m_0}{L^3 E_{\rho n} \hbar^2} \right) (E_{\rho n}^2 - m_0^2 c^4) + \left( \frac{m_0}{L^3 E_{\rho n} \hbar^2} \right) (m_0^2 c^4) \right] \\
&= \frac{E_{\rho n}}{L^3}
\end{aligned}$$

entonces

$$\begin{aligned}
\int_{L^B} T_0^0(n, +) dx^3 &= \int_{L^B} \frac{E_{\rho n}}{L^3} dV \\
&= \frac{E_{\rho n}}{L^3} \int_{L^B} dV \\
&= E_{\rho n}
\end{aligned}$$

por lo tanto

$$H(+) = E_{\rho n}$$

Para  $H(-)$ , calculando  $\frac{\partial\psi^*}{\partial t}$  y  $\frac{\partial\psi}{\partial t}$ :

$$\begin{aligned}
\frac{\partial\psi^*}{\partial t} &= \frac{-i}{\hbar} E_{\rho n} \psi^* & \frac{\partial\psi}{\partial t} &= \frac{i}{\hbar} E_{\rho n} \psi \\
\frac{1}{c^2} \frac{\partial\psi^*}{\partial t} \frac{\partial\psi}{\partial t} &= \frac{E_{\rho n}^2}{\hbar^2 c^2} \psi^* \psi \\
&= \frac{E_{\rho n} m_0}{\hbar^2 L^3}
\end{aligned}$$

Calculando  $\nabla\psi^*$  y  $\nabla\psi$

$$\begin{aligned}\nabla\psi^* &= \frac{-i\vec{P}}{\hbar}\psi^* & \nabla\psi &= \frac{i\vec{P}}{\hbar}\psi \\ (\nabla\psi^*) \cdot (\nabla\psi) &= \frac{\vec{p} \cdot \vec{p}}{\hbar^2} \psi^* \psi \\ &= \frac{P^2}{\hbar^2} \left( \frac{m_0 c^2}{L^3 E_{\rho n}} \right) \\ &= \frac{1}{c^2 \hbar^2} \left( \frac{m_0 c^2}{L^3 E_{\rho n}} \right) (E_{\rho n}^2 - m_0^2 c^4) \\ &= \left( \frac{m_0}{L^3 E_{\rho n} \hbar^2} \right) (E_{\rho n}^2 - m^2 c^4)\end{aligned}$$

por lo tanto

$$\begin{aligned}T_0^0 &= \frac{\hbar^2}{2m_0} \left[ \frac{1}{c^2} \frac{\partial\psi^*}{\partial t} \frac{\partial\psi}{\partial t} + (\nabla\psi^*) \cdot (\nabla\psi) + \frac{m_0^2 c^2}{\hbar^2} \psi^* \psi \right] \\ &= \frac{\hbar^2}{2m_0} \left[ \frac{E_{\rho n} m_0}{\hbar^2 L^3} + \left( \frac{m_0}{L^3 E_{\rho n} \hbar^2} \right) (E_{\rho n}^2 - m_0^2 c^4) + \left( \frac{m_0}{L^3 E_{\rho n} \hbar^2} \right) (m_0^2 c^4) \right] \\ &= \frac{E_{\rho n}}{L^3}\end{aligned}$$

entonces

$$\begin{aligned}\int_{L^B} T_0^0(n, -) dx^3 &= \int_{L^B} \frac{E_{\rho n}}{L^3} dV \\ &= \frac{E_{\rho n}}{L^3} \int_{L^B} dV \\ &= E_{\rho n}\end{aligned}$$

por lo tanto

$$H(-) = E_{\rho n}$$

## Ejercicio 18

Obtener la constante de la función de onda para  $E = -E_p$ .

Se tiene que:

$$\psi^{(-)}(\rho) = A_{(-)} \begin{pmatrix} \varphi_0^{(-)} \\ \chi_0^{(-)} \end{pmatrix} \exp[i(\vec{p} \cdot \vec{x} + Et)] \equiv \begin{bmatrix} \varphi^{(-)}(\rho) \\ \chi^{(-)}(\rho) \end{bmatrix}$$

con

$$\begin{bmatrix} \rho_0^{(-)} \\ \chi_0^{(-)} \end{bmatrix} = \begin{bmatrix} m_0 c^2 - E_\rho \\ m_0 c^2 + E_\rho \end{bmatrix}$$

como se sabe que esta función se encuentra normalizada, entonces se tiene que cumplir que:

$$\int \psi^{(-)*} \hat{\tau}_3 \psi^{(-)} dx^3 = -1$$

realizando la integral se tiene que:

$$\begin{aligned} \int \psi^{(-)*} \hat{\tau}_3 \psi^{(-)} dx^3 &= \int (\varphi \varphi^* - \chi \chi^*) dV \\ &= \int (A_{(-)} \varphi_0 e^{i\xi} A_{(-)}^* \varphi_0^* e^{-i\xi} - A_{(-)} \chi_0 e^{i\xi} A_{(-)}^* \chi_0^* e^{-i\xi}) dV \\ &= \int (|A_{(-)}|^2 \varphi_0 \varphi_0^* - |A_{(-)}|^2 \xi_0 \xi_0^*) dV \\ &= |A_{(-)}|^2 \int (\varphi_0 \varphi_0^* - \xi_0 \xi_0^*) \\ &= |A_{(-)}|^2 \int ((m_0 c^2 - E_\rho)^2 - (m_0 c^2 + E_\rho)^2) dV \\ &= |A_{(-)}|^2 (-4m_0 c^2 E_\rho) \int dV \\ &= |A_{(-)}|^2 (-4m_0 c^2 E_\rho) L^3 \end{aligned}$$

entonces:

$$|A_{(-)}|^2 (-4m_0 c^2 E_\rho) L^3 = -1$$

por lo tanto

$$A_{(-)} = \frac{1}{\sqrt{4m_0 c^2}} \frac{1}{\sqrt{L^3 E_\rho}}$$

## Ejercicio 19

Mostrar que:

$$\vec{J} = -\frac{i\hbar e}{2m_0} [\psi^* \nabla \psi - \psi \nabla \psi^*] - \frac{e^2}{m_0 c} \vec{A} \psi \psi^*$$

## Ejercicio 20

Sea

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad (3)$$

- Determinar las ecuaciones que satisface el campo  $A_\nu$

Se tiene que la ecuación de Euler-Lagrange para campos es la siguiente:

$$\partial_\nu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\nu A_\mu)} \right) = \frac{\partial \mathcal{L}}{\partial A_\mu} \quad (4)$$

Como la ecuación 3 no depende del campo  $A_\mu$ , entonces:

$$\frac{\partial \mathcal{L}}{\partial A_\mu} = 0$$

por lo tanto, la ecuación 4 se escribe de la siguiente manera:

$$\partial_\nu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\nu A_\mu)} \right) = 0 \quad (5)$$

Calculando  $\frac{\partial \mathcal{L}}{\partial (\partial_\nu A_\mu)}$  se tiene que :

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial (\partial_\nu A_\mu)} &= \frac{\partial}{\partial (\partial_\nu A_\mu)} \left( \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \right) \\ &= \frac{\partial}{\partial (\partial_\nu A_\mu)} ((\partial_\mu A_\nu - \partial_\nu A_\mu) F^{\mu\nu}) \\ &= F^{\mu\nu} \end{aligned}$$

entonces

$$\partial_\nu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\nu A_\mu)} \right) = \partial_\nu F^{\mu\nu}$$

por lo tanto el campo  $A_\nu$  debe cumplir la siguiente ecuación:

$$\partial_\nu F^{\mu\nu} = 0$$

- Determinar el tensor  $T^\mu{}_\nu T^{\mu\nu}$   
Se tiene que

$$T^\mu{}_\nu = \frac{\partial \mathcal{L}}{\partial (\partial_\mu A_\nu)} - g^\mu{}_\nu \mathcal{L} \quad T^{\mu\nu} = \frac{\partial \mathcal{L}}{\partial (\partial_\mu A_\nu)} - g^{\mu\nu} \mathcal{L}$$

Calculando  $T^\mu{}_\nu (T^{\mu\nu})$

$$\begin{aligned} T^\mu{}_\nu (T^{\mu\nu}) &= \left( \frac{\partial \mathcal{L}}{\partial (\partial_\mu A_\nu)} - g^\mu{}_\nu \mathcal{L} \right) \left( \frac{\partial \mathcal{L}}{\partial (\partial_\mu A_\nu)} - g^{\mu\nu} \mathcal{L} \right) \\ &= (F^\mu{}_\nu \partial_\nu A_\mu) (F^{\mu\nu} \partial_\nu A_\mu) - (F^\mu{}_\nu \partial_\nu A_\mu) (g^{\mu\nu} \mathcal{L}) \\ &\quad - (g^\mu{}_\nu \mathcal{L}) (F^{\mu\nu} \partial_\nu A_\mu) + (g^\mu{}_\nu \mathcal{L}) (g^{\mu\nu} \mathcal{L}) \\ &= (F^\mu{}_\nu \partial_\nu A_\mu) (F^{\mu\nu} \partial_\nu A_\mu) \end{aligned}$$

por lo tanto

$$T^\mu{}_\nu (T^{\mu\nu}) = (F^\mu{}_\nu \partial_\nu A_\mu) (F^{\mu\nu} \partial_\nu A_\mu)$$

## Ejercicio 21

- Usando la ecuación de Euler-Lagrange para campos, determinar que  $\psi$  satisface

$$\left( p^\mu - \frac{e}{c} A^\mu \right) \left( p_\mu - \frac{e}{c} A_\mu \right) \psi = m_0^2 c^2 \psi$$

- Mostrar que la ecuación para  $A_\mu$

$$\partial^\mu F_{\mu\nu} = J_\nu = \frac{ie\hbar}{2m_0} \left[ \psi^* \left[ \partial_\nu + \frac{ie}{\hbar c} A_\nu \right] \psi - \psi \left[ \partial_\nu - \frac{ie}{\hbar c} A_\nu \right] \psi^* \right]$$

## Ejercicio 22

Mostrar que:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

es invariante ante la transformacion

$$A'_\mu = A_\mu + \partial_\mu \xi(x)$$

Se tiene que:

$$F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$$

entonces:

$$\begin{aligned} F'_{\mu\nu} &= \partial_\mu A'_\nu - \partial_\nu A'_\mu \\ &= \partial_\mu [A_\nu + \partial_\nu \xi(x)] - \partial_\nu [A_\mu + \partial_\mu \xi(x)] \\ &= \partial_\mu A_\nu + \partial_\mu \partial_\nu \xi(x) - \partial_\nu A_\mu - \partial_\nu \partial_\mu \xi(x) \\ &= \partial_\mu A_\nu + \partial_\mu \partial_\nu \xi(x) - \partial_\nu A_\mu - \partial_\mu \partial_\nu \xi(x) \\ &= \partial_\mu A_\nu - \partial_\nu A_\mu \\ &= F_{\mu\nu} \end{aligned}$$

$$\begin{aligned} F'^{\mu\nu} &= \partial^\mu A'^\nu - \partial^\nu A'^\mu \\ &= \partial^\mu [A^\nu + \partial^\nu \xi(x)] - \partial^\nu [A^\mu + \partial^\mu \xi(x)] \\ &= \partial^\mu A^\nu + \partial^\mu \partial^\nu \xi(x) - \partial^\nu A^\mu - \partial^\nu \partial^\mu \xi(x) \\ &= \partial^\mu A^\nu + \partial^\mu \partial^\nu \xi(x) - \partial^\nu A^\mu - \partial^\mu \partial^\nu \xi(x) \\ &= \partial^\mu A^\nu - \partial^\nu A^\mu \\ &= F^{\mu\nu} \end{aligned}$$

por lo tanto:

$$\begin{aligned} -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ \mathcal{L}' &= \mathcal{L} \end{aligned}$$

por lo tanto  $\mathcal{L}$  es invariante ante la transformacion.

## Ejercicio 23

Mostrar que

$$\left[ i\hbar \frac{\partial}{\partial t} - eA_0 \right]^2 \psi \approx \left[ -ie\hbar \frac{\partial}{\partial t} A_0 \varphi + 2i\hbar m_0 c^2 \frac{\partial}{\partial t} \varphi - 2eA_0 m_0 c^2 \varphi + m_0^2 c^4 \varphi \right] e^{\frac{-im_0 c^2 t}{\hbar}}$$

se han omitido

$$(i\hbar A_0 \frac{\partial}{\partial t} \varphi) \ll A_0 m_0 c^2 |\varphi| \quad |A_0 \varphi_e| \ll m_0 c^2 |\varphi|$$

tomando en cuenta que:

$$\psi = \varphi e^{\frac{-i}{\hbar} m_0 c^2 t}$$

Calculando  $\left[ i\hbar \frac{\partial}{\partial t} - eA_0 \right]^2$

$$\left[ i\hbar \frac{\partial}{\partial t} - eA_0 \right]^2 \psi = \left[ -\hbar^2 \frac{\partial^2}{\partial t^2} - 2i\hbar e A_0 \frac{\partial}{\partial t} + e^2 A_0 \right] \psi$$

calculando  $\frac{\partial \psi}{\partial t}$

$$\frac{\partial \psi}{\partial t} = \left[ \frac{-i}{\hbar} m_0 c^2 \varphi + \frac{\partial \varphi}{\partial t} \right] e^{\frac{-i}{\hbar} m_0 c^2 t}$$

calculando  $\frac{\partial^2 \psi}{\partial t^2}$

$$\frac{\partial^2 \psi}{\partial t^2} = \left[ \frac{\partial^2 \varphi}{\partial t^2} - \frac{2i}{\hbar} m_0 c^2 \frac{\partial \varphi}{\partial t} - \frac{1}{\hbar^2} m_0^2 c^4 \varphi \right] e^{\frac{-i}{\hbar} m_0 c^2 t}$$

por lo tanto:

$$\begin{aligned} \left[ i\hbar \frac{\partial}{\partial t} - eA_0 \right]^2 \psi &= \left[ -\hbar^2 \frac{\partial^2}{\partial t^2} - 2i\hbar e A_0 \frac{\partial}{\partial t} + e^2 A_0 \right] \psi \\ &= \left[ -\hbar^2 \frac{\partial^2 \varphi}{\partial t^2} + 2i\hbar m_0 c^2 \frac{\partial \varphi}{\partial t} + m_0^2 c^4 \varphi - 2m_0 c^2 e A_0 \varphi - 2i\hbar e A_0 \frac{\partial \varphi}{\partial t} \right] e^{\frac{-i}{\hbar} m_0 c^2 t} \\ &\approx \left[ 2i\hbar m_0 c^2 \frac{\partial \varphi}{\partial t} + m_0^2 c^4 \varphi - 2m_0 c^2 e A_0 \varphi - 2i\hbar e A_0 \frac{\partial \varphi}{\partial t} \right] e^{\frac{-i}{\hbar} m_0 c^2 t} \end{aligned}$$

## Ejercicio 24

Mostrar que al desarrollar

$$\left[ i\hbar \vec{\nabla} + \frac{e}{c} \vec{A} \right]^2 \varphi$$

de la ecuación:

$$i\hbar \frac{\partial}{\partial t} \varphi = \left[ \frac{1}{2m_0} \left[ i\hbar \vec{\nabla} + \frac{e}{c} \vec{A} \right]^2 + \frac{i\hbar e}{2m_0 c^2} \frac{\partial}{\partial t} A_0 + eA_0 \right] \varphi$$

se escribe como:

$$i\hbar \frac{\partial}{\partial t} \varphi = \left[ \frac{\vec{P}^2}{2m} - \frac{e}{m_0 c} \vec{A} \cdot \vec{P} + eA_0 + \frac{i\hbar e}{2m_0} \left[ \vec{\nabla} \cdot \vec{A} \right] + \frac{i\hbar e}{2m_0 c^2} \frac{\partial}{\partial t} A_0 \right] \varphi$$

Desarrollando el termino  $\left[ i\hbar \vec{\nabla} + \frac{e}{c} \vec{A} \right]^2 \varphi$ , se tiene que:

$$\begin{aligned} \frac{1}{2m_0} \left[ i\hbar \vec{\nabla} + \frac{e}{c} \vec{A} \right]^2 \varphi &= \frac{1}{2m_0} \left[ -\hbar^2 \vec{\nabla}^2 + \frac{i\hbar e}{c} \vec{\nabla} \cdot \vec{A} + \frac{e i \hbar}{c} \vec{A} \cdot \vec{\nabla} + \frac{e^2}{c^2} (\vec{A} \cdot \vec{A}) \right] \\ &= \frac{\vec{P}^2}{2m_0} + \frac{i\hbar e}{2m_0 c} \vec{\nabla} \cdot \vec{A} + \frac{e^2}{2m_0 c^2} \vec{A} \cdot \vec{A} + \frac{e i \hbar}{2m_0 c} \vec{A} \cdot \vec{\nabla} \\ &= \frac{\vec{P}^2}{2m_0} + \frac{i\hbar e}{2m_0 c} \vec{\nabla} \cdot \vec{A} + \frac{e^2}{2m_0 c^2} \vec{A} \cdot \vec{A} - \frac{e}{2m_0 c} \vec{A} \cdot \vec{P} \end{aligned}$$

entonces:

$$\begin{aligned}
\frac{1}{2m_0} \left[ i\hbar \vec{\nabla} + \frac{e}{c} \vec{A} \right]^2 + \frac{i\hbar e}{2m_0 c^2} \frac{\partial}{\partial t} A_0 + eA_0 &= \frac{\vec{P}}{2m_0} + \frac{i\hbar e}{2m_0 c} \vec{\nabla} \cdot \vec{A} + \frac{e^2}{2m_0 c^2} \vec{A} \cdot \vec{A} - \frac{e}{2m_0 c} \vec{A} \cdot \vec{P} + \frac{i\hbar e}{2m_0 c^2} \frac{\partial}{\partial t} A_0 \\
&= \frac{\vec{P}}{2m_0} - \frac{e}{2m_0 c} \vec{A} \cdot \vec{P} + \frac{i\hbar e}{2m_0 c} \left( \frac{\partial}{\partial t} A_0 + \vec{\nabla} \cdot \vec{A} \right) + eA_0 \\
&= \frac{\vec{P}}{2m_0} - \frac{e}{2m_0 c} \vec{A} \cdot \vec{P} + eA_0
\end{aligned}$$

por lo tanto:

$$i\hbar \frac{\partial}{\partial t} \varphi = \left[ \frac{\vec{P}}{2m_0} - \frac{e}{2m_0 c} \vec{A} \cdot \vec{P} + eA_0 \right] \varphi$$

## Ejercicio 25

Mostrar que se cumple:

$$\alpha_i \alpha_j + \alpha_j \alpha_i = 2\delta_{ij} \mathbb{I}$$

Calculando  $\alpha_i \alpha_j$

$$\alpha_i \alpha_j = \begin{bmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{bmatrix} \begin{bmatrix} 0 & \sigma_j \\ \sigma_j & 0 \end{bmatrix} = \begin{bmatrix} \sigma_i \sigma_j & 0 \\ 0 & \sigma_i \sigma_j \end{bmatrix}$$

Calculando  $\alpha_j \alpha_i$

$$\alpha_j \alpha_i = \begin{bmatrix} 0 & \sigma_j \\ \sigma_j & 0 \end{bmatrix} \begin{bmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{bmatrix} = \begin{bmatrix} \sigma_j \sigma_i & 0 \\ 0 & \sigma_j \sigma_i \end{bmatrix}$$

entonces

$$\alpha_i \alpha_j + \alpha_j \alpha_i = \begin{bmatrix} \sigma_i \sigma_j + \sigma_j \sigma_i & 0 \\ 0 & \sigma_i \sigma_j + \sigma_j \sigma_i \end{bmatrix}$$

donde

$$\sigma_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad \sigma_2 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad \sigma_3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Calculando todas las permutaciones se tiene que:

$$\begin{aligned}
\sigma_1\sigma_2 &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} = \begin{bmatrix} i & 0 \\ 0 & -i \end{bmatrix} \\
\sigma_2\sigma_1 &= \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} -i & 0 \\ 0 & i \end{bmatrix} \\
\sigma_1\sigma_3 &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \\
\sigma_3\sigma_1 &= \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \\
\sigma_2\sigma_3 &= \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} = \begin{bmatrix} 0 & i \\ i & 0 \end{bmatrix} \\
\sigma_3\sigma_2 &= \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} = \begin{bmatrix} 0 & -i \\ -i & 0 \end{bmatrix} \\
\sigma_1\sigma_1 &= \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\
\sigma_2\sigma_2 &= \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\
\sigma_3\sigma_3 &= \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\end{aligned}$$

con lo cual se puede observar que :

$$\{\sigma_i, \sigma_j\} = 2\delta_{ij}\mathbb{I}$$

para  $i \neq j$ , y

$$\sigma_i\sigma_j = \mathbb{I}$$

para  $i = j$ , por lo tanto:

$$\alpha_i\alpha_j + \alpha_j\alpha_i = \begin{bmatrix} \sigma_i\sigma_j + \sigma_j\sigma_i & 0 \\ 0 & \sigma_i\sigma_j + \sigma_j\sigma_i \end{bmatrix} = \begin{bmatrix} 2\delta_{ij}\mathbb{I} & 0 \\ 0 & 2\delta_{ij}\mathbb{I} \end{bmatrix} = 2\delta_{ij}\mathbb{I}$$

## Ejercicio 26

Determinar los eigenvalores de  $\sigma_i$

Para  $\sigma_1$ , se tiene que:

$$\sigma_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

entonces,

$$|\sigma_1 - \lambda\mathbb{I}| = \begin{vmatrix} -\lambda & 1 \\ 1 & -\lambda \end{vmatrix} = \lambda^2 - 1 = \begin{cases} \lambda_1 = 1 \\ \lambda_2 = -1 \end{cases}$$

Para  $\sigma_2$ , se tiene que:

$$\sigma_2 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$



entonces,

$$|\sigma_2 - \lambda \mathbb{I}| = \begin{vmatrix} -\lambda & i \\ -i & -\lambda \end{vmatrix} = \lambda^2 - 1 = \begin{cases} \lambda_1 = 1 \\ \lambda_2 = -1 \end{cases}$$

Para  $\sigma_3$ , se tiene que:

$$\sigma_3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

entonces,

$$|\sigma_3 - \lambda \mathbb{I}| = \begin{vmatrix} 1 - \lambda & 0 \\ 0 & -1 - \lambda \end{vmatrix} = \lambda^2 - 1 = \begin{cases} \lambda_1 = 1 \\ \lambda_2 = -1 \end{cases}$$

## Ejercicio 27

A partir de la ecuación

$$i\hbar \frac{\partial \psi}{\partial t} = \left[ \frac{\hbar c}{i} \sum \alpha_i \frac{\partial}{\partial x_i} + \beta m_0 c^2 \right] \psi$$

mostrar que

$$\frac{\partial \rho}{\partial t} + \sum \frac{\partial}{\partial x_i} [c\psi^* \alpha_i \psi] = 0$$

Multiplicando a la ecuación de Schrödinger que propuso Dirac por  $\psi^*$  por la izquierda, se tiene que:

$$i\hbar \psi^* \frac{\partial \psi}{\partial t} = \psi^* \left[ \frac{\hbar c}{i} \sum \alpha_i \frac{\partial}{\partial x_i} + \beta m_0 c^2 \right] \psi$$

Multiplicando  $\psi$  por la izquierda a la ecuación de Schrödinger para  $\psi^*$ , se tiene que:

$$i\hbar \psi \frac{\partial \psi^*}{\partial t} = \psi \left[ \frac{\hbar c}{i} \sum \alpha_i \frac{\partial}{\partial x_i} + \beta m_0 c^2 \right] \psi^*$$

restando estas dos ecuaciones se tiene que:

$$i\hbar \left[ \psi^* \frac{\partial \psi}{\partial t} - \psi \frac{\partial \psi^*}{\partial t} \right] = \frac{\hbar c}{i} \left[ \sum \alpha_i \psi^* \frac{\partial \psi}{\partial x_i} - \alpha_i \psi \frac{\partial \psi^*}{\partial x_i} \right] + \beta m_0 c^2 [\psi^* \psi - \psi \psi^*]$$

de la ecuación de Schrödinger se tiene que:

$$\psi \frac{\partial \psi^*}{\partial t} = \frac{\psi}{\hbar i} \left[ \frac{\hbar c}{i} \sum \alpha_i \frac{\partial}{\partial x_i} + \beta m_0 c^2 \right] \psi^*$$

y tomando en cuenta que:

$$\frac{\partial \rho}{\partial t} = \psi \frac{\partial \psi^*}{\partial t} + \psi^* \frac{\partial \psi}{\partial t}$$

entonces:

$$i\hbar \left[ \frac{\partial \rho}{\partial t} - 2\psi \frac{\partial \psi^*}{\partial t} \right] = \frac{\hbar c}{i} \left[ \sum \alpha_i \psi^* \frac{\partial \psi}{\partial x_i} - \alpha_i \psi \frac{\partial \psi^*}{\partial x_i} \right] + \beta m_0 c^2 [\psi^* \psi - \psi \psi^*]$$

$$i\hbar \frac{\partial \rho}{\partial t} = \frac{\hbar c}{i} \left[ \sum \alpha_i \psi^* \frac{\partial \psi}{\partial x_i} - \alpha_i \psi \frac{\partial \psi^*}{\partial x_i} \right] + \beta m_0 c^2 [\psi^* \psi - \psi \psi^*] + 2i\hbar \psi \frac{\partial \psi^*}{\partial t}$$

$$\begin{aligned}
i\hbar \frac{\partial \rho}{\partial t} &= \frac{\hbar c}{i} \left[ \sum \psi^* \alpha_i \frac{\partial \psi}{\partial x_i} + \psi \alpha_i \frac{\partial \psi^*}{\partial x_i} \right] \\
\frac{\partial \rho}{\partial t} &= - \sum c \alpha_i \left( \psi^* \alpha_i \frac{\partial \psi}{\partial x_i} + \psi \alpha_i \frac{\partial \psi^*}{\partial x_i} \right) \\
\frac{\partial \rho}{\partial t} &= - \sum \frac{\partial c \psi^* \alpha_i \psi}{\partial x_i}
\end{aligned}$$

por lo tanto

$$\frac{\partial \rho}{\partial t} + \sum \frac{\partial}{\partial x_i} [c \psi^* \alpha_i \psi] = 0$$

## Ejercicio 28

Mostrar la identidad

$$(\vec{\sigma} \cdot \vec{A}) (\vec{\sigma} \cdot \vec{B}) = \vec{A} \cdot \vec{B} \mathbb{I} + i \vec{\sigma} \cdot (\vec{A} \times \vec{B})$$

tomando en cuenta que

$$\{\sigma_i \sigma_j\} = 2\delta_{ij} \mathbb{I} \quad [\sigma_i, \sigma_j] = 2i\epsilon_{ijk} \sigma_k$$

calculando  $\{\sigma_i \sigma_j\} + [\sigma_i, \sigma_j]$ , se tiene que:

$$\begin{aligned}
[\sigma_i, \sigma_j] &= 2\delta_{ij} \mathbb{I} + 2i\epsilon_{ijk} \sigma_k \\
2\sigma_i \sigma_j &= 2\delta_{ij} \mathbb{I} + 2i\epsilon_{ijk} \sigma_k \\
\sigma_i \sigma_j &= \delta_{ij} \mathbb{I} + i\epsilon_{ijk} \sigma_k
\end{aligned}$$

multiplicando por  $a_i b_j$

$$\begin{aligned}
\sigma_i \sigma_j a_i b_j &= (\delta_{ij} \mathbb{I} + i\epsilon_{ijk} \sigma_k) a_i b_j \\
\sigma_i a_i \sigma_j b_j &= \delta_{ij} \mathbb{I} a_i b_j + i\epsilon_{ijk} \sigma_k a_i b_j \\
\sigma_i a_i \sigma_j b_j &= \delta_{ij} a_i b_j \mathbb{I} + i\epsilon_{ijk} a_i b_j \sigma_k
\end{aligned}$$

tomando en cuenta que

$$\begin{aligned}
\sigma_i a_i &= \vec{\sigma} \cdot \vec{A} \\
\sigma_j b_j &= \vec{\sigma} \cdot \vec{B} \\
\delta_{ij} a_i b_j &= \vec{A} \cdot \vec{B} \\
\epsilon_{ijk} a_i b_j &= \vec{A} \times \vec{B} \\
\epsilon_{ijk} a_i b_j \sigma_k &= \vec{A} \times \vec{B} \cdot \vec{\sigma}
\end{aligned}$$

por lo tanto:

$$(\vec{\sigma} \cdot \vec{A}) (\vec{\sigma} \cdot \vec{B}) = \vec{A} \cdot \vec{B} \mathbb{I} + i \vec{\sigma} \cdot (\vec{A} \times \vec{B})$$

## Ejercicio 29

Mostrar que

$$\left[ \hat{\Sigma} \cdot \hat{P}, \hat{\vec{H}} \right] \psi_{p,\lambda} = 0$$

Reescribiendo se tiene que:

$$\begin{aligned} \left[ \hat{\Sigma} \cdot \hat{P}, \hat{\vec{H}} \right] &= [\delta_{ij} \Sigma_i P_j, c \delta_{ij} \alpha_i P_j + m_0 c^2 \beta] \\ &= c [\delta_{ij} \Sigma_i P_j, \delta_{ij} \alpha_i P_j] + m_0 c^2 [\delta_{ij} \Sigma_i P_j, \beta] \end{aligned}$$

calculando  $[\delta_{ij} \Sigma_i P_j, \beta]$ :

$$\begin{aligned} [\delta_{ij} \Sigma_i P_j, \beta] &= \delta_{ij} \Sigma_i P_j \beta - \beta \delta_{ij} \Sigma_i P_j \\ &= (\Sigma_i \beta - \beta \Sigma_i) P_i \end{aligned}$$

calculando  $\Sigma_i \beta$ , se tiene que:

$$\Sigma_i \beta = \begin{bmatrix} \sigma_i & 0 \\ 0 & \sigma_i \end{bmatrix} \begin{bmatrix} \mathbb{I} & 0 \\ 0 & -\mathbb{I} \end{bmatrix} = \begin{bmatrix} \sigma_i & 0 \\ 0 & -\sigma_i \end{bmatrix}$$

calculando  $\beta \Sigma_i$ , se tiene que:

$$\beta \Sigma_i = \begin{bmatrix} \mathbb{I} & 0 \\ 0 & -\mathbb{I} \end{bmatrix} \begin{bmatrix} \sigma_i & 0 \\ 0 & \sigma_i \end{bmatrix} = \begin{bmatrix} \sigma_i & 0 \\ 0 & -\sigma_i \end{bmatrix}$$

por lo tanto:

$$[\delta_{ij} \Sigma_i P_j, \beta] = 0$$

calculando  $[\delta_{ij} \Sigma_i P_j, \delta_{ij} \alpha_i P_j]$

$$\begin{aligned} [\delta_{ij} \Sigma_i P_j, \delta_{ij} \alpha_i P_j] &= \Sigma_i P_i \alpha_i P_i - \alpha_i P_i \Sigma_i P_i \\ &= (\Sigma_i \alpha_i - \alpha_i \Sigma_i) P_i^2 \end{aligned}$$

calculando  $\Sigma_i \alpha_i$ :

$$\Sigma_i \alpha_i = \begin{bmatrix} \sigma_i & 0 \\ 0 & \sigma_i \end{bmatrix} \begin{bmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{bmatrix} = \begin{bmatrix} 0 & \mathbb{I} \\ \mathbb{I} & 0 \end{bmatrix}$$

calculando  $\alpha_i \Sigma_i$ :

$$\alpha_i \Sigma_i = \begin{bmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{bmatrix} \begin{bmatrix} \sigma_i & 0 \\ 0 & \sigma_i \end{bmatrix} = \begin{bmatrix} 0 & \mathbb{I} \\ \mathbb{I} & 0 \end{bmatrix}$$

entonces:

$$[\delta_{ij} \Sigma_i P_j, \delta_{ij} \alpha_i P_j] = 0$$

por lo tanto:

$$\left[ \hat{\Sigma} \cdot \hat{P}, \hat{\vec{H}} \right] \psi_{p,\lambda} = 0$$

## Ejercicio 30

Mostrar que

$$T^i_j = -\psi^* \alpha^i \hat{P}_j c \psi$$

Se tiene que el lagrangiano es:

$$\mathcal{L} = \psi^* [i\hbar c \gamma^\mu \partial_\mu + m_0 c^2] \psi$$

y el tensor energía momento es

$$T^\mu_\nu = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)} \partial_\nu \psi + \frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi^*)} \partial_\nu \psi^* - \delta^\mu_\nu \mathcal{L}$$

calculando  $\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)} \partial_\nu \psi$ :

$$\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi)} \partial_\nu \psi = \psi^* c i \hbar \gamma^\mu \psi$$

como la lagrangiana no depende de  $\partial_\mu \psi^*$ , entonces

$$\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi^*)} \partial_\nu \psi^* = 0$$

por lo tanto, el tensor energía momento es

$$T^\mu_\nu = \psi^* c i \hbar \gamma^\mu \delta_\nu \psi - \delta^\mu_\nu [\psi^* [i\hbar c \gamma^\mu \partial_\mu + m_0 c^2] \psi]$$

Tomando el caso de  $\mu = i, \nu = j$ , se tiene que:

$$T^i_j = \psi^* c i \hbar \alpha^i \partial_j \psi$$

Como el operador del momento lineal es  $\hat{P}_j = -i\hbar \partial_j$ , entonces

$$\begin{aligned} T^i_j &= -\psi^* c \alpha^i (-i\hbar \partial_j) \psi \\ &= \psi^* c \alpha^i \hat{P}_j \psi \end{aligned}$$

por lo tanto:

$$T^i_j = -\psi^* \alpha^i \hat{P}_j c \psi$$