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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**  
**Problemas propuestos**  
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# Índice

## 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:

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

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:

$$(U_d)_\perp = (U_d)_x = \frac{(U'_d)_\perp}{\gamma_v \left(1 + \frac{v \cdot u'_d}{c^2}\right)}$$

$$(U_d)_\parallel = (U_d)_z = \frac{(U'_d)_\parallel + v}{1 + \frac{v \cdot u'_d}{c^2}}$$

pero, del diagrama

$$(U'_d)_\perp = U'_d \sin(\theta')$$

$$(U'_d)_\parallel = U'_d \cos(\theta')$$

por lo tanto:

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

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

pero  $U'_d = -v$

$$(U_d)_x = \frac{-v \sin(\theta')}{\gamma_v \left(1 - \frac{v^2}{c^2} \cos(\theta')\right)}$$

$$= \frac{-c\beta \sin(\theta')}{\gamma_v (1 - \beta^2 \cos(\theta'))}$$

$$(U_d)_z = \frac{c\beta(1 - \cos(\theta'))}{1 - \beta^2 \cos(\theta')}$$

### Ejercicio 3

Mostrar que

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

$$(U_c)_x = \frac{c\beta \sin(\theta')}{\gamma_v [1 + \beta^2 \cos(\theta')]}$$

$$\approx \frac{c\beta \theta}{\gamma_v \left[1 + \beta^2 \left(1 - \frac{\theta^2}{2}\right)\right]}$$

$$(U_c)_z \approx \frac{c\beta \left(1 + \left(1 - \frac{\theta^2}{2}\right)\right)}{1 + \beta^2 \left(1 - \frac{\theta^2}{2}\right)}$$

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  $F^{\gamma\delta}g_{\delta\beta}$

$$\begin{aligned} F^{\gamma\delta}g_{\delta\beta} &= \begin{pmatrix} 0 & -Ex & -Ey & -Ez \\ Ex & 0 & -B_z & B_y \\ Ey & B_z & 0 & -B_x \\ Ez & -B_y & B_x & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \\ &= \begin{pmatrix} 0 & Ex & Ey & Ez \\ Ex & 0 & B_z & -B_y \\ Ey & -B_z & 0 & B_x \\ Ez & B_y & -B_x & 0 \end{pmatrix} \end{aligned}$$

por lo tanto:

$$F_{\beta}^{\gamma} = \begin{pmatrix} 0 & Ex & Ey & Ez \\ Ex & 0 & B_z & -B_y \\ Ey & -B_z & 0 & B_x \\ Ez & B_y & -B_x & 0 \end{pmatrix}$$

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

$$\begin{aligned} g_{\alpha\gamma}F_{\beta}^{\gamma} &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 0 & Ex & Ey & Ez \\ Ex & 0 & B_z & -B_y \\ Ey & -B_z & 0 & B_x \\ Ez & B_y & -B_x & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & Ex & Ey & Ez \\ -Ex & 0 & -B_z & B_y \\ -Ey & B_z & 0 & -B_x \\ -Ez & -B_y & B_x & 0 \end{pmatrix} \end{aligned}$$

por lo tanto:

$$F_{\alpha\beta} = \begin{pmatrix} 0 & Ex & Ey & Ez \\ -Ex & 0 & -B_z & B_y \\ -Ey & B_z & 0 & -B_x \\ -Ez & -B_y & B_x & 0 \end{pmatrix}$$

## 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 Particle 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

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

## Ejercicio 12

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

$$\begin{aligned} s &= (p_A + p_B)^2/c^2 \\ t &= (p_A - p_C)^2/c^2 \\ u &= (p_A - p_D)^2/c^2 \end{aligned}$$

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

$$\rho'_+ = \frac{e|E_p|}{m_0c^2}\psi_+^*\psi_+$$
$$\rho'_- = \frac{e|E_p|}{m_0c^2}\psi_-^*\psi_-$$

considerando que:

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

Sea

$$\rho' = \frac{i\hbar e}{2m_0c^2} \left[ \psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* \right]$$

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

$$\frac{\partial}{\partial t} \psi_+ = -\frac{|E_p|i}{\hbar} \psi_+ \quad \frac{\partial}{\partial t} \psi_+^* = \frac{|E_p|i}{\hbar} \psi_+^*$$
$$\psi_+^* \frac{\partial}{\partial t} \psi_+ = -\frac{|E_p|i}{\hbar} \psi_+^* \psi_+ \quad \psi_+ \frac{\partial}{\partial t} \psi_+^* = \frac{|E_p|i}{\hbar} \psi_+^* \psi_+$$

entonces:

$$\psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* = -\frac{2|E_p|i}{\hbar} \psi_+^* \psi_+$$
$$\frac{i\hbar e}{2m_0c^2} \left[ \psi^* \frac{\partial}{\partial t} \psi - \psi \frac{\partial}{\partial t} \psi^* \right] = \frac{e|E_p|}{m_0c^2} \psi_+^* \psi_+$$

por lo tanto:

$$\rho'_+ = \frac{e|E_p|}{m_0c^2} \psi_+^* \psi_+$$

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

$$\frac{\partial}{\partial t} \psi_- = \frac{|E_p|i}{\hbar} \psi_- \quad \frac{\partial}{\partial t} \psi_-^* = -\frac{|E_p|i}{\hbar} \psi_-^*$$
$$\psi_-^* \frac{\partial}{\partial t} \psi_- = \frac{|E_p|i}{\hbar} \psi_-^* \psi_- \quad \psi_- \frac{\partial}{\partial t} \psi_-^* = -\frac{|E_p|i}{\hbar} \psi_-^* \psi_-$$

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

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

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:

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

## Ejercicio 17

Mostrar que

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

## Ejercicio 18

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

## 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

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

- Determinar las ecuaciones que satisface el campo  $A_{\nu}$
- Determinar el tensor  $T_{\nu}^{\mu} T^{\mu\nu}$

## 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  $A_\mu$

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

## Ejercicio 22

Mostrar que:

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

es invariante ante la transformacion

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