Lorentz Dönüşümlerine Göre Hız Bileşenleri

$S \to S'$

$$x_1' = \gamma(x_1 - vt)$$
$$x_2' = x_2$$
$$x_3' = x_3$$
$$t' = \gamma\left(t - \frac{v}{c^2}x_1\right)$$

$S' \to S$

$$x_1 = \gamma(x_1' + vt)$$
$$x_2 = x_2'$$
$$x_3 = x_3'$$
$$t = \gamma\left(t' + \frac{v}{c^2}x_1'\right)$$

$$u_1 = \dot{x}_1 = \frac{dx_1}{dt}$$
$$u_i = \dot{x}_i = \frac{dx_i}{dt}$$
$$u_i' = \dot{x}_i' = \frac{dx_i'}{dt'}$$

$$dx_1' = \gamma(dx_1 - v\,dt)$$
$$dx_2' = dx_2$$
$$dx_3' = dx_3$$
$$dt' = \gamma\left(dt - \frac{v}{c^2}dx_1\right)$$

$$dx_1 = \gamma(dx_1' + v\,dt')$$
$$dx_2 = dx_2'$$
$$dx_3 = dx_3'$$
$$dt = \gamma\left(dt' + \frac{v}{c^2}dx_1'\right)$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}, \quad \beta = \frac{v}{c}$$

- $$u_1' = \dot{x}_1' = \frac{dx_1'}{dt'} = \frac{\gamma(dx_1 - v\,dt)}{\gamma\left(dt - \frac{v}{c^2}dx_1\right)} = \frac{dx_1 - v\,dt}{dt - \frac{v}{c^2}dx_1} = \frac{\frac{dx_1}{dt} - v}{1 - \frac{v}{c^2}\frac{dx_1}{dt}} = \frac{u_1 - v}{1 - \frac{v}{c^2}u_1}$$

(u_1 = $\frac{dx_1}{dt}$)

$$u_1' = \frac{u_1 - v}{1 - \frac{v}{c^2}u_1} \quad // \qquad \dot{x}_1' = \frac{\dot{x}_1 - v}{1 - \frac{v}{c^2}\dot{x}_1} \quad //$$

$S \to S'$

$$u_1 = \frac{u_1' + v}{1 + \frac{v}{c^2}u_1'} \quad // \qquad \dot{x}_1 = \frac{\dot{x}_1' + v}{1 + \frac{v}{c^2}\dot{x}_1'} \quad //$$

$S' \to S$

- $$u_2' = \dot{x}_2' = \frac{dx_2'}{dt'} = \frac{dx_2'}{\gamma\left(dt - \frac{v}{c^2}dx_1\right)} = \frac{\frac{dx_2'}{dt}}{\gamma\left(1 - \frac{v}{c^2}\frac{dx_1}{dt}\right)} = \frac{\frac{dx_2}{dt}}{\gamma\left(1 - \frac{v}{c^2}\frac{dx_1}{dt}\right)}$$

(u_2 = $\frac{dx_2}{dt}$, u_1 = $\frac{dx_1}{dt}$)

$$u_2' = \frac{u_2}{\gamma\left(1 - \frac{v}{c^2}u_1\right)} \quad // \qquad \dot{x}_2' = \frac{\dot{x}_2}{\gamma\left(1 - \frac{v}{c^2}\dot{x}_1\right)} \quad //$$

$S \to S'$

$$u_2 = \frac{u_2'}{\gamma\left(1 - \frac{v}{c^2}u_1'\right)}$$
$$\dot{x}_2 = \frac{\dot{x}_2'}{\gamma\left(1 - \frac{v}{c^2}\dot{x}_1'\right)}$$

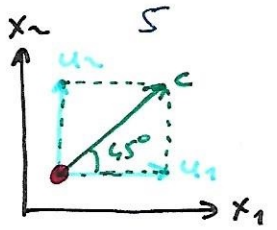
$S' \to S$

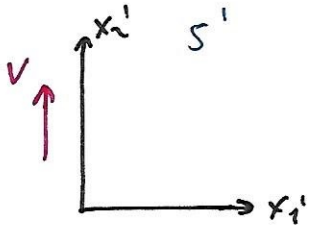
- $u_3' = \frac{dx_3'}{dt'} = \dot{x}_3' = \frac{dx_3'}{\gamma(dt - \frac{v}{c^2}dx_1)} = \frac{\frac{dx_3}{dt}}{\gamma(1 - \frac{v}{c^2}\frac{dx_1}{dt})} = \frac{u_3}{\gamma(1 - \frac{v}{c^2}u_1)}$

$$u_3' = \frac{u_3}{\gamma(1-\frac{v}{c^2}u_1)}, \quad \dot{x}_3' = \frac{\dot{x}_3}{\gamma(1-\frac{v}{c^2}\dot{x}_1)} \quad \Big\} \; S \to S'$$

$$u_3 = \frac{u_3'}{\gamma(1-\frac{v}{c^2}u_1')}, \quad \dot{x}_3 = \frac{\dot{x}_3'}{\gamma(1-\frac{v}{c^2}\dot{x}_1')} \quad \Big\} \; S \to S'$$

2.1. S sistemine göre hızı c, x_1 yönü yatay eksenle $45°$ olan bir hızla hareket eden bir taneciğin S sistemine göre y doğrultusunda $\frac{4c}{5}$ hızıyla hareket eden bir sistemden bakıldığında hızı nedir?





$\vec{v} = v\hat{e}_2$ (ayrıcalıklı eksen y ekseni)

$\vec{v} = \frac{4c}{5}\hat{e}_2$

$u_1 = c\cos 45° = \frac{c\sqrt{2}}{2}$

$u_2 = c\sin 45° = \frac{c\sqrt{2}}{2}$

$u_3 = 0$

$\vec{u} = u_1\hat{e}_1 + u_2\hat{e}_2$

$|\vec{u}| = c$

$S' \to S$

$x_1 = x_1'$

$x_2 = \gamma(x_2' - vt)$

$x_3 = x_3'$

$t = \gamma(t - \frac{v}{c^2}x_2')$

$S \to S'$

$x_1' = x_1$

$x_2' = \gamma(x_2 + vt)$

$x_3' = x_3$

$t' = \gamma(t + \frac{v}{c^2}x_2)$

S' deki hız istendiğine göre S → S' dönüşümlerini kullanıyoruz.

$$u_1' = \frac{u_1}{\gamma(1-\frac{v}{c^2}u_2)}, \quad u_3' = \frac{u_3}{\gamma(1-\frac{v}{c^2}u_2)}$$

$$u_2' = \frac{u_2 - v}{1 - \frac{v}{c^2}u_2}$$

$$\gamma = \frac{1}{\sqrt{1-(\frac{v}{c})^2}} = \frac{1}{\left(1-(\frac{4c}{5c})^2\right)^{1/2}} = \frac{5}{3}$$

$$\bullet\ u_1' = \frac{u_1}{\gamma\left(1-\frac{v}{c^2}u_1\right)} = \frac{\frac{c\sqrt{2}}{3}}{\frac{5}{3}\left(1-\frac{4}{5c}\left(\frac{c\sqrt{2}}{3}\right)\right)} = \frac{c3\sqrt{2}}{10\left(1-\frac{2\sqrt{2}}{5}\right)} = \frac{c3\sqrt{2}}{(10-4\sqrt{2})}$$

$u_1' = 0{,}976\,c$

$$\bullet\ u_3' = \frac{u_3^{\,0}}{\gamma\left(1-\frac{v}{c^2}u_1\right)} \Rightarrow u_3' = 0 \parallel$$

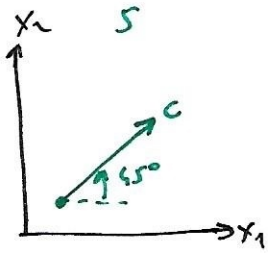
$$\bullet\ u_1' = \frac{u_1 - v}{1-\frac{v}{c^2}u_1} = \frac{\frac{c\sqrt{2}}{3}-\frac{4c}{5}}{1-\frac{c2\sqrt{2}}{5c}} = \frac{(5\sqrt{2}-8)}{(10-4\sqrt{2})}c \parallel \quad u_1' = -0{,}114c$$

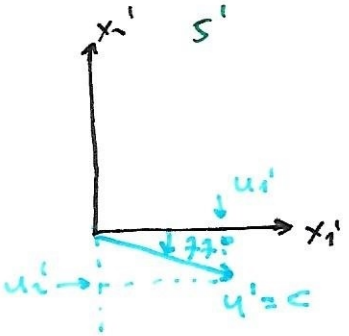
$$\bullet\ \vec{u}' = u_1'\hat{e}_1 + u_2'\hat{e}_2 + u_3'\hat{e}_3$$

$$|\vec{u}'| = \sqrt{u_1'^2 + u_2'^2 + u_3'^2} = \left[\left(\frac{3\sqrt{2}c}{(10-4\sqrt{2})}\right)^2 + \left(\frac{(5\sqrt{2}-8)c}{(10-4\sqrt{2})}\right)^2 + 0\right]^{1/2} = c \parallel \quad |u'| = |u| = c$$

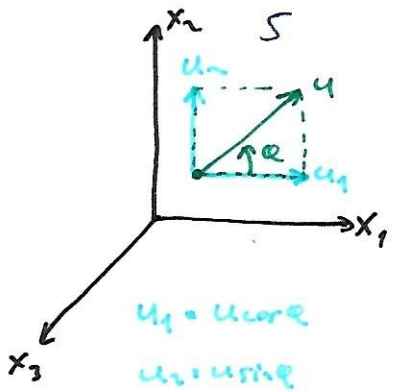
$$\bullet\ \tan\theta' = \frac{u_2'}{u_1'} = \frac{\frac{(5\sqrt{2}-8)c}{(10-4\sqrt{2})}}{\frac{3\sqrt{2}c}{(10-4\sqrt{2})}} = -4{,}56 \Rightarrow \arctan(-4{,}56) = \theta'$$

$\theta' = -77{,}65^\circ$





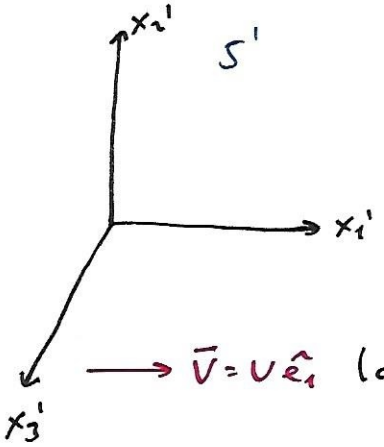
3.2. Bir tanecik S sisteminde X_1 ekseni ile α açısı yapacak şekilde sabit bir u hızıyla hareket etmektedir. S'ye göre X_1-X_1' doğrultusunda sabit bir v hızıyla hareket eden bir gözlemci taneciğin hızını ve hareket doğrultusunu nasıl görür?



$u_1 = u\cos\alpha$

$u_2 = u\sin\alpha$

$u_3 = 0$



$\rightarrow \vec{V} = V\hat{e}_1$ (ayrıcalıklı eksen x_1 ekseni)

$\vec{u} = u_1\hat{e}_1 + u_2\hat{e}_2 + u_3\hat{e}_3$

$|\vec{u}| = \left[u_1^2 + u_2^2 + u_3^2\right]^{1/2} = u$

$\vec{u}' = u_1'\hat{e}_1 + u_2'\hat{e}_2 + u_3'\hat{e}_3$

$|\vec{u}'| = \left[u_1'^2 + u_2'^2 + u_3'^2\right]^{1/2}$

$S \rightarrow S'$

$$u_1' = \frac{u_1 - V}{1 - \frac{V}{c^2}u_1}, \quad u_2' = \frac{u_2}{\gamma\left(1 - \frac{V}{c^2}u_1\right)}, \quad u_3' = \frac{\cancel{u_3}^{\,0}}{\gamma\left(1 - \frac{V}{c^2}u_1\right)} = 0$$

$$|\vec{u}'| = u' = \left[\left(\frac{u\cos\alpha - V}{1 - \frac{V}{c^2}u\cos\alpha}\right)^2 + \left(\frac{u\sin\alpha}{\gamma\left(\frac{V}{c^2}u\cos\alpha\right)}\right)^2 + 0\right]^{1/2}$$

$$u' = \left[\left(u\cos\alpha - V\right)^2 + \frac{u^2\sin^2\alpha}{\gamma^2}\right]^{1/2} \frac{1}{\left(1 - \frac{V}{c^2}u\cos\alpha\right)}$$

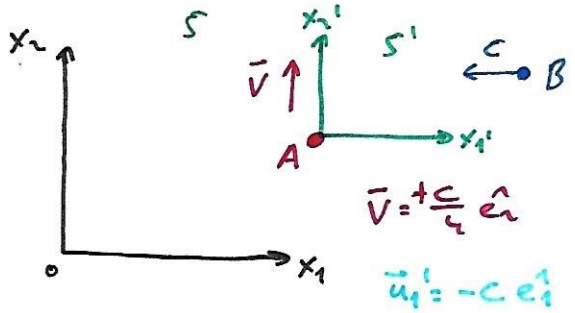
$$u' = \frac{1}{\left(1 - \frac{V}{c^2}u\cos\alpha\right)}\left[u^2\cos^2\alpha + V^2 - 2uV\cos\alpha + \frac{u^2\sin^2\alpha}{\gamma^2}\right]^{1/2}$$

$$u' = \frac{1}{\gamma(1-\frac{v}{c^2}u\cos\theta)}\left[\gamma^2(u\cos\theta - 2uv\cos\theta + v^2) + u^2\sin^2\theta\right]^{1/2} //$$

$$\cdot \tan\theta' = \frac{u_2'}{u_1'} = \frac{\frac{u_2}{\gamma(1-\frac{v}{c^2}u_1)}}{\frac{u_1-v}{(1-\frac{v}{c^2}u_1)}} = \frac{\frac{u\sin\theta}{\gamma(1-\frac{v}{c^2}u\cos\theta)}}{\frac{u\cos\theta-v}{(1-\frac{v}{c^2}u\cos\theta)}} = \frac{u\sin\theta}{\gamma(u\cos\theta-v)}$$

$$\tan\theta' = \frac{u\sin\theta}{\gamma(u\cos\theta-v)} //$$

3.3. Şekildeki gibi A S'ye göre $\frac{c}{4}$ hızıyla, B'de A'ya göre c hızıyla hareket etmektedir. B'nin S'ye göre hızı ve hareket doğrultusu nedir?



$\bar{v} = +\frac{c}{4}\hat{e}_2$

$\bar{u}_1' = -c\,\hat{e}_1'$

$u_2' = 0$

$u_3' = 0$

ayrıcalıklı eksen : x_2

$S' \to S$

$\gamma = \frac{1}{\sqrt{1-(\frac{v}{c})^2}}$ $\gamma = \frac{4}{\sqrt{15}}$

$$\cdot u_1 = \frac{u_1'}{\gamma(1+\frac{v}{c^2}u_2')} = \frac{-c}{\frac{4}{\sqrt{15}}(1+\frac{c}{4c^2}\cdot 0)} = -\frac{\sqrt{15}}{4}c, \quad u_1 = -\frac{\sqrt{15}}{4}c //$$

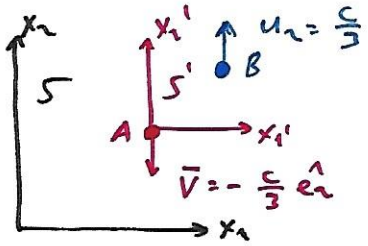
$$\cdot u_2 = \frac{u_2' + v}{(1+\frac{v}{c^2}u_2')} \Rightarrow u_2 = \frac{c}{4} //, \quad u_3 = \frac{u_3'}{\gamma(1+\frac{v}{c^2}u_2')} = 0, \Rightarrow u_3 = 0 //$$

$$u = \left[u_1^2+u_2^2+u_3^2\right]^{1/2} = \left[\left(\frac{\sqrt{15}}{4}c\right)^2 + \left(\frac{c}{4}\right)^2 + 0\right]^{1/2} \Rightarrow u = c //$$

$$\tan\alpha = \frac{u_2}{u_1} = \frac{c/4}{-\frac{\sqrt{15}c}{4}}$$

$$\tan\alpha = -\frac{1}{\sqrt{15}}, \quad \alpha = -14.5^\circ //$$

3.4. A ve B'nin S sistemine göre hızları ters yönde $\frac{c}{3}$ 'tür. B'nin A'ya göre hızını bulunuz.



$\vec{u}_1 = \vec{0}$ $\quad \vec{u}_1' = ?$

$\vec{u}_2 = \frac{c}{3}\hat{e}_2$ $\quad S \to S'$ $\quad \vec{u}_2' = ?$

$\vec{u}_3 = \vec{0}$ $\quad \vec{u}_3' = ?$

$\vec{V} = -\frac{c}{3}\vec{e}_2$ $\quad |\vec{u}'| = ?$

(ayrıcalıklı eksen x_2)

$S \to S'$

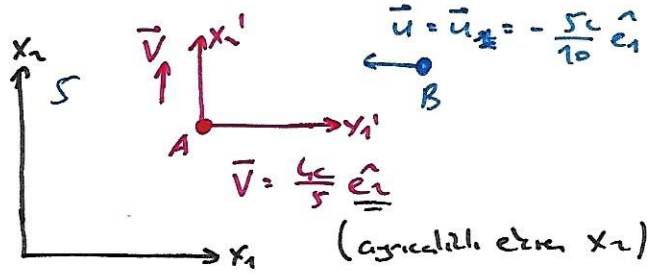
$$\vec{u}_1' = \frac{\vec{u}_1 \to 0}{\gamma\left(1 - \frac{\vec{V}.\vec{u}_2}{c^2}\right)} = \vec{0} \Rightarrow u_1' = 0 \quad , \quad \vec{u}_3' = \frac{\vec{u}_3 \to 0}{\gamma\left(1 - \frac{\vec{V}.\vec{u}_2}{c^2}\right)} = \vec{0} \Rightarrow u_3' = 0$$

$$\vec{u}_2' = \frac{\vec{u}_2 - \vec{V}}{1 - \frac{\vec{V}.\vec{u}_2}{c^2}} = \frac{\left[\frac{c}{3}\hat{e}_2 - \left(-\frac{c}{3}\vec{e}_2\right)\right]}{1 - \frac{1}{c^2}\left(\frac{c}{3}\hat{e}_2 . \frac{c}{3}\hat{e}_2\right)} = \frac{\frac{2c}{3}\hat{e}_2}{1 - \frac{1}{9}} = \frac{3c}{5}\hat{e}_2$$

$$u_2' = \frac{3c}{5} //$$

$$\vec{u}' = \vec{u}_1 + \vec{u}_2 + \vec{u}_3 = \vec{0} + \frac{3c}{5}\hat{e}_2 + \vec{0} \Rightarrow \vec{u}' = \frac{3c}{5}\hat{e}_2 \Rightarrow |\vec{u}'| = \frac{3c}{5} //$$

3.5. S sistemine göre bir A tanecigi pozitif y yönünde $\frac{4c}{5}$ hızıyla, bir B tanecigi de $-x$ yönünde $\frac{5c}{10}$ hızıyla hareket ediyor. B'nin A'ya göre hızı nedir?



$S \rightarrow S'$

$\vec{u}_2 = \vec{0}$	$\vec{u}_2' = ?$
$\vec{u}_1 = -\frac{5c}{10}\hat{e}_1$	$\vec{u}_1' = ?$
$\vec{u}_3 = \vec{0}$	$\vec{u}_3' = ?$

$\gamma = \frac{1}{\sqrt{1-\frac{V^2}{c^2}}} = \frac{5}{3}$

- $\vec{u}_1' = \frac{\vec{u}_1}{\gamma\left(1-\frac{\vec{V}\cdot\vec{u}_2}{c^2}\right)} = \frac{-\frac{5c}{10}\vec{e}_1}{\frac{5}{3}\left(1-\left(\frac{4c}{5}\vec{e}_2\cdot\vec{0}\right)\right)}$ ($\vec{e}_2\cdot\vec{0}=0$)

$\vec{u}_1' = -\frac{3c}{10}\hat{e}_1 \;//$

- $\vec{u}_2' = \frac{\vec{u}_2 - \vec{V}}{\left(1-\frac{\vec{V}\cdot\vec{u}_2}{c^2}\right)} = \vec{u}_2 - \vec{V} = -\vec{V} \Rightarrow \vec{u}_2' = -\frac{4c}{5}\hat{e}_2 \;//$ ($\vec{V}\cdot\vec{u}_2 = 0$)

- $\vec{u}_3' = \frac{\vec{u}_3}{\gamma\left(1-\frac{\vec{V}\cdot\vec{u}_2}{c^2}\right)} = \vec{0} \Rightarrow \vec{u}_3' = \vec{0}$

$\vec{u}' = \vec{u}_1' + \vec{u}_2' + \vec{u}_3' = -\frac{3c}{10}\hat{e}_1 - \frac{4c}{5}\hat{e}_2 + \vec{0} \Rightarrow |\vec{u}'| = u' = \frac{c\sqrt{13}}{10} \;//$

Relativistik Dinamik

- Relativistik kütle : $m = \gamma m_0 \Rightarrow m = \dfrac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$

- Relativistik momentum : $\vec{p} = m\vec{v} = \gamma m_0 \vec{v} = \dfrac{m_0 \vec{v}}{\sqrt{1-\frac{v^2}{c^2}}}$

- Relativistik kuvvet : $\vec{F} = \dfrac{d\vec{p}}{dt} = \dfrac{d}{dt}(m\vec{v}) = m\dfrac{d\vec{v}}{dt} + \vec{v}\dfrac{dm}{dt} = \dfrac{d}{dt}\left[\dfrac{m_0\vec{v}}{\sqrt{1-\frac{v^2}{c^2}}}\right]$

- Relativistik kinetik enerji : $K = T = E - E_0 = mc^2 - m_0c^2$

$T = (m-m_0)c^2 = \Delta m c^2$

$m = \dfrac{m_0}{\sqrt{1-v^2/c^2}} \rightarrow m^2 = \dfrac{m_0^2}{[1-v^2/c^2]}$, $m^2 - \dfrac{m^2v^2}{c^2} = m_0^2$

$\Rightarrow m^2c^2 - m^2v^2 = m_0^2c^2 \Rightarrow m^2c^4 - m^2v^2c^2 = m_0^2c^4$

$m^2c^4 = m_0^2c^4 + m^2v^2c^2$ $\quad p = mv$ $\quad E_0 = m_0c^2$ $\quad E = mc^2$

$\Rightarrow (mc^2)^2 = (m_0c^2)^2 + (mv)^2c^2$

$E \quad E_0 \quad p$

Foton için; $m_0 = 0 \Rightarrow$

$E = pc$ olur; $p = \dfrac{E}{c}$

$\Rightarrow E^2 = E_0^2 + p^2c^2$ } Toplam enerji ifadesi

3.6. Momentumu 130 MeV/c ve kinetik enerjisini 50 MeV olan parçacığın durgun kütlesini hesaplayınız.

$T = 50\ MeV$ $\quad T = E - E_0 \longrightarrow E = T + E_0$

$p = 130\ MeV/c$ $\quad E^2 = E_0^2 + (pc)^2 \longrightarrow E^2 - E_0^2 = (pc)^2$

$$\Rightarrow (T+E_0)^2 - E_0^2 = (pc)^2 \Rightarrow T^2 + 2E_0T + E_0^2 - E_0^2 = (pc)^2$$

$$\Rightarrow E_0 = \frac{(pc)^2 - T^2}{2T} \Rightarrow m_0c^2 = \frac{p^2c^2 - T^2}{2T} \Rightarrow m_0 = \frac{p^2c^2 - T^2}{2Tc^2} //$$

$$\Rightarrow m_0 = \frac{(130\ MeV/c)^2 (3\times10^8\ m/s)^2 - (50\ MeV)^2}{2(50\ MeV)(3\times10^8\ m/s)^2} \Rightarrow m_0 = 144\ MeV/c^2 //$$

3.7. Bir elektronun kütlesinin protonun durgun kütlesine eşit olması için hızı ne olmalıdır?

$m_{e_0} = 9,108\times10^{-31}\ kg$

$m_{p_0} = 1,672\times10^{-27}\ kg$

$$m_e = \gamma m_{e_0} = m_{p_0} \Rightarrow \frac{m_{e_0}}{m_{p_0}} = \frac{1}{\gamma} = \sqrt{1 - \frac{v^2}{c^2}}$$

$$\Rightarrow v^2 = \left(1 - \frac{m_{e_0}^2}{m_{p_0}^2}\right) \Rightarrow v = \left[1 - \left(\frac{m_{e_0}}{m_{p_0}}\right)^2\right]^{1/2} c$$

$$\Rightarrow v = \left[1 - \left(\frac{9,108\times10^{-31}\ kg}{1,672\times10^{-27}\ kg}\right)^2\right]^{1/2} c \Rightarrow v = 2,9993\times10^8\ m/s$$

3.8. 200.000 km/s hızı olan bir elektronun kütlesi nedir?

$$m_e = \frac{m_{e_0}}{\sqrt{1-(v/c)^2}} = \frac{9,108\times10^{-31}\ kg}{\sqrt{1 - \left(\frac{2\times10^8}{3\times10^8}\right)^2}}$$

$v = 200000\ km/s = 2\times10^5\ km/s$

$v = 2\times10^8\ m/s$

$m_e = 12,08\times10^{-31}\ kg$ ü $\quad$ %34 artmıştır.

3.9. Momentum ve enerji korunumu ilkelerinden hareket ederek durgun elektronlar üzerine gönderilmiş olan yüksek enerjili başka elektronların çarpışmada elektron-pozitron çifti meydana getirmeleri için merkezi rolü oynayan elektronların $6mc^2$'lik bir minimum enerjiye (kinetik enerji) sahip olmaları gerektiğini gösterip bu enerjiyi hesaplayınız.

Elektron-pozitron çifti üretilmesi amacıyla merkezi çekirdeğin hem bu çifti doğuracak ve hem de böylece sayıları dörde yükselen taneciklere bir hız verebilecek kadar kinetik enerjiye sahip olmasıyla mümkün olur.

Şimdi merkezi elektronun çarpışma öncesi momentumunu $\vec{P}$ ve çarpışma sonrası ortada bulunan dört taneciğin toplam momentumlarını da $\vec{P}_1$ ile gösterelim. Momentum korunumuna göre;

$$\vec{P} = \vec{P}_1$$

olmalıdır. Enerji korunum ilkesine göre ise, sistemin çarpışma öncesi toplam enerjisi

$$E = \sqrt{m^2c^4 + p^2c^2} + mc^2$$

ve çarpışma sonrası toplam enerjisi ise;

$$E' = \sqrt{(4mc^2)^2 + P_1^2c^2} = \sqrt{16m^2c^4 + p^2c^2}$$

olur. Yani,

$$\sqrt{m^2c^4 + p^2c^2} + mc^2 = \sqrt{16m^2c^4 + p^2c^2}$$

çıkar. Bu ifade de zaten gösterilmek istenen sonuçtur:

$$T = \sqrt{m^2c^4 + p^2c^2} - mc^2 = 6mc^2 = 3.06\,eV$$

3.10. 2 MeV'luk bir elektronun hızını ve kütlesini bulunuz.

$$T = mc^2 - moc^2 \longrightarrow \quad m = m_0 + \frac{T}{c^2} = 9,109\times10^{-31} + \frac{2\times1,602\times10^{-13}\ \text{joule}}{[3\times10^8\ m/s]^2}$$

- $m = 4,608\times10^{-31}\ kg$ //

- $T = moc^2\left[\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right] \Rightarrow \quad v = c\sqrt{1-\left(\frac{moc^2}{T+moc^2}\right)^2} = 2,9367\times10^8\ m/s$

3.11. 0,1 MeV'luk bir elektronun önce rölativite teorisine göre sonra da klasik mekaniğe göre hızını bulunuz.

Rölativistik teorisine göre;

$$T = mc^2 - moc^2 = moc^2\left[\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right] \Rightarrow v = c\sqrt{1-\frac{1}{\left(1+\frac{T}{moc^2}\right)^2}}$$

$$v = 3\times10^8\ m/s\left[1-\frac{1}{\left(1+\frac{0,1\times10^6\times1,602\times10^{-19}}{9,109\times10^{-31}\ kg\times 9\times10^{16}}\right)^2}\right]^{1/2} = 1,643\times10^8\ m/s\ //$$

Klasik mekaniğe göre;

$$T = \frac{1}{2}m_0v^2 \Rightarrow \quad v = \sqrt{\frac{2T}{m_0}} = \sqrt{\frac{2\times0,1\times10^6\times1,602\times10^{-19}}{9,109\times10^{-31}\ kg}} = 1,874\times10^8\ m/s$$