1.

$$E = \frac{mc^2}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$E^2 - E^2\frac{v^2}{c^2} = m^2c^4 \qquad \Rightarrow \quad v = \sqrt{\frac{(E^2 - m^2c^4)c^2}{E^2}} = c\sqrt{1 - \frac{m^2c^4}{E^2}}$$

$$\tau \geq S\left(\frac{1}{v_1} - \frac{S}{v_2}\right) = \frac{S}{c}\left(\frac{1}{\sqrt{1-\frac{m^2c^4}{E_1^2}}} - \frac{1}{\sqrt{1-\frac{m^2c^4}{E_2^2}}}\right) =$$

$$\frac{1}{\sqrt{1-x^2}} \simeq 1 + \frac{1}{2}x^2$$

$$= \frac{S}{c}\left(\cancel{1} + \frac{1}{2}\frac{m^2c^4}{E_1^2} - \cancel{1} - \frac{1}{2}\frac{m^2c^4}{E_2^2}\right) =$$

$$\frac{2\tau}{c^3 S} \geq \frac{m^2}{E_1^2} - \frac{m^2}{E_2^2}$$

$$\frac{2\tau}{c^3 S}\left(\frac{1}{\frac{1}{E_1^2} - \frac{1}{E_2^2}}\right) \geq m^2$$

$\tau = 10\,s$

$E_1 = 10\,MeV$

$E_2 = 40\,MeV$

$S = 1{,}5 \cdot 10^5\ ly =$

$= 1{,}5 \cdot 10^5 \cdot 10^{16}\,m$

$$\frac{1}{1{,}5\cdot 10^5} \cdot \frac{20}{27\cdot 10^{40}}\left(\frac{s}{m}\right)^2 \cdot \frac{40}{3}\ MeV \geq m^2$$

$$\boxed{m^2 \leq 10^{-44}\ MeV\left(\frac{s}{m}\right)^2}$$

$$\tau E = \hbar = \frac{\hbar c}{c} = \frac{200\ MeV \cdot 10^{-15}\,m}{3\cdot 10^8\,\frac{m}{s}} =$$

$$= 10^{-19}\ MeV\,s$$

$$\tau \gtrsim 10^{-20}\,s$$

BLEEEE !!!

1.

(2.)

$$p = \frac{h}{\lambda} = \frac{\hbar c}{\lambda c} = \frac{200\ \mathrm{MeV\,fm}}{0{,}8\ \mathrm{fm}\ 3\cdot 10^{8}\ \mathrm{m/s}} = 10^{6}\ \mathrm{MeV}\,\frac{s}{m}$$

$$E^2 = p^2c^2 + \underbrace{m^2c^4}_{0{,}5\ \mathrm{MeV}} \Rightarrow E^2 \approx p^2c^2 = 10^{5}\ \mathrm{MeV}^2$$

$$E = 316\ \mathrm{MeV}$$

(3.)

$$p = \frac{\hbar}{\lambda} = 10^{-6}\ \mathrm{MeV}\,\frac{s}{m}$$

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

Más a π tömege, ezért kell nagyobb energia.

(4.) $\xrightarrow{30\,\mathrm{GeV}}$ $\xleftarrow{800\,\mathrm{GeV}}$

$$p^{\mu} = \begin{pmatrix} (30+800)\ \mathrm{GeV} \\ \vec{p} - \vec{p} \end{pmatrix}$$

$$E_{TKP}^2 = p_\mu p^\mu = 16\cdot 10^{4}\ (\mathrm{GeV})^2$$

$$E_{TKP} = 800\ \mathrm{GeV}$$

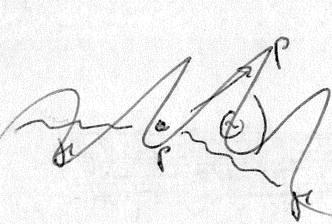
$$pc \cong E$$

$$\frac{\hbar \cancel{c}}{\lambda c} = p\cancel{c}$$

$$\lambda = \left(\frac{c\,p}{\hbar c}\right)^{-1} = 0{,}25\cdot 10^{-3}\ \mathrm{fm}$$

(5.)

① Energia megmaradás



$$E_\gamma + m_pc^2 = \frac{m_pc^2}{\sqrt{1-\beta^2}} + E_\gamma'$$

② Impulzus megmaradás

$$p_\gamma = p_p + p_\gamma'$$

$$p_{\gamma'}^2 = p_p^2 + p_{\gamma}^2 + 2\cos\Theta\, p_p p_\gamma$$

$$E_\gamma' = E_\gamma - \frac{1}{2}m_pv^2$$ ← sorfejtés

$$E_\gamma^2 = p_\gamma^2c^2 \qquad m_p^2c^4 = p^2c^2$$

$$\left(\frac{E_\gamma}{c}\right)^2 = \left(\frac{cm_p}{\sqrt{1-\beta^2}}\right)^2 + \left(\frac{E_\gamma - \frac{1}{2}m_pv^2}{c}\right)^2 + 2\cos\vartheta\, m_pv\,\frac{E_\gamma'}{c}$$

$$\cancel{0 = \frac{m_pc^4}{\sqrt{1-\beta^2}} + E_\gamma m_pv^2 + 2\cos\vartheta\, m_pvc\,E_\gamma' = (1000\,\mathrm{MeV})^2 + 2\cos\vartheta\,(1000\,\mathrm{MeV})\,0{,}1}$$ $m_p \approx 0{,}1$

2./

(5.)

1.) Energia megmaradás

$$E_\gamma + m_p c^2 = \frac{m_p c^2}{\sqrt{1-\beta^2}} + E_\gamma'$$

$\leftarrow$ sorf.

$$\downarrow$$

$$E_\gamma' = E_\gamma - \frac{1}{2} m_p v^2$$

2.) Impulzus megmaradás

$$p_\gamma = p_p + p_\gamma'$$

$$p_\gamma^2 = p_p^2 + p_\gamma'^2 + 2\cos\Theta\, p_p p_\gamma'$$

$$E^2 = p^2 c^2$$

$$\cancel{\left(\frac{E_\gamma}{c}\right)^2} = \left(\frac{m_p c}{\sqrt{1-\beta^2}}\right)^2 + \left(\frac{\cancel{E_\gamma} - \frac{1}{2} m_p v^2}{c}\right)^2 + 2\cos\Theta\, m_p v \left(\frac{E_\gamma - \frac{1}{2} m_p v^2}{c}\right)$$

$$0 = \frac{m_p^2 c^2}{\cancel{1-\beta^2}} + \frac{\frac{m_p^2 v^4}{4} - m_p v^2 E_\gamma}{c^2} + 2\cos\Theta \left(\frac{m_p v E_\gamma - \frac{1}{2} m_p^2 v^3}{c}\right)$$

$$0 = m_p^2 c^4 + m_p^2 c^4 (0{,}1)^4 - (0{,}1)^2 m_p c^2 E_\gamma + 2c\cos\Theta\left(m_p 0{,}1\, c E_\gamma - \frac{1}{2} m_p^2 \cdot (0{,}1)^3 c^3\right)$$

$$E_\gamma \left((0{,}1)^2 m_p c^2 - 2c\cos\Theta\, m_p\, 0{,}1\, c\right) =$$

$$= (100\cancel{0}\ \mathrm{MeV})^2 + \frac{(100\cancel{0}\ \mathrm{MeV})^2}{1000\cancel{0}} \cancel{-\ \ \cos\Theta \frac{(100\cancel{0}\ \mathrm{MeV})^2}{1000}}$$

$$E_\gamma = \frac{(100\cancel{0}\ \mathrm{MeV})^{\cancel{2}}}{\frac{\cancel{1000\ \mathrm{MeV}}}{\cancel{10}100} - \frac{\cos\Theta\ \cancel{1000\ \mathrm{MeV}}}{10}} = \frac{100\cancel{0}\ \mathrm{MeV}}{\frac{1}{\cancel{10}100} - \frac{\cos\Theta}{10}} \neq 50\ \mathrm{MeV}$$

~~(13.)~~ [illegible]

(6.)

$N=14 \Rightarrow \leftarrow \circ \rightsquigarrow^{\gamma}$ $E_\gamma = 50\ MeV$

$E_{mag} = 400\ keV$

1.) Energia megmaradás

$$E_N = E_\gamma - E_{mag}$$

$$14 \cdot 1000\,MeV = 50\ MeV -$$

(6.) γ N Compton szórás

$$E_\gamma = E_\gamma' + E_{kin}$$

$$p_\gamma = p_\gamma' + p_{mag} \quad = [illegible]$$

$$p = p_{mag} - \frac{E_\gamma'}{c}$$

(6.)

1.) $p_\gamma = p_m - p_{\gamma'} = \sqrt{2 m E_{kin}} - \frac{E_\gamma'}{c}$ 2.) $E_\gamma = E_{kin} + E_\gamma'$

$$E_\gamma' = E_\gamma - E_{kin}$$

$$\frac{E_\gamma}{c} + \frac{E_\gamma'}{c} = \sqrt{2 E_{kin} m}$$

$$\frac{E_\gamma}{c} + \frac{E_\gamma - E_{kin}}{c} = \sqrt{2 E_{kin} m}$$

$$\left(\frac{2E_\gamma}{c} - \frac{E_{kin}}{c}\right)^2 = 2 E_{kin} m \cong \frac{4E_\gamma^2}{c^2}\left(1 - \frac{E_{kin}}{2E_\gamma}\right)^2 \cong$$

sorf.

$$\cong \frac{4E_\gamma^2}{c^2}\left(1 + 2\frac{E_{kin}}{2E_\gamma}\right) = 2 E_{kin} m$$

$$\frac{\cancel{4}^{\,2} E_\gamma}{c^2}(E_\gamma + E_{kin}) = \cancel{2} m E_{kin} \cancel{E_\gamma}$$

[illegible]

[illegible]

$$2E_\gamma (E_\gamma + E_{kin}) = mc^2 E_{kin}$$

$$E_{kin}(2E_\gamma - mc^2) = 2E_\gamma^2$$

$$E_{kin} = \frac{2E_\gamma^2}{2E_\gamma - mc^2} \cong 200\,keV$$

4.

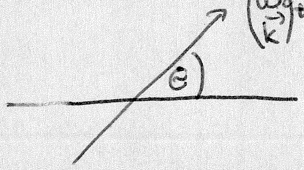
7.

$\pi^0 \to \gamma\gamma$

π^0 rendszerében

$$p^\mu = \begin{pmatrix} m_\pi c^2 \\ \vec{0} \end{pmatrix} \qquad E_{TKP} = p^\mu p_\mu = m_\pi^2 c^4$$

$$\begin{pmatrix} m_\pi c^2 \\ \vec{0} \end{pmatrix} = \begin{pmatrix} \frac{\hbar\omega_1}{c} + \frac{\omega_2 \hbar}{c} \\ \hbar\vec{k}_1 + \vec{k}_2\hbar \end{pmatrix} \qquad \begin{aligned} \vec{k}_1 &= -\vec{k}_2 \\ \omega_1 = \omega_2 = \omega &= \frac{1}{2} m_\pi c^2 \frac{1}{\hbar} \end{aligned}$$



$$\begin{pmatrix} \omega/c \\ \vec{k} \end{pmatrix}\hbar \xrightarrow{\mathcal{L}} \Lambda \begin{pmatrix} \hbar\omega/c \\ \hbar\vec{k} \end{pmatrix}$$

$$\Lambda = \begin{pmatrix} \frac{1}{\sqrt{1-\beta^2}} & 0 & 0 & \frac{\beta}{\sqrt{1-\beta^2}} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \frac{\beta}{\sqrt{1-\beta^2}} & 0 & 0 & \frac{1}{\sqrt{1-\beta^2}} \end{pmatrix}$$

$$p_L^0 = \frac{1}{\sqrt{1-\beta^2}}\left(\frac{\hbar\omega}{c} + \hbar k_z \beta\right) =$$

$$= \frac{1}{\sqrt{1-\beta^2}}\left(\frac{\hbar\omega}{c} + \frac{m_\pi c}{2}\cos\Theta\,\beta\right) = p_L^0$$

$$k_z = |k|\cos\Theta$$

$$p_L^0 = \frac{\hbar\omega}{c\sqrt{1-\beta^2}}(1+\cos\Theta\,\beta) = \frac{E_\pi}{2}(1+\cos\Theta\,\beta) = \frac{m_\pi c^2}{2\cancel{c}\sqrt{1-\beta^2}}(1+\cos\Theta\,\beta)$$

valahol hiányzik egy c

$$\omega = \frac{1}{2} m_\pi c^2 \frac{1}{\hbar}$$

$$\hbar\omega = \frac{1}{2} m_\pi c^2 \qquad \boxed{\omega \sim E_\pi \sim (1+\cos\Theta\,\beta)}$$

$$\boxed{\frac{dN}{d(\cos\Theta)} = \frac{dN}{d\omega}\cdot\frac{d\omega}{d(\cos\Theta)} \sim \frac{dN}{d\omega}}$$

8.) π^0 élettartama $\tau = 0{,}83 \cdot 10^{-16}$ s

Milyen messzire repül

1, 10, 100, 1000 GeV

$$E_{kin} = \frac{mc^2}{2\sqrt{1-\beta^2}} \Rightarrow v = c\sqrt{1 - \frac{m^2c^4}{E^2}} = \ldots$$

$$\cancel{1\,\text{GeV} \quad \frac{1}{2}mv^2 = 1\,\text{GeV} \quad v^2 = \frac{2\,\text{GeV}}{mc^2}c^2 = \ldots}$$

9.

$$\frac{1}{2}mv^2 = \frac{3}{2}k_B T$$

10.

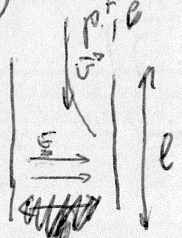
$B = 4{,}5$ T $\qquad p = 63\ \frac{\text{MeV}}{c} \qquad E^2 = p^2c^2 + m^2c^4$

$$\frac{mv^2}{r} = qvB$$

$$p = rqB$$

$$r = \frac{p}{qB}$$

11.



$l = 1$ m

$E = 2000\ \frac{V}{cm}$

Mennyire térül el

$$v_x = c\sqrt{1 - \frac{m^2c^4}{E^2}} \Rightarrow t = \frac{l}{v_x}$$

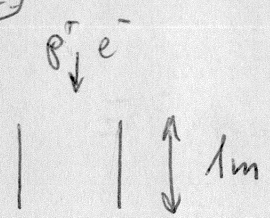
$$F = Eq = ma$$

$$Ft = p = \frac{m v_y}{\sqrt{1-\beta^2}} = Eqt$$

$$\Rightarrow v_y$$

eltérülés $= t\, v_y$

(12)



$B = 2T$ $\qquad v = c\sqrt{1-\frac{m^2c^4}{E^2}} \Rightarrow t$

$$F = Bvq$$

(13)

$\pi \to \mu + \nu_\mu$ $\qquad N(t) = N_0 e^{-\frac{t}{\tau}}$

$\frac{N}{N_0} = e^{-1}$ $\qquad t = \tau$

$$s = vt = ct\sqrt{1-\frac{m^2c^4}{E^2}}$$

(15)

$pp \to p\bar{p}^- pp$

Labor $\qquad$ TKP

$$p_k^\mu = \begin{pmatrix} E_k + 2m_pc^2 \\ \vec{p}_p + \vec{0} \end{pmatrix} \qquad p_v^\mu = \begin{pmatrix} 4m_pc^2 \\ \vec{0} \end{pmatrix}$$

$$p_k^\mu p_{k\mu} = (E_k + 2m_pc^2)^2 - \vec{p}_p^{\,2} = 16 m_p^2 c^4 = p_v^\mu p_{v\mu}$$

$$E_k^2 + 4m_p^2c^4 + 4E_k m_pc^2 - p_p^2 = 16 m_p^2 c^4$$

$$E_k^2 + 4m_pc^2 E_k - 12 m_p^2 c^4 - \underbrace{p_p^2}_{2E_k m_p} = 0$$

$$E_k^2 + (4m_pc^2 - 2m_p)E_k - 12 m_p^2 c^4 = 0$$

$$E_{k_{1,2}} = \frac{(2m_pc^2 - 4m_pc^2) \pm \sqrt{(4m_pc^2 - 2m_pc^2)^2 + 48 m_p^2 c^4}}{2} =$$

$$= \frac{(2000 - 4000) \pm \sqrt{(4000-2000)^2 + 48\cdot 10^6}}{2} =$$

$$= \frac{-2000 \pm \sqrt{4\cdot 10^6 + 48\cdot 10^6}}{2} = \frac{-2000 \pm 7000}{2} = 2{,}5 \text{ GeV}$$

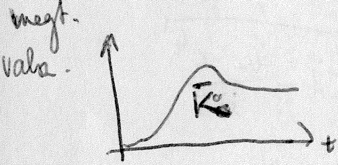
17. u. a. mint 17

18. tehetetlen ~ magok tömege = barionszám - kötési
gravitáló ~ barionszám ⟹ nagy kötési energia: Fe

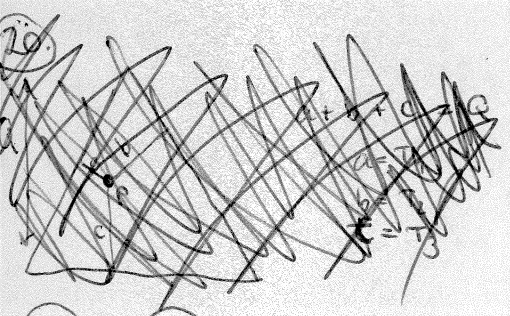
19.
$$|K_j\rangle = e^{-i\left(m_j - i\frac{M_j}{2}\right)t}\,|K_j(0)\rangle \qquad j=1,2 \qquad K_0 = \frac{K_1 + K_2}{\sqrt{2}} \qquad \bar{K}_0 = \frac{K_1 + K_2}{\sqrt{2}}$$

$$\langle \bar{K}^0 | \bar{K}^0 \rangle = \frac{1}{2}\, e^{+i\left(m_1 + i\frac{M_1}{2}\right)t}\, e^{-i\left(m_2 - i\frac{M_2}{2}\right)t}$$

...



20.



28. - 32.

B-B formula

$$\frac{dE}{dx} = \frac{4\pi}{m_e c^2}\,\frac{n z^2}{\beta^2}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\left[\ln\left(\frac{2 m_e c^2 \beta^2}{I\sqrt{1-\beta^2}}\right) - \beta^2\right]$$

proton a vízben

10GeV → ~~...~~ nem integrálható

1MeV

$$R = \int_0^E \frac{dx}{dE}\,dE = \int_0^E \frac{m_e c^2}{4\pi}\,\frac{2E}{c^2 m_p n z^2}\left(\frac{4\pi\varepsilon_0}{e^2}\right)^2 \frac{dE}{\ln\left(\frac{2 m_e 2E}{I m_p}\right)} =$$

$$= \frac{m_e}{2\pi m_p}\,\frac{(4\pi\varepsilon_0)^2}{n z^2 e^4}\int_0^E E\,\frac{1}{\ln\left(\frac{2 m_e 2E}{I m_p}\right)}\,dE = \frac{8\pi\varepsilon_0^2}{z^2 e^4 n} \ \ldots$$

$$\Rightarrow E = (\quad)\ x$$

↑

?

(20) impulzusmegm.

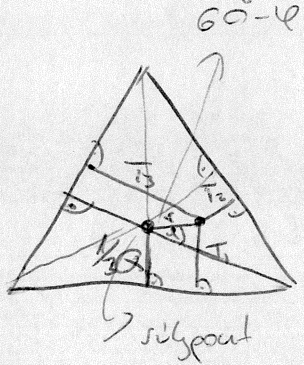
$$p_1 + p_2 + p_3 = 0 \longrightarrow p_3 = -(p_1 + p_2) \Rightarrow p_3^2 = p_1^2 + p_2^2 - 2p_1p_2$$

$$\underset{\substack{\uparrow \\ T_1}}{\frac{p_1^2}{2m}} + \underset{\substack{\uparrow \\ T_2}}{\frac{p_2^2}{2m}} + \underset{\substack{\uparrow \\ T_3}}{\frac{p_3^2}{2m}} = Q \Rightarrow T_3 = T_1 + T_2 + \frac{p_1p_2}{m}$$

$$(p_1p_2)^2 \leq p_1^2 p_2^2$$

$$\Downarrow$$

ide vive vissza $\Rightarrow m^2(T_3 - T_1 - T_2)^2 \leq (2m)^2 T_1T_2$



$$T_1 = \frac{1}{3}Q - r\cos(60° + \varphi)$$

$$T_2 = \frac{1}{3}Q - r\cos(60° - \varphi)$$

$$T_3 = \frac{1}{3}Q + r\cos\varphi$$

addíciós tétellel

$$3r^2(\cos^2\varphi + \sin^2\varphi) = \frac{1}{3}Q^2$$

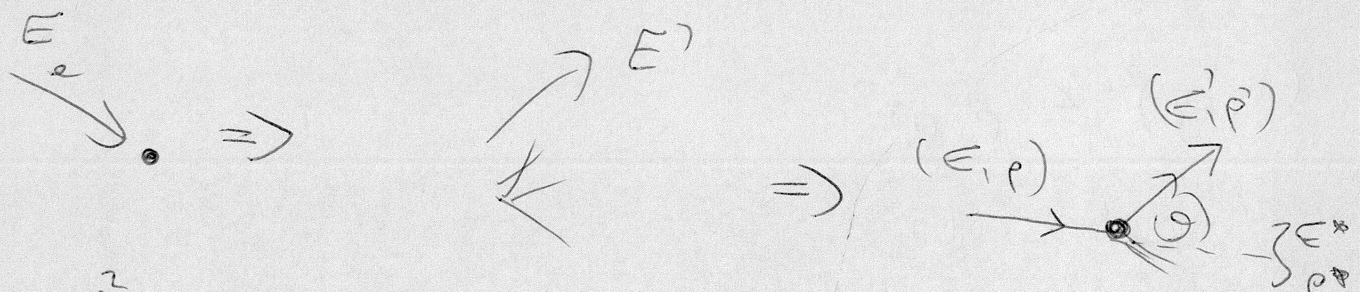
$$r^2 = \frac{1}{9}Q^2$$

(26)

$$N = \frac{V}{(2\pi)^3}\int d^3k \, \frac{1}{e^{\beta\left(\frac{\hbar^2 k^2}{2m}-\mu\right)}+1} = \text{áll}$$

$$E = \frac{V}{(2\pi)^3}\int d^3k \, \frac{\varepsilon}{e^{\beta(\varepsilon-\mu)}+1} = \text{áll}$$

(24)



$p^2 \cong 0$ elhanyagoltuk

$E^{*2} - p^{*2} = W^2$ → tömegjellegű

↑ össz impulzus

összenergiája a végtermékeknek

$\Rightarrow$ $p = q + p'$

$\left.\begin{aligned} p_0 &= \nu + p_0' \\ \vec{p} &= \vec{q} + \vec{p}\,' \end{aligned}\right\}$ ez def $\nu, \vec{q}$-t (impulzus & E átadás)

$$q^2 = (p-p')^2 = \underbrace{(p_0-p_0')^2}_{\nu^2} - (\vec{p}-\vec{p}\,')^2 =$$

$$= \nu^2 - \underbrace{p_0^2}_{E^2} - \underbrace{p_0'^2}_{(E-\nu)^2} - 2 \underset{E}{p_0} \underset{E-\nu}{p_0'} \cos\vartheta$$

$\vec{p}^{\,2} + \vec{p}\,'^2 - 2|\vec{p}||\vec{p}\,'|\cos\vartheta$, $\vec{p}^{\,2} = p_0^2$, $\vec{p}\,'^2 = p_0'^2$ $\Rightarrow$ a tömeg ~ 0.

$E(x) = E_0 e^{-x/x_0}$

$\geq$

E_c eddig megy ez a folyamat

$$x = x_0 \ln \frac{E_0}{E_c}$$

$$\hookrightarrow \quad E(x) = E_0 e^{-\frac{x}{2Z}}$$

$$\Rightarrow \quad x = \frac{2Z}{\ln 2} \ln\left(\frac{E_0}{E_c}\right)$$

$c = 3 \cdot 10^8 \frac{m}{s}$

$\hbar c = 200$ MeV fm

$m_{e^-} = 0{,}5$ MeV

$m_\pi = 135$ MeV

$1\,ly = 9 \cdot 10^{15}$ m

$m_p = 2000 \cdot 0{,}5\,\text{MeV} = m_n$

$1\,eV = 11600\,k_B$

$q_{e^-} = 1{,}6 \cdot 10^{-19}$

$T = \frac{kg}{s^2 A} = \frac{kg}{s\,C}$

$m_{\Omega^-} = 1{,}7$ MeV ← barion (sss)
800 MeV ← mezon ($u\bar{u}+d\bar{d}$)

16

20–25	20
26	26
27	27
33–35	28?
	33