30

IZOSPIN $I_-|u\rangle = I_-|I=\frac{1}{2}, I_3=+\frac{1}{2}\rangle = |I=\frac{1}{2}, I_3=-\frac{1}{2}\rangle = |d\rangle$; $I_+|d\rangle = |u\rangle$

$I_3(u) = +\frac{1}{2}$, $I_3(d) = -\frac{1}{2}$; $I_3(\bar{u}) = -\frac{1}{2}$, $I_3(\bar{d}) = +\frac{1}{2}$

$I_-|\bar{d}\rangle = -|\bar{u}\rangle$; $I_+|\bar{u}\rangle = -|\bar{d}\rangle$

$I_-(|d\bar{d}\rangle - |u\bar{u}\rangle) = -|d\bar{u}\rangle - |d\bar{u}\rangle = -2|d\bar{u}\rangle$

$|\pi^+\rangle = |u\bar{d}\rangle$ $|\pi^0\rangle = \frac{1}{\sqrt{2}}(|d\bar{d}\rangle - |u\bar{u}\rangle)$ $|\pi^-\rangle = |d\bar{u}\rangle$

$I=1$, $I_3 = +1$ $I_3 = 0$ $I_3 = -1$

$d \to s$ $|\pi^+\rangle \to |u\bar{s}\rangle = |K^+\rangle$; $I_3 = \frac{1}{2}$ $|\pi^-\rangle \to |s\bar{u}\rangle = |K^-\rangle$; $I_3 = -\frac{1}{2}$

$u \to s$ $|\pi^+\rangle = |s\bar{d}\rangle = |\bar{K}^0\rangle$; $I_3 = \frac{1}{2}$ $|\pi^-\rangle \to |d\bar{s}\rangle = |K^0\rangle$ $I_3 = -\frac{1}{2}$

VSEH KOMBINACIJ $3 \times 3 = 9$

30.3.

$\frac{1}{\sqrt{3}}(|d\bar{d}\rangle + |u\bar{u}\rangle + |s\bar{s}\rangle) = |\eta_0\rangle$ SINGLET

$|\eta_8\rangle = a|u\bar{u}\rangle + b|d\bar{d}\rangle + c|s\bar{s}\rangle$

$\langle\eta_0|\eta_8\rangle = b + a + c = 0$ $\langle\pi^0|\eta_8\rangle = \frac{1}{\sqrt{2}}(b - a) = 0$

$\Rightarrow b = a$ $2b = -c$

$\Rightarrow |\eta_8\rangle = \frac{1}{\sqrt{6}}(|u\bar{u}\rangle + |d\bar{d}\rangle - 2|s\bar{s}\rangle)$

SPINSKI DEL VALOVNE FUNKCIJE $|\uparrow\uparrow\rangle = |S=1, S_3=+1\rangle$

$S_-|\uparrow\uparrow\rangle = \sum_{i=1}^{2} S_{i-}|\uparrow\uparrow\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle) = |S=1, S_3=0\rangle$

$S_-\left(\frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)\right) = |\downarrow\downarrow\rangle = |S=1, S_3=-1\rangle$

$\left.\right\} S=1$

$\frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle) = |S=0, S_3=0\rangle$ $\left.\right\} S=0$

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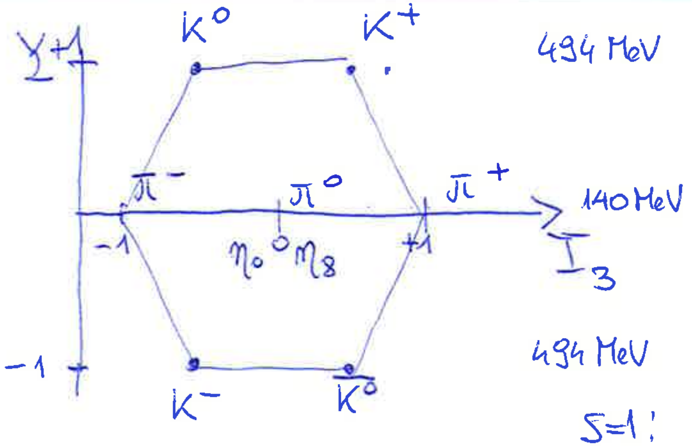
Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Science, Novosibirsk, Russia
February 28 - March 5, 2008

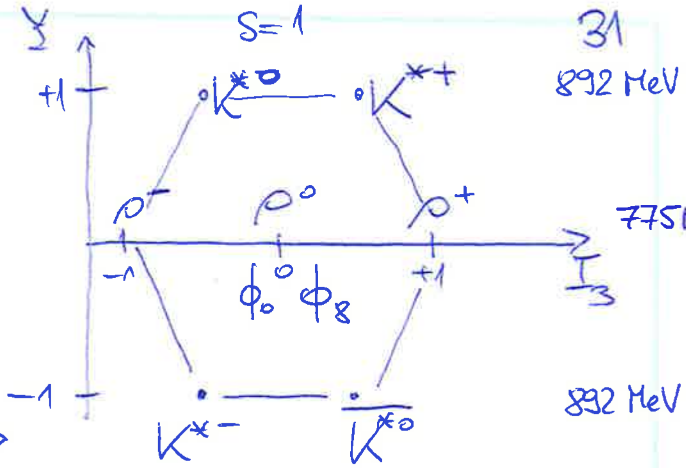
$S=0$



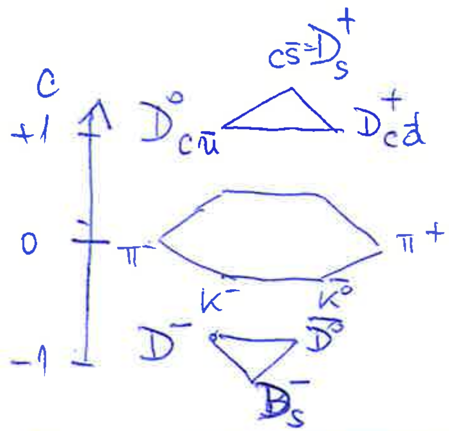
3π, $4\times K$, η_8 : OKTET
η_0 : SINGLET

$|\eta\rangle = \sin\theta\,|\eta_0\rangle + \cos\theta\,|\eta_8\rangle$
$|\eta'\rangle = \cos\theta\,|\eta_0\rangle + \sin\,|\eta_8\rangle$

$S=1$



$S=1$: $|\phi\rangle = \sin\theta'\,|\phi_0\rangle + \cos\theta'\,|\phi_8\rangle$
$|\omega\rangle = \cos\theta'\,|\phi_0\rangle - \sin\theta'\,|\phi_8\rangle$
$\theta' = -0{,}615 \Rightarrow |\phi\rangle \simeq |s\bar{s}\rangle$



$S=0$ $S=1$: D^{*0}, D^{*+}

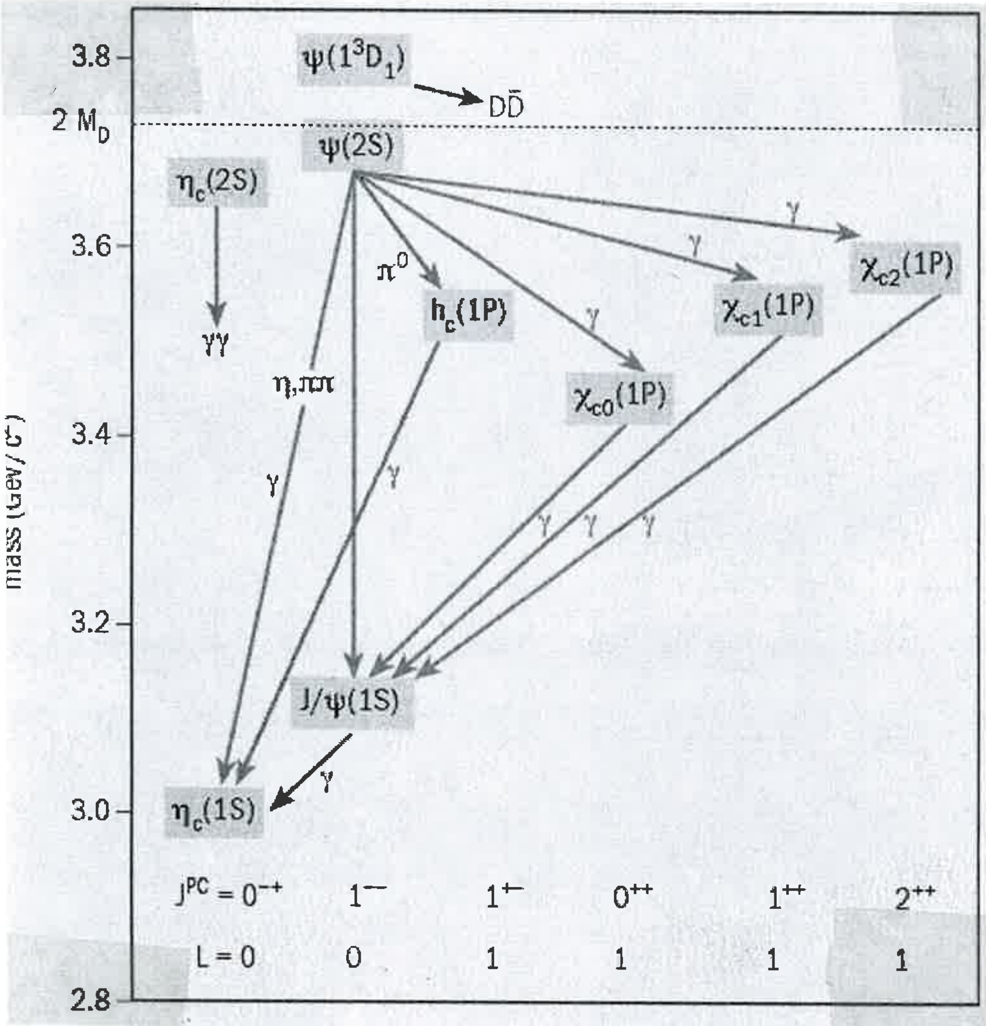
MEZONI S KVARKI c

MEZONI S KVARKI b

$b\bar{d} = \overline{B^0}$, $b\bar{u} = B^-$
$\bar{b}d = B^0$, $\bar{b}u = B^+$

$c\bar{c}$: ČARMONIJ J/ψ, $S=1$ η_c, $S=0$
$mc^2 = 3{,}1$ GeV

POLEG BARIONOV IN MEZONOV : TETRAKVARKI $c\bar{c}u\bar{d} = Z_c^+$ $b\bar{b}u\bar{d} = Z_b^+$
PENTAKVARKI $c\bar{c}uud$



SPEKTER ČARMONIJA $c\bar{c}$

VERJETNOSTNA GOSTOTA, TOK DELCEV, ANTIDELCI

NERELATIVISTIČNO $E = \frac{p^2}{2m}$

$E \to \hat{E} = +i\hbar\frac{\partial}{\partial t} \qquad p \to \hat{p} = -i\hbar\vec{\nabla}$

$\hat{E}\psi = \frac{\hat{p}^2}{2m}\psi \to i\hbar\frac{\partial\psi}{\partial t} + \frac{\hbar^2}{2m}\nabla^2\psi = 0$

$|\psi|^2 = \psi^*\psi$ VERJETNOSTNA GOSTOTA

TOK DELCEV $\vec{j}$

KONTINUITETNA E. $\frac{\partial\rho}{\partial t} + \vec{\nabla}\cdot\vec{j} = 0$

DO IZRAZA ZA TOK PREKO KONT. ENAČBE

$$i\hbar\frac{\partial\psi}{\partial t} + \frac{\hbar^2}{2m}\nabla^2\psi = 0 \;\Big|\cdot i\psi^* \qquad -i\hbar\frac{\partial\psi^*}{\partial t} + \frac{\hbar^2}{2m}\nabla^2\psi^* = 0 \;\Big|\cdot i\psi$$

$$\hbar\psi^*\frac{\partial\psi}{\partial t} \cancel{-} i\frac{\hbar^2}{2m}\psi^*\nabla^2\psi = 0 \qquad \hbar\psi\frac{\partial\psi^*}{\partial t} + i\frac{\hbar^2}{2m}\psi\nabla^2\psi^* = 0$$

$$\psi^*\frac{\partial\psi}{\partial t} + \psi\frac{\partial\psi^*}{\partial t} + \frac{i\hbar}{2m}\left[\psi\vec{\nabla}^2\psi^* - \psi^*\vec{\nabla}^2\psi\right] = 0$$

$$\frac{\partial}{\partial t}(\psi^*\psi) + \frac{i\hbar}{2m}\vec{\nabla}\left[\psi\vec{\nabla}\psi^* - \psi^*\vec{\nabla}\psi - \vec{\nabla}\psi\vec{\nabla}\psi^* + \vec{\nabla}\psi^*\vec{\nabla}\psi\right]$$

$$\frac{\partial}{\partial t}(\psi^*\psi) + \frac{i\hbar}{2m}\vec{\nabla}\cdot\left[\psi\vec{\nabla}\psi^* - \psi^*\vec{\nabla}\psi\right] = 0 = \frac{\partial\rho}{\partial t} + \vec{\nabla}\cdot\vec{j} \Rightarrow \boxed{\vec{j} = \frac{i\hbar}{2m}\left[\psi\vec{\nabla}\psi^* - \psi^*\vec{\nabla}\psi\right]}$$

NARAVNE ENOTE $\boxed{\hbar = 1, \quad c = 1}$ $\hbar c = 197\ \mathrm{MeV\,fm}$, $c = 3.10^8\ \frac{m}{s}$

RAVNI VAL

$$\psi = \frac{1}{\sqrt{V}} e^{i\vec{p}\cdot\vec{r} - iEt} \qquad \vec{p} = \vec{k}, \quad E = \omega$$

$$\rho = \frac{1}{V} = \psi^* \psi \qquad \vec{j} = \frac{i}{2m} \left[\psi \vec{\nabla} \psi^* - \psi^* \nabla \psi\right] = \frac{i}{2m}\left[i\vec{p}\frac{1}{V} - i\vec{p}\frac{1}{V}\right] =$$

$$= \frac{2\vec{p}}{2m}\frac{1}{V} = \frac{\vec{v}}{V} \qquad (\vec{j} = \rho\vec{v})$$

KLEIN-GORDONOVA E.

$$\hat{E}^2 \phi = (\hat{p}^2 + m^2)\phi$$

$$-\frac{\partial^2 \phi}{\partial t^2} + \nabla^2 \phi = m^2 \phi \quad \big| \cdot(-i\phi^*) \qquad -\frac{\partial^2 \phi^*}{\partial t^2} + \nabla^2 \phi^* = m^2 \phi^* \quad \big| \cdot(-i\phi)$$

$$i\left(\phi^* \frac{\partial^2 \phi}{\partial t^2} - \phi \frac{\partial^2 \phi^*}{\partial t^2}\right) - i\left[\phi^* \nabla^2 \phi - \phi \nabla^2 \phi^*\right] = 0$$

$$\frac{\partial}{\partial t}\rho + \vec{\nabla}\cdot\vec{j} = 0$$

$$i\frac{\partial}{\partial t}\left(\phi^* \frac{\partial \phi}{\partial t} - \phi \frac{\partial \phi^*}{\partial t}\right) - i\vec{\nabla}\left[\phi^* \nabla \phi - \phi \nabla \phi^*\right] = 0$$

$$\boxed{\rho = i\left(\phi^* \frac{\partial \phi}{\partial t} - \phi \frac{\partial \phi^*}{\partial t}\right)} \qquad \boxed{\vec{j} = i(\phi \nabla \phi^* - \phi^* \nabla \phi)}$$

ZA RAVNI VAL: $\rho = \frac{2E}{V}$ $\qquad \vec{j} = \frac{1}{V} 2\vec{p}$

NORMALIZACIJA: SCHRÖDING. E. 1 DELEC NA V

KLEIN-GORDON 2E DELCEV NA V

$$d^3x \xrightarrow[\text{LORENTZOVA T.}]{} d^3x \sqrt{1 - \left(\frac{v}{c}\right)^2} \qquad \rho \to \frac{\rho}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \qquad \Big\} \rho\, d^3x \to \rho\, d^3x$$

ČETVEREC ODVODOV

$$\partial^\mu = \left(\frac{\partial}{\partial t}, -\vec{\nabla}\right) \qquad \partial_\mu = \left(\frac{\partial}{\partial t}, \vec{\nabla}\right)$$

$$\partial^\mu \partial_\mu \equiv \sum_{\mu=0}^{3} \partial^\mu \partial_\mu = \frac{\partial^2}{\partial t^2} - \vec{\nabla}^2$$

KLEIN-GORD. $\boxed{(\partial^\mu \partial_\mu + m)\phi = 0}$

KONTINUITET. E. $j^\mu = (\rho, \vec{j}) \Rightarrow \boxed{\partial^\mu j_\mu = 0}$

ANTIDELCI

KLEIN-GORD. E., PROSTI DELEC $\phi = \frac{1}{\sqrt{V}} e^{i p^\mu x_\mu}$

$x_\mu = (t, -\vec{r})$, $p_\mu = (E, -\vec{p})$

$E^2 = p^2 + m^2 \Rightarrow E = \pm\sqrt{p^2+m^2}$ KAJ SO REŠITVE Z $E<0$?

$j^\mu = \frac{2}{V}(E, \vec{p})$ TOK ; ELEKTRONI TOK ZA ELEKTRON $j^\mu = -e_0 \frac{2}{V}(E, \vec{p})$

EL. TOK ZA POZITRON e^+ ! $j^\mu = e_0 \frac{2}{V}(E, \vec{p}) = -e_0 \frac{2}{V}(-E, -\vec{p})$

ANTIDELEC = DELEC Z NEG. ENERGIJO IN $-\vec{p}$ OBR. SMERJO $\vec{p}$

FEYNMAN-STÜCKELBERGOVA INTERPRETACIJA ANTIDELCEV

DIRACOVA ENAČBA

$\hat{H}\psi = i\hbar \frac{\partial \psi}{\partial t}$, $\hat{H}\psi = [\vec{\alpha}\cdot\hat{\vec{p}} + \beta m]\psi$

EN. ZA REL. DELEC S PRVIMI ODVODI $\Rightarrow \hat{H}^2 = \hat{p}^2 + m^2$

$$[\vec{\alpha}\cdot\vec{p} + \beta m]^2 = (\vec{\alpha}\cdot\hat{\vec{p}})^2 + \vec{\alpha}\cdot\vec{p}\,\beta m + \beta m\,\vec{\alpha}\cdot\vec{p} + \beta^2 m^2 =$$

$$(\alpha_1\hat{p}_1 + \alpha_2\hat{p}_2 + \alpha_3\hat{p}_3)(\alpha_1\hat{p}_1 + \alpha_2\hat{p}_2 + \alpha_3\hat{p}_3) + (\alpha_1\hat{p}_1 + \alpha_2\hat{p}_2 + \alpha_3\hat{p}_3)\beta m + \beta m(\alpha_1\hat{p}_1 + \alpha_2\hat{p}_2 + \alpha_3\hat{p}_3)$$

$$+ \beta^2 m^2 = \alpha_1^2\hat{p}_1^2 + \alpha_2^2\hat{p}_2^2 + \alpha_3^2\hat{p}_3^2 + (\alpha_1\alpha_2 + \alpha_2\alpha_1)\hat{p}_1\hat{p}_2 + (\alpha_1\alpha_3 + \alpha_3\alpha_1)\hat{p}_1\hat{p}_3 + (\alpha_2\alpha_3 + \alpha_3\alpha_2)\hat{p}_2\hat{p}_3 +$$

$$+ (\alpha_1\beta + \beta\alpha_1 + \alpha_2\beta + \beta\alpha_2 + \alpha_3\beta + \beta\alpha_3)m + \beta^2 m^2 = \hat{p}^2 + m^2$$

$$\Rightarrow \alpha_1^2 = \alpha_2^2 = \alpha_3^2 = 1 \quad \alpha_1\alpha_2 + \alpha_2\alpha_1 = 0 \quad \alpha_1\alpha_3 + \alpha_3\alpha_1 = 0 \quad \alpha_2\alpha_3 + \alpha_3\alpha_2 = 0 \quad \alpha_i\beta + \beta\alpha_i = 0$$

$\beta^2 = 1$

$\Rightarrow \vec{\alpha}, \beta$ 4x4 MATRIKE $\vec{\alpha} = \begin{bmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{bmatrix}$ $\beta = \begin{bmatrix} I & 0 \\ 0 & -I \end{bmatrix}$

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