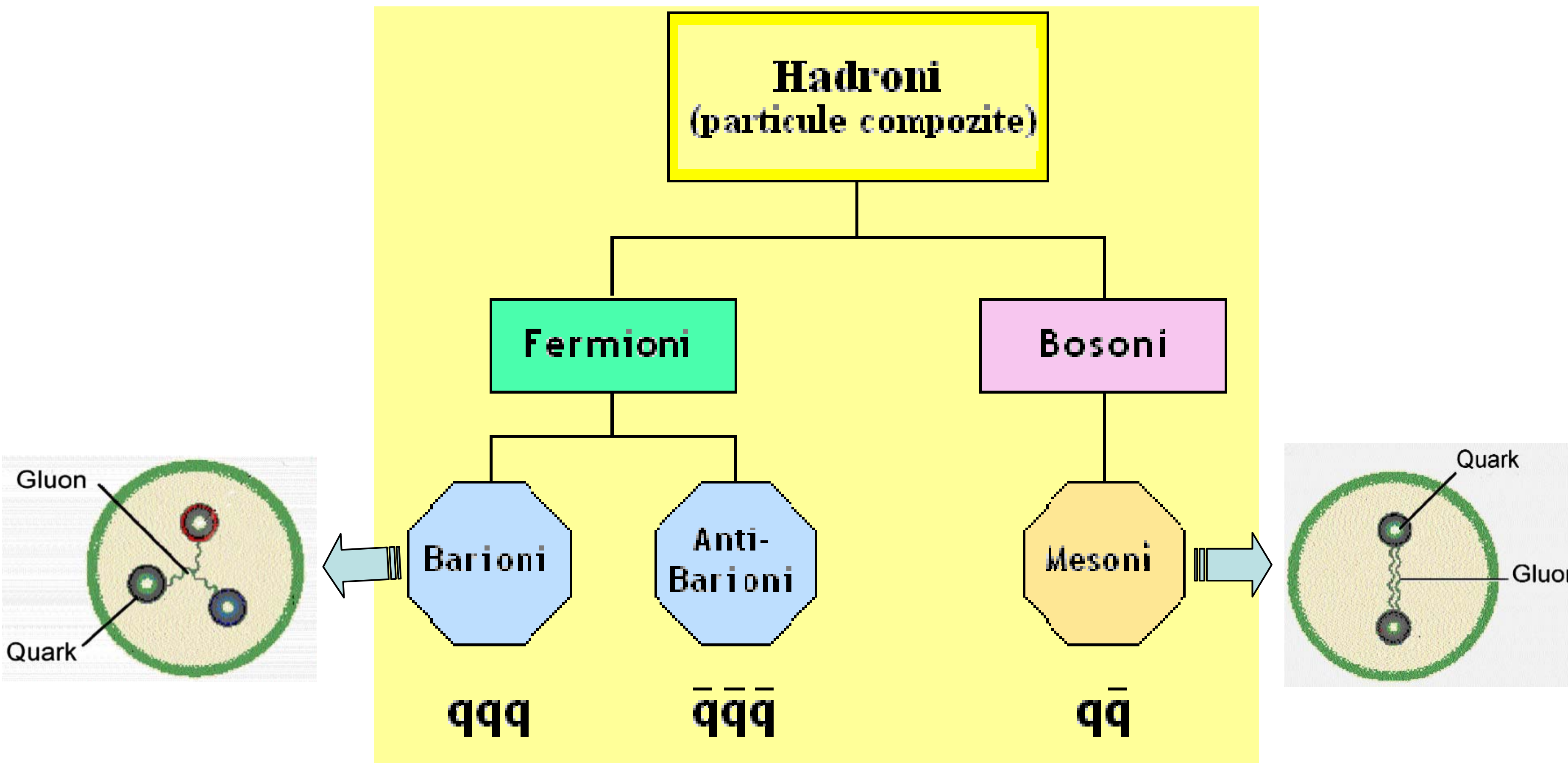
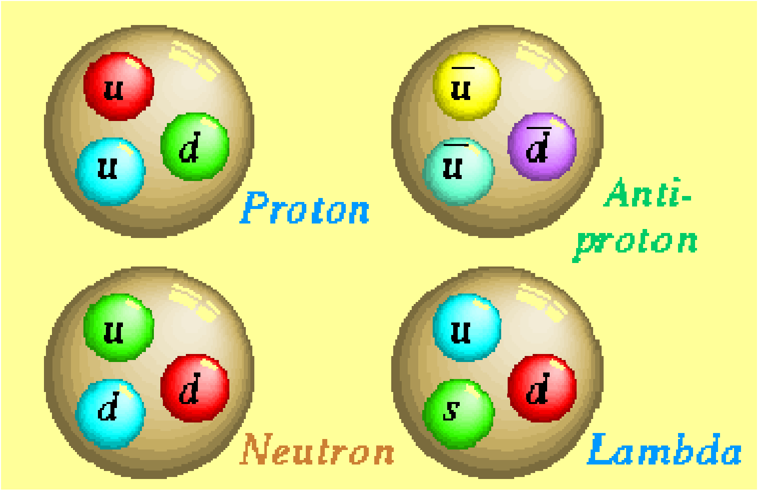
Particule compozite- Hadronii

Particule subatomice, care sunt compuse din două sau mai multe particule elementare ca stări legate de quarci si antiquarci



Hadronii care conțin quarcul strange (s) mai poartă *numele de particule stranii*

Barionii



-particule compozite cu spin semiîntreg (fermioni)-se supun principiului de excluziune Pauli
- sunt formați din 3 quarci sau antiquarci de diferite culori
-masa este mai mare sau egală cu a protonilor
-se dezintegrează prin interactiuni tari
-timpul de viață este sub 10^{-23} s

Fiecare barion trebuie să conțină un bosonul Z şi un boson W

Se considera ca pot exista barioni "exotici", cunoscut sub numele de pentaquarci, deci sunt compusi din patru quarci si un antiquarc, dar existența lor nu este general acceptata. Fiecare barion are o antiparticulă corespunzătoare, numite **anti-barion,** în care quarcii se înlocuiesc cu antiquarci corespunzătoari. În SU(3) hiperonii conțin quarci u, d şi s

Funcția de unda

$$\psi_{\mathrm{baryon}} = \psi_{\mathrm{space}}\psi_{\mathrm{flavour}}\psi_{\mathrm{spin}}\psi_{\mathrm{colour}}$$

ψ_{baryon} antisimetrica la schimbarea a 2 quarci

starea fundameta (L=0)
(momentul unghiular egal cu zero)

$\Rightarrow$ ψ_{space} simetrica

★ **toti hadronii au singleti de culoare**

$$\psi_{colour} = \frac{1}{\sqrt{6}}(rgb+gbr+brg-grb-rbg-bgr)$$

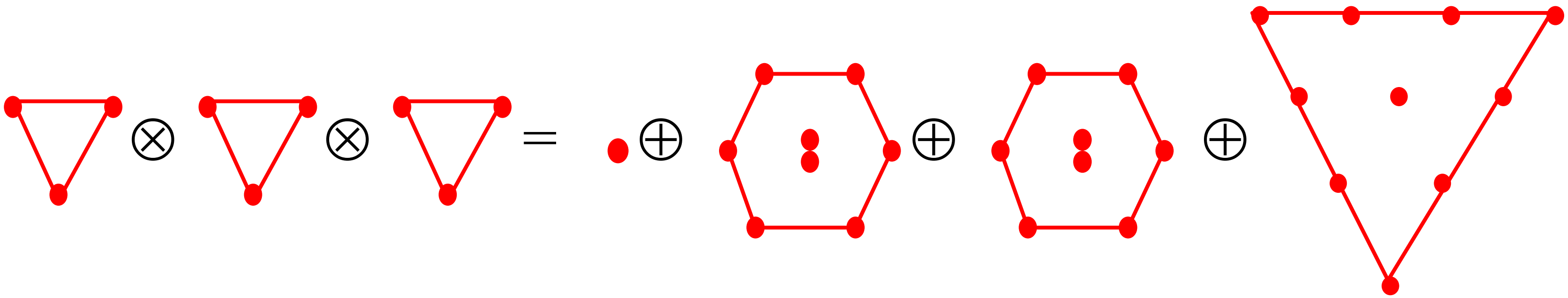
$i.e.$ ψ_{colour} anti-simetrica

prin urmare $\psi_{\mathrm{space}}\psi_{\mathrm{colour}}$ anti-simetrica

$\Rightarrow$ $\psi_{\mathrm{spin}}\psi_{\mathrm{flavour}}$ simetrica

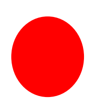
Particula	Simbol	Compozitie	Masa MeV/c^2	Spin	B	S	Timp viata (s)	Mod dezintegrare
Proton	p	uud	938.3	1/2	+1	0	Stable	...
Neutron	n	ddu	939.6	1/2	+1	0	920	$pe^-\underline{\nu}_e$
Lambda	Λ^0	uds	1115.6	1/2	+1	-1	2.6×10^{-10}	$p\pi^-$, $n\pi^0$
Sigma	Σ^+	uus	1189.4	1/2	+1	-1	0.8×10^{-10}	$p\pi^0$, $n\pi^+$
Sigma	Σ^0	uds	1192.5	1/2	+1	-1	6×10^{-20}	$\Lambda^0\gamma$
Sigma	Σ^-	dds	1197.3	1/2	+1	-1	1.5×10^{-10}	$n\pi^-$
Delta	Δ^{++}	uuu	1232	3/2	+1	0	0.6×10^{-23}	$p\pi^+$
Delta	Δ^+	uud	1232	3/2	+1	0	0.6×10^{-23}	$p\pi^0$
Delta	Δ^0	udd	1232	3/2	+1	0	0.6×10^{-23}	$n\pi^0$
Delta	Δ^-	ddd	1232	3/2	+1	0	0.6×10^{-23}	$n\pi^-$
Xi Cascade	Ξ^0	uss	1315	1/2	+1	-2	2.9×10^{-10}	$\Lambda^0\pi^0$
Xi Cascade	Ξ^-	dss	1321	1/2	+1	-2	1.64×10^{-10}	$\Lambda^0\pi^-$
Omega	Ω^-	sss	1672	3/2	+1	-3	0.82×10^{-10}	$\Xi^0\pi^-$, $\Lambda^0 K^-$
Lambda	Λ^+_c	udc	2281	1/2	+1	0	2×10^{-13}	...

În stările de bază, 3 quarci pot forma 3x3x3=27 combinatii care pot fi grupate în 1+8+8+10 stări ireductibile pentru un set de valori (*I*,*S*) . Vom avea, prin urmare, un singlet, 2 octeți şi un decuplet de barioni



Singletul de barioni cu spinul 1/2 este dat de starea antisimetrică sub transformarea aromei, cu functia de unda:

Singlet:

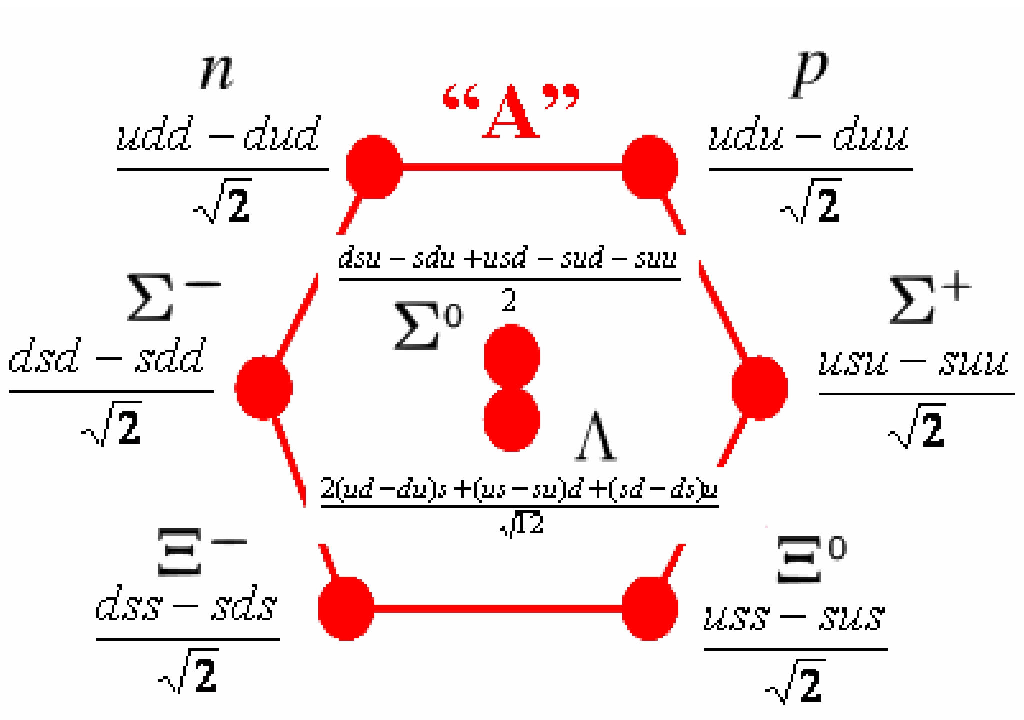


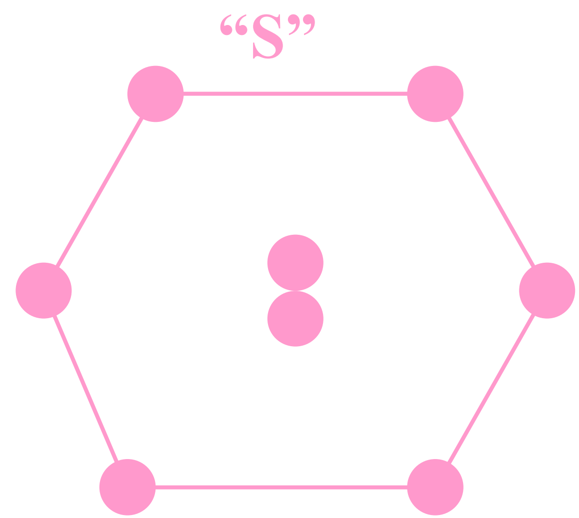
$$\frac{uds-dus-usd-sdu+dsu+sud}{\sqrt{6}}$$

2 Octeți – spin ½ - cu conventiile

“A” asimetric in 1↔2

“S” simetric in 1↔2





dubleti de nucleoni $(N(939))$ și $\Xi(1320)$

$$\begin{pmatrix} uud \\ ddu \end{pmatrix} = \begin{pmatrix} p \\ n \end{pmatrix}$$

$$\begin{pmatrix} ssu \\ ssd \end{pmatrix} = \begin{pmatrix} \Xi^0 \\ \Xi^- \end{pmatrix}$$

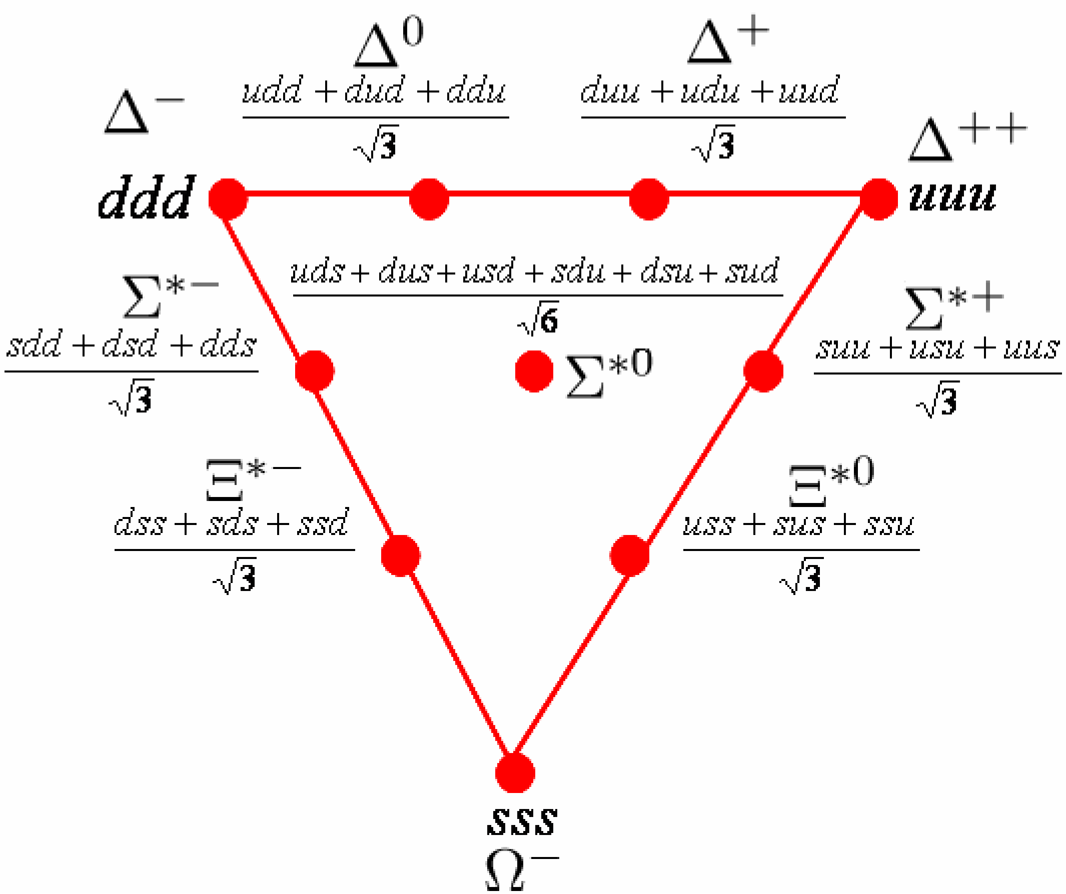
triplet $\Sigma(1190)$ $\begin{pmatrix} uus \\ uds \\ dds \end{pmatrix} = \begin{pmatrix} \Sigma^+ \\ \Sigma^0 \\ \Sigma^- \end{pmatrix}$

singlet

$uds \quad \Lambda(1116)$

Decupleți – spin 3/2

simetric in 1↔2



singlet isotopic $\Omega^-(1672)$

quartet isobari $\Delta(1232)$

$$\begin{pmatrix} uuu \\ uud \\ ddu \\ ddd \end{pmatrix} = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \\ \Delta^{-} \end{pmatrix}$$

triplet isotopic $\Sigma^*(1385)$

$$\begin{pmatrix} uus \\ uds \\ dds \end{pmatrix} = \begin{pmatrix} \Sigma^{*+} \\ \Sigma^{*0} \\ \Sigma^{*-} \end{pmatrix}$$

dublet isotopic $\Xi^*(1530)$

$$\begin{pmatrix} ssu \\ ssd \end{pmatrix} = \begin{pmatrix} \Xi^{*0} \\ \Xi^{*-} \end{pmatrix}$$

Formula masei barionilor (L=0)

$$M_{qqq}=m_1+m_2+m_3+A'\left(\frac{\tilde{S}_1.\tilde{S}_2}{m_1m_2}+\frac{\tilde{S}_1.\tilde{S}_3}{m_1m_3}+\frac{\tilde{S}_2.\tilde{S}_3}{m_2m_3}\right)$$

A' - o constanta

Exemplu $m_1=m_2=m_3=m_q$

deci $M_{qqq}=3m_q+A'\sum_{i<j}\frac{\tilde{S}_i.\tilde{S}_j}{m_q^2}$

$$\tilde{S}^2 = (\tilde{S}_1+\tilde{S}_2+\tilde{S}_3)^2$$

$$\tilde{S}^2 = \tilde{S}_1^{\ 2}+\tilde{S}_2^{\ 2}+\tilde{S}_3^{\ 2}+2\sum_{i<j}\tilde{S}_i.\tilde{S}_j$$

$$2\sum_{i<j}\tilde{S}_i.\tilde{S}_j = S(S+1)-3\tfrac{1}{2}(\tfrac{1}{2}+1)$$

$$2\sum_{i<j}\tilde{S}_i.\tilde{S}_j = S(S+1)-\tfrac{9}{4}$$

$$\sum_{i<j}\tilde{S}_i.\tilde{S}_j = -\frac{3}{4} \qquad J=\tfrac{1}{2} \qquad (\,S{=}3/2\,)$$

$$\sum_{i<j}\tilde{S}_i.\tilde{S}_j = +\frac{3}{4} \qquad J=\tfrac{3}{2} \qquad (\,S{=}1/2\,)$$

proton(uud)

$$m_p = 3m_u-\frac{3}{4}\frac{A'}{m_u^2}$$

Δ(uud)

$$m_\Delta = 3m_u+\frac{3}{4}\frac{A'}{m_u^2}$$

Dand diferite valori pentru $m_{u/d}$ m_s si pentru A', se pot reproduce rezultatele experimentale

Baryon	Mass/MeV Predicted	Mass/MeV Experiment
p/n	939	939
Λ	1116	1114
Σ	1193	1179
Ξ	1318	1327
Δ	1232	1239
Σ^*	1384	1381
Ξ^*	1533	1529
Ω	1672	1682

Concordanta foarte buna se obtine pentru:

$$m_u = m_d = 363 \text{ MeV}$$

$$m_s = 538 \text{ MeV},$$

$$A' = 0.026 \text{ GeV}^3.$$

QCD prezice $A' = A/2$ unde A este valoarea corespondenta pentru formula masei mezonilor

Momentele Magnetice ale barionilor

Considerand quarcii legati in barioni ca particule de masa m_q cu spinul ½ si sarcina fractionara q_q, momentul magnetic de dipol va fi:

$$\hat{\mu}_q = \frac{q_q}{m_q}\hat{S}$$

Iar marimea acestuia:

$$\mu_q = \langle q\uparrow | \frac{q_q}{m_q}\hat{S}|q\uparrow\rangle$$

intrucat $\hat{S}|q\uparrow\rangle = \frac{1}{2}\hbar|q\uparrow\rangle \Rightarrow \mu_q = \frac{q_q\hbar}{2m_q}$

$$\mu_u = \frac{2}{3}\frac{e\hbar}{2m_u}, \mu_d = -\frac{1}{3}\frac{e\hbar}{2m_d}, \mu_s = -\frac{1}{3}\frac{e\hbar}{2m_s}$$

Pentru quarcii legati in barionul X cu L=0, momentul magnetic este suma momentelor magnetice a quarcilor individuali.

$$\hat{\mu}_B = \frac{q_1}{m_1}\hat{S}_1 + \frac{q_2}{m_2}\hat{S}_2 + \frac{q_3}{m_3}\hat{S}_2$$
$$\mu_X = \langle X \uparrow | \hat{\mu}_B | X \uparrow \rangle$$

$|X \uparrow\rangle$ este functia de unda a barionului cu spinul orientat in sus

proton spin-up

$$p\uparrow = \frac{1}{\sqrt{6}}(2u\uparrow u\uparrow d\downarrow - (u\uparrow u\downarrow + u\downarrow u\uparrow)d\uparrow)$$
$$\Rightarrow \mu_p = \frac{1}{6}\langle (2\uparrow\uparrow\downarrow - (\uparrow\downarrow + \downarrow\uparrow)\uparrow) | \hat{\mu}_1 + \hat{\mu}_2 + \hat{\mu}_3 | (2\uparrow\uparrow\downarrow - (\uparrow\downarrow + \downarrow\uparrow)\uparrow)\rangle$$

Contributia unui quarc-up

$$\frac{1}{6}\langle (2\uparrow\uparrow\downarrow - (\uparrow\downarrow + \downarrow\uparrow)\uparrow) | \hat{\mu}_1 | (2\uparrow\uparrow\downarrow - (\uparrow\downarrow + \downarrow\uparrow)\uparrow)\rangle$$
$$= \frac{1}{6}\langle (2\uparrow\uparrow\downarrow - (\uparrow\downarrow + \downarrow\uparrow)\uparrow) | (2\mu_1\uparrow\uparrow\downarrow - (\mu_1\uparrow\downarrow - \mu_1\downarrow\uparrow)\uparrow)\rangle$$
$$= \frac{2}{3}\mu_1 = \frac{2}{3}\mu_u = \frac{4}{9}\frac{e\hbar}{2m_u}$$

Suma contributiei tuturor quarcilor

$$\mu_p = \frac{4}{3}\mu_u - \frac{1}{3}\mu_d = \frac{4}{9}\frac{e\hbar}{2m_u} + \frac{4}{9}\frac{e\hbar}{2m_u} + \frac{1}{9}\frac{e\hbar}{2m_d}$$

$$= \frac{e\hbar}{2m_{u/d}} = \frac{m_p}{m_{u/d}}\mu_N \qquad \mu_N = e\hbar/2m_p$$

predictie

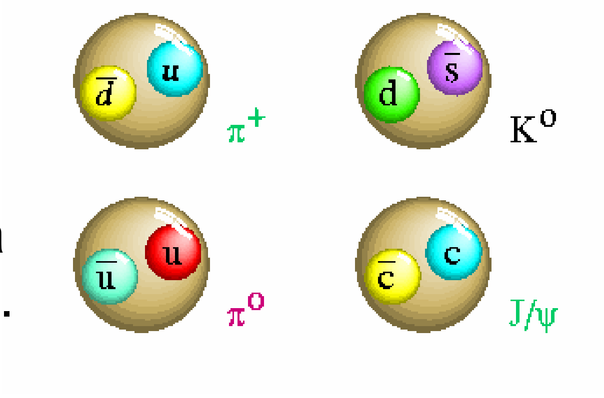
$m_u = m_d$
$= 336$ MeV
$m_s = 509$ MeV

$$\frac{\mu_n}{\mu_p} = -\frac{2}{3}$$

experimental -0.685

Baryon	μ_B in Quark Model	Predicted $[\mu_N]$	Experiment $[\mu_N]$
p	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_d$	$+2.79$	$+2.793$
n	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_u$	-1.86	-1.913
Λ	μ_s	-0.61	-0.614 ± 0.005
Σ^+	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_s$	$+2.68$	$+2.46 \pm 0.01$
Ξ^0	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_u$	-1.44	-1.25 ± 0.014
Ξ^-	$\frac{4}{3}\mu_s - \frac{1}{3}\mu_d$	-0.51	-0.65 ± 0.01
Ω^-	$3\mu_s$	-1.84	-2.02 ± 0.05

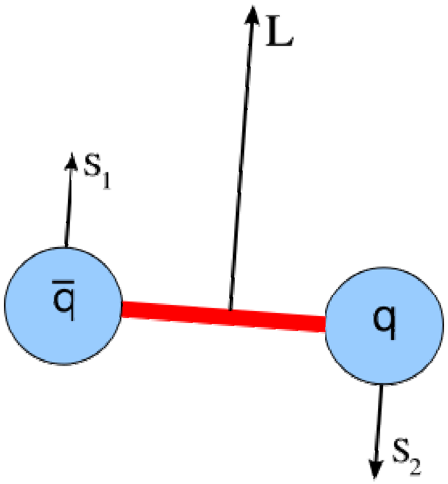
Mezonii



► **mezonii** sunt particule compozite formate din perechi quarc-antiquarc.
► au spin întreg deci sunt bosoni si nu se supun principiului de excluziune Pauli
► deoarece mezonii sunt compuşi din quarci, aceştia se dezintegreaza atat prin interacțiuni slabe cat şi tari.
► fiecare mezon are o antiparticula corespunzătoare (antimezon) în care cuarcii se înlocuiesc cu antiquarcii corespunzătoari

În funcție de modul de cuplaj a momentelor cinetice de spin și orbitale [$J=L+S$] a quarcilor și a parității funcției de undă [$P=(-1)^{L+1}$], există mezoni vectoriali, mezoni pseudovectoriali și mezoni scalari.

Tip de mezon	S	L	P	J	J^P
mezon pseudoscalar	0	0	−	0	0^-
mezon pseudovectorial	0	1	+	1	1^+
mezon vectorial	1	0	−	1	1^-
mezon scalar	1	1	+	0	0^+
mezon tensorial	1	1	+	2	2^+



Funcția de undă

Toți mezonii au singleți de culoare

$$\psi^{q\bar{q}}_{colour} = \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b})$$

În stare fundamentală (*L=0*) avem numai mezoni pseudoscalari (**S=0, J=0**) şi mezoni vectoriali (***S=1, J=1***)

$$\left.\begin{aligned} \pi^0(140) &= \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \\ \eta(550) &= \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}) \\ \eta'(960) &= \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}) \end{aligned}\right\} J^P = 0^-$$

$$\left.\begin{aligned} \rho^0(770) &= \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \\ \omega^0(780) &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \\ \phi(1020) &= s\bar{s} \end{aligned}\right\} J^P = 1^-$$

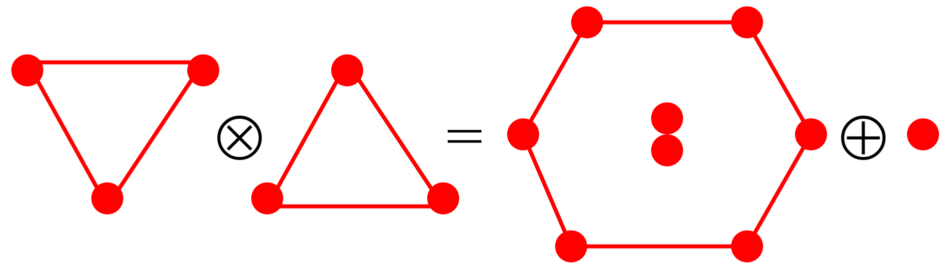
Particula	Simbol	Anti-partic.	Comp	Rest masa MeV/c^2	S	C	B	Timp viata	Dezintegr.
Pion	π^+	π	$u\underline{d}$	139.6	0	0	0	2.60×10^{-8}	$\mu^+ \nu_\mu$
Pion	π^0	*Self*	$\frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$	135.0	0	0	0	0.83×10^{-16}	2γ
Kaon	K^+	K^-	$u\underline{s}$	493.7	+1	0	0	1.24×10^{-8}	$\mu^+ \nu_\mu$, $\pi^+ \pi^0$
Kaon	$K^0{}_s$	$K^0{}_s$	1*	497.7	+1	0	0	0.89×10^{-10}	$\pi^+ \pi, 2\pi^0$
Kaon	$K^0{}_L$	$K^0{}_L$	1*	497.7	+1	0	0	5.2×10^{-8}	$\pi^+ e^- \underline{\nu}_e$
Eta	η^0	*Self*	2*	548.8	0	0	0	$<10^{-18}$	2γ, 3μ
Eta prim	$\eta^{0'}$	*Self*	2*	958	0	0	0	...	$\pi^+ \pi \eta$
Rho	ρ^+	ρ	$u\underline{d}$	770	0	0	0	0.4×10^{-23}	$\pi^+ \pi^0$
Rho	ρ^0	*Self*	$u\underline{u}$, $d\underline{d}$	770	0	0	0	0.4×10^{-23}	$\pi^+ \pi$

Particula	Simbol	Anti-partic	Comp.	Rest masa MeV/c^2	S	C	B	Timp viata	Dezinteg
Omega	ω^0	Self	$u\underline{u}$, $d\underline{d}$	782	0	0	0	$0.8x10^{-22}$	$\pi^+\pi^-\pi^0$
Phi	φ	Self	$s\underline{s}$	1020	0	0	0	$20x10^{-23}$	K^+K^- ,$K^0\underline{K}^0$
D	D^+	D^-	$c\underline{d}$	1869.4	0	+1	0	$10.6x10^{-13}$	K + _, e + _
D	D^0	$\underline{D}^0$	$c\underline{u}$	1864.6	0	+1	0	$4.2x10^{-13}$	[K,μ,e] + _
D	D^+_s	D^-_s	$c\underline{s}$	1969	+1	+1	0	$4.7x10^{-13}$	K + _
J/Psi	J/ψ	Self	$c\underline{c}$	3096.9	0	0	0	$0.8x10^{-20}$	e^+e^-, $\mu^+\mu^-$ ...
B	B^-	B^+	$b\underline{u}$	5279	0	0	-1	$1.5x10^{-12}$	D^0 + _
B	B^0	$\underline{B}^0$	$d\underline{b}$	5279	0	0	-1	$1.5x10^{-12}$	D^0 + _
B_s	B_s^0	$\underline{B}_s^0$	$s\underline{b}$	5370	0	0	-1	...	B^-_s + _
Upsilon	ϒ	Self	$b\underline{b}$	9460.4	0	0	0	$1.3x10^{-20}$	e^+e^-, $\mu^+\mu^-$ ..

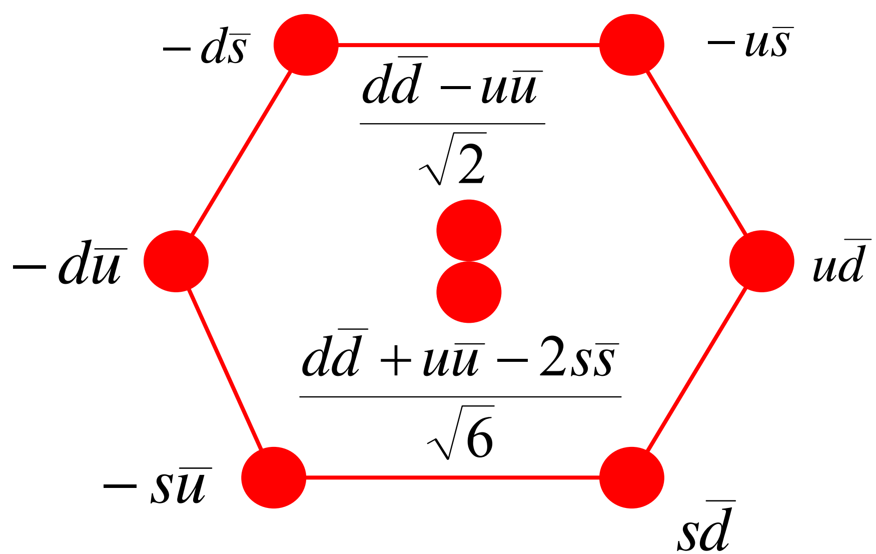
Stari de baza

Cuarcii implicați: u, s, d ; 3x3=9=8+1

$$u\bar{d},\ u\bar{s},\ d\bar{u},\ d\bar{s},\ s\bar{u},\ s\bar{d},\ u\bar{u},\ d\bar{d},\ s\bar{s}$$



Octet:



Singlet:

$$\frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$$

Exemple:

tripletul izotopic π(140) şi ρ (770)

pseudoscalar vectorial

$$\begin{pmatrix} u\bar{d} \\ \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \\ d\bar{u} \end{pmatrix} = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}, \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix}$$

dubletul izotopic K(490) şi K*(890)

pseudoscalar vectorial

$$\begin{pmatrix} u\bar{s} \\ d\bar{s} \end{pmatrix} = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix}, \begin{pmatrix} K^{+*} \\ K^{0*} \end{pmatrix}$$

$$\begin{pmatrix} s\bar{d} \\ s\bar{u} \end{pmatrix} = \begin{pmatrix} \bar{K}^0 \\ K^- \end{pmatrix}, \begin{pmatrix} \bar{K}^{0*} \\ K^{-*} \end{pmatrix}$$

singleții pseudoscalari izotopici η, η'

$$\frac{1}{\sqrt{(6)}}(u\bar{u} + d\bar{d} - 2s\bar{s}) = \eta(550)$$

$$\frac{1}{\sqrt{(3)}}(u\bar{u} + d\bar{d} + s\bar{s}) = \eta'(960)$$

singleții izotopici vectoriali ω, φ

$$\frac{1}{\sqrt{(2)}}(u\bar{u} + d\bar{d}) = \omega(780)$$

$$s\bar{s} = \phi(1020)$$

Formula masei mezonilor (L=0)

$$M_{q\bar{q}} = m_1 + m_2 + A\frac{\tilde{S}_1.\tilde{S}_2}{m_1 m_2}$$

A - o constanta

Pentru o stare de spin $\tilde{S} = \tilde{S}_1 + \tilde{S}_2$

$$\tilde{S}^2 = \tilde{S}_1{}^2 + \tilde{S}_2{}^2 + 2\tilde{S}_1.\tilde{S}_2$$

$$\tilde{S}_1.\tilde{S}_2 = \frac{1}{2}(\tilde{S}^2 - \tilde{S}_1{}^2 - \tilde{S}_2{}^2)$$

$$S_1^2 = S_2^2 = S_1(S_1+1) = \frac{1}{2}(1+\frac{1}{2}) = \frac{3}{4}$$

rezulta $\tilde{S}_1.\tilde{S}_2 = \frac{1}{2}\tilde{S}^2 - \frac{3}{4}$

Pentru mezoni $J^P = 0^-$: $\tilde{S}^2 = 0$

$J^P = 1^-$: $\tilde{S}^2 = S(S+1) = 2$

deci

$$\tilde{S}_1.\tilde{S}_2 = \frac{1}{2}\tilde{S}^2 - \frac{3}{4} = -\frac{3}{4} \quad (0^-)$$

$$\tilde{S}_1.\tilde{S}_2 = \frac{1}{2}\tilde{S}^2 - \frac{3}{4} = +\frac{1}{4} \quad (1^-)$$

Folosind formula masei (L=0)

$$M = m_1 + m_2 - \frac{3A}{4m_1 m_2} \quad (0^-)$$

$$M = m_1 + m_2 + \frac{A}{4m_1 m_2} \quad (1^-)$$

mezonii 0^- mai usori decat mezonii 1^-

Cu diferite valori pentru $m_{u/d}$, m_s si A, se pot reproduce rezultatele experimentale

Meson	Mass/MeV Predicted	Mass/MeV Experiment
π	140	138
K	484	496
ρ	780	770
ω	780	782
K^*	896	894
ϕ	1032	1019

Concordanta foarte buna se obtine pentru:

$$m_u = m_d = 310 \text{ MeV},$$

$$m_s = 483 \text{ MeV},$$

$$A = 0.06 \text{ GeV}^3.$$