Prediction for PENTAQUARK in Relativistic Heavy Ion Collision

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Quarks

Quarks

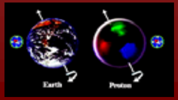
- Quarks are fundamental matter particles that are constituents of neutrons and protons and other hadrons.
- In the present standard model, there are six different quarks.
- Each quark has its anti-quark.
- Each quark type is called a flavor .

Quarks

- Quarks and anti-quarks can successfully account for all known mesons and baryons, which are each constructed from up, down, strange, and charm quarks.
- Quarks are observed to occur only in combinations of two quarks (mesons), three quarks (baryons), and the recently discovered particles with five quarks (pentaquark).

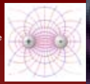
Spin

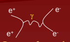
- S = the spin of a particle; similar to how earth spins on its own axis.
- Each quark has spin equal to ½.
- S_z = the z projection of the spin



Color

Electromagnetic force comes from charge + charge − anti-charge





Exchange a neutral photon

Strong force has 3 different kind of charges called “colors”

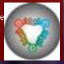
Exchange a gluon which is colored

Hadrons are neutral (White)!

$\bar{R}\ \bar{G}\ \bar{B}$
R G B

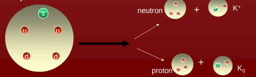
Electromagnetic force tends to form neutral object;
but with enough energy one can ionize them –> charged particle

But strong interaction is strong and doesn’t allow the observation of colored particles. This is known as confinement!

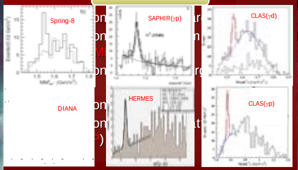


Pentaquark

- It’s called Theta-plus, with a composition of two up quarks, two down quarks and an anti-strange quark
- Mass of 1540 MeV
- Narrow width Γ< 5MeV (~$1.3*10^{-22}$ s)
- Positive 1 charge decays into K^+ n, K_0 p :
  quark content uudd$\bar{s}$

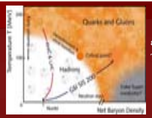


Experiments



What about ultrarelativistic heavy ion collision?

Transition to a QGP phase



QCD
$\varepsilon_c \sim 0.7\ \mathrm{GeV/fm^3}$
$T_c \sim 170$ MeV

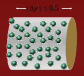
Highest Energy reached on terrestial experiment
RHIC -> Au+Au @ 200 AGeV

How many pentaquarks can you form from this soup?

HADRONIZATION

Fireball before Hadronization

Au+Au @ 200 AGeV



Initial energy density estimation
ε ~5-10 GeV/fm³

- RHIC –> the total energy E_T ~ 750 GeV

T_c =170 MeV

Total quark number according to thermal distribution N_{qtot}~1200

- RHIC –> $\bar{p}/p \sim 0.7 \sim (N_{\bar{q}}/N_q)^3$
- Strange Conservation $N_s=N_{\bar{s}}$

Reconstruct the internal chemistry and the volume

$N_{u,d}=245$, $N_{\overline{u,d}}=218$, $N_{\bar{s}}=149$

$V \sim 1000\ \mathrm{fm^3}$ ($\rho_q \sim 1.2\ \mathrm{fm^{-3}}$)

Coalescence Equation for Mesons

$r = r_1 - r_2$ $\qquad q = \frac{p_1 - p_2}{2}$

$$N_M = g_s g_c \int d^3r_1 d^3r_2 f_q(r_1) f_{\bar{q}}(r_2) \psi(r) \times \int d^3p_1 d^3p_2 f_q(p_1) f_{\bar{q}}(p_2) \psi(q)$$

$f_q(r)$ & $f_q(p)$
Probability of having one quark with position r or momentum p

$\psi(r)$ & $\psi(q)$
Binding probability

$f_q(r_1) f_{\bar{q}}(r_2) \psi(r)$ & $f_q(p_1) f_{\bar{q}}(p_2) \psi(q)$
Probability to form a bound state from two quarks at a distance r, q

Probability in the Spin space

- Quarks recombine to form particles with certain spins.

q
$\bar{q}$

4 combinations
Only one is spin 0
g_s =1/4
Three are spin 1
g_s=3/4

q
q
q

8 combinations
Two are spin ½
g_s=2/8=1/4
Four are spin 3/2
g_s=4/8=1/2

- g_s is then given as the probability of the quarks that recombine having the same spin as the particle you are interested in.
  g_s=(2S+1)/(# of possible recombination)

For 2 quarks -> meson spin 1 g_s=3/4
For 3 quark -> baryon spin ½ g_s=1/4 spin 3/2 g_s=1/2

Coalescence Formula for Mesons

$s=0 \quad \frac{1}{4}\times\frac{1}{9}=\frac{1}{36}$

\# combinations

Probability of them recombining in the momentum space

Number of Mesons

$$N_M = g_M N_q N_{\bar{q}} \frac{(4\pi)^{3/2}\sigma^3}{V} \left(\frac{1}{1+mT\sigma^2}\right)^{3/2}$$

Probability to have a white quark combination with the same spin as the particle of interest.

Probability in the r space that the particles are close enough to form a bound state

Coalescence Equation for Mesons

Assumed V= *uniform*:
Used Non-relativistic Boltzmann

$$\psi(q,r) = e^{-q^2\sigma^2} e^{-r^2/\sigma^2} \qquad \sigma = 0.86\,fm$$

$$f_q(p) = e^{-p^2/2mT}$$

$$N_M = g_s g_c \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} d^3r_1 d^3r_2 e^{-(p_1-p_2)^2\sigma^2} e^{-(r_1-r_2)^2/\sigma^2} e^{-(p_1+p_2)^2/2mT}$$

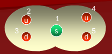
$R = \frac{r_1 + r_2}{2}$ $\quad r_1, r_2 \to R, r$ $\quad P = p_1 + p_2$ $\quad p_1, p_2 \to p, q$

Going to relative coordinates allows to get 4 independent integrals

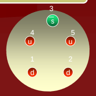
$$N_M = \frac{g_s g_c}{(2\pi)^6} \int_V d^3R \int_{-\infty}^{\infty} d^3r\, e^{-r^2\sigma^2} \int_{-\infty}^{\infty} d^3P\, e^{-P^2/4mT} \int_{-\infty}^{\infty} d^3q\, e^{-q^2(\sigma^2+(mT)^{-1})}$$

Different Scenarios for Pentaquark

Small width

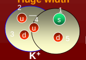


Diquark with “peanut” shape



Harmonic Oscillator

Huge width



Molecular Bound State

Probability in the Color Space

- g_c is given as the probability of having different colored quarks to combine and giving a particle with neutral color.
- g_c=1/(# of possible ways of combining to obtain neutral final color)

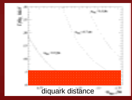
Ex. 2 quarks each 3 colors -> 9 combinations , but only 1 is color neutral
3 quarks -> 27 combinations

Width and Structure

$$\Gamma = \frac{h}{2\pi\tau}$$

Width lifetime

We know from experiments that the Γ < 5 MeV



From the paper D. Melikhov PLB 594 (2004) 265
σ=0.9 fm for diquarks (=proton)
if
σ ~0.6 fm for distance from center of mass to $\bar{s}$ quark
σ> 1.0 fm for distance of diquarks

Γ is independent on the diquarks size but it does depend on the distance from the 2 diquarks

Formula for Pentaquark

$$N_\theta = g_\theta \prod_1^5 N_{q_i} \prod_1^4 \frac{(4\pi)^{3/2}\sigma_i^{\,3}}{V} \left(\frac{1}{1+2\mu_i T\sigma_i^{\,2}}\right)^{3/2}$$

Reduced mass

$$\mu_i = \frac{i+1}{i}\left(\frac{1}{m_{i+1}} + \frac{1}{\sum_{k=1}^{i} m_k}\right)^{-1}$$

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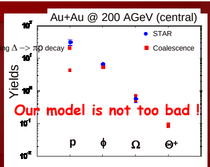
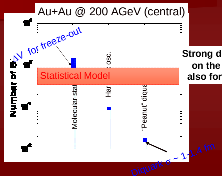
Results

Prediction from Coalescence Model



Our model is not too bad !

Predictions for the three scenarios



Strong dependence on the structure also for the yield !