Fourth Week Report

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On week 4, a motivation on QCD Spectroscopy and Resonance was given by Dr. Raul Briceno. Spectroscopy of atoms and molecules are well studied for the past 100 years but the Spectroscopy of quantum chromodynamic states are not well studied also the QCD spectroscopy is a new field of research compared to atomic or molecular spectroscopy. The theory of quantum chromodynamics is itself far more complicated than the atomic or molecular theory. Also the novelty of the theory rises more open questions. All these factors made the study of the spectroscopy quantum chromodynamic state more tedious.

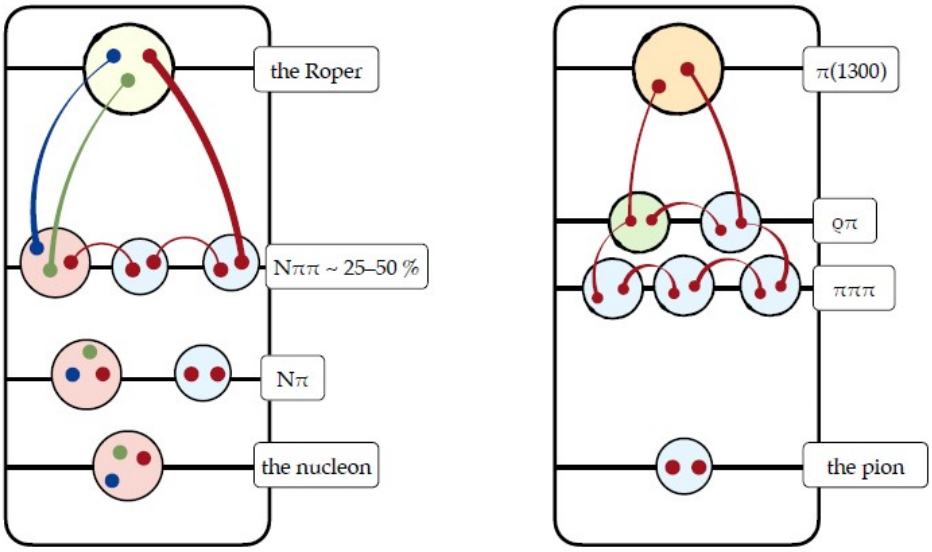

Figure 1: The Spectroscopy of a nucleon and a pion

On the context of QCD, the proton and neutron have a lot of similarities, so they are collectively named as nucleon. The first excited state of nucleon is called the Roper and the first excited state of pion is $\pi(1300)$ which is constitutes the same quark and anti quark pair but lot heavier the pion.

But the first excited state of these particles are so unstable and decay rapidly. Figure(1), we can observe that the Roper, the first excited state of a nucleon, can decay either into a nucleon and a pion ($N\pi$) for about 50 to 70 % of the time or a nucleon and 2 pions ($N\pi\pi$) for about 25 to 50 % of the time. Also the $\pi(1300)$ decays into 3π with intermediate decay as $\varrho\pi$. These particles decay rapidly in the order of 10^{-23} seconds. Because of their short lifetime they are treated as the Resonance states. The 99 % of states of the theory of QCD have this nature of resonance. Thus very few states are stable under strong interactions.

Since the theory of QCD allows lot of possible composite states, we have many composite particles of Baryons and Mesons. The **Particle Data Group** has listed them all in their website https://pdg.lbl.gov/ where they provide all the information regarding the particle of interest like its mass, mean lifetime, decay modes, electric charge etc and all of them are updated often to provide more precision on the data. A screenshot of the webpage is given in the figure(2).

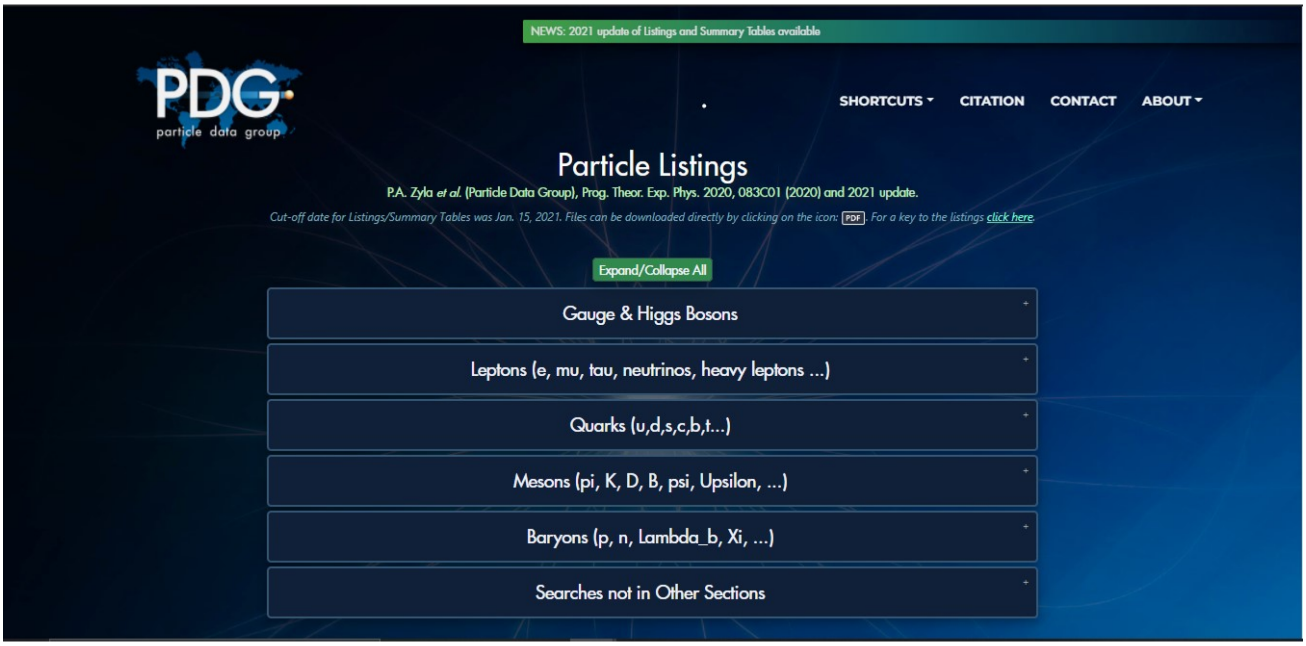

Figure 2: A Screenshot of particle listing in Particle Data Group website

In Table(1), some unflavored mesons and their properties are mentioned where Γ is the reciprocal of the mean life(τ) and the colored texts represent what type of mechanism through which it decays, the violet represents Weak mechanism, the blue represents quantum electrodynamics (QED) and the red represents quantum chromodynamics (QCD)

Particle	Mass	Mean life	Decay channels
π^+	140 MeV	$\sim 3 \times 10^{-8}s$	$\mu^+\nu_\mu$ ($\sim$ 100%)
π^0	135 MeV	$\sim 9 \times 10^{-17}s$	2γ ($\sim$ 99%)
η	550 MeV	$\sim 5 \times 10^{-17}s$ ($\Gamma \sim 1.3$ keV)	$2\gamma(\sim 39\%)$ $3\pi^0(\sim 32\%)$ $\pi^+\pi^-\pi^0(\sim 23\%)$
$f_0(500)/\sigma$	400 - 550 MeV	$\sim 10^{-24}$s ($\Gamma \sim 400 - 700$ MeV)	$\pi\pi(\sim 100\%)$
ρ	770 MeV	$\sim 10^{-23}$s ($\Gamma \sim 147$ MeV)	$\pi\pi(\sim 100\%)$

Table 1: Some unflavored mesons and their properties are tabulated above.

Remember that when a particle undergoes decay process some properties has to be conserved like energy, electric charge etc before and after the decay process. We can infer some observations from the table(1), as the lifetime of the particle decreases, the decaying mechanism goes from weak to QED and to QCD.

The strong nuclear force is very hard to study and comprehend. Since it is hardest to study mathematically and the decay mechanism of a QCD state happens very rapidly thus making hard to resolve them experimentally. Because of this, QCD has many open questions than other sectors inside the standard model.

So when we are interested in the dynamics of QCD, we usually tend to consider a simplified version of standard model where we can remove the weak and electromagnetic force and just considering QCD on its own. Under this assumptions, we can get lot of information about the dynamics of a QCD state.

Under this consideration, we can see that many particles which are unstable in original theory is now stable under this simplified version of standard model. These states are known as ”QCD stable” states. For example,

1. π^+ which predominantly decays into $\mu^+\nu_\mu$ i.e. decay through weak mechanism. Since in the simplified version of the theory we turn off Weak force and electromagnetic force, this above decay process is not allowed. Thus making the π^+ particle stable i.e. $\tau \to \infty$.

2. π^0 which predominantly decays through QED mechanism as 2γ. Under our simplified version of the theory, this process is not allowed. Thus π^0 is stable i.e. $\tau \to \infty$ under this consideration.

3. Similarly neutron, n which decays into $pe^-\nu_e$. This process is also not allowed in the simplified version of the theory. Thus n is stable i.e. $\tau \to \infty$ under this consideration.

Initially, the simplified version of the standard model may seems like an overkill but it is not. This is because most of the heavier QCD states decay into other lighter QCD states. Therefore many QCD states remain unstable even in this simplified version of standard model. These states are ”QCD unstable” and some of them are listed below,

1. $\eta \to 3\pi$
2. $f_0(500)/\sigma \to 2\pi$
3. $\rho \to 2\pi$
4. $\omega \to 3\pi$
5. $\eta' \to \pi^+\pi^-\eta$
6. $f_0(980) \to \pi\pi/K\bar{K}$

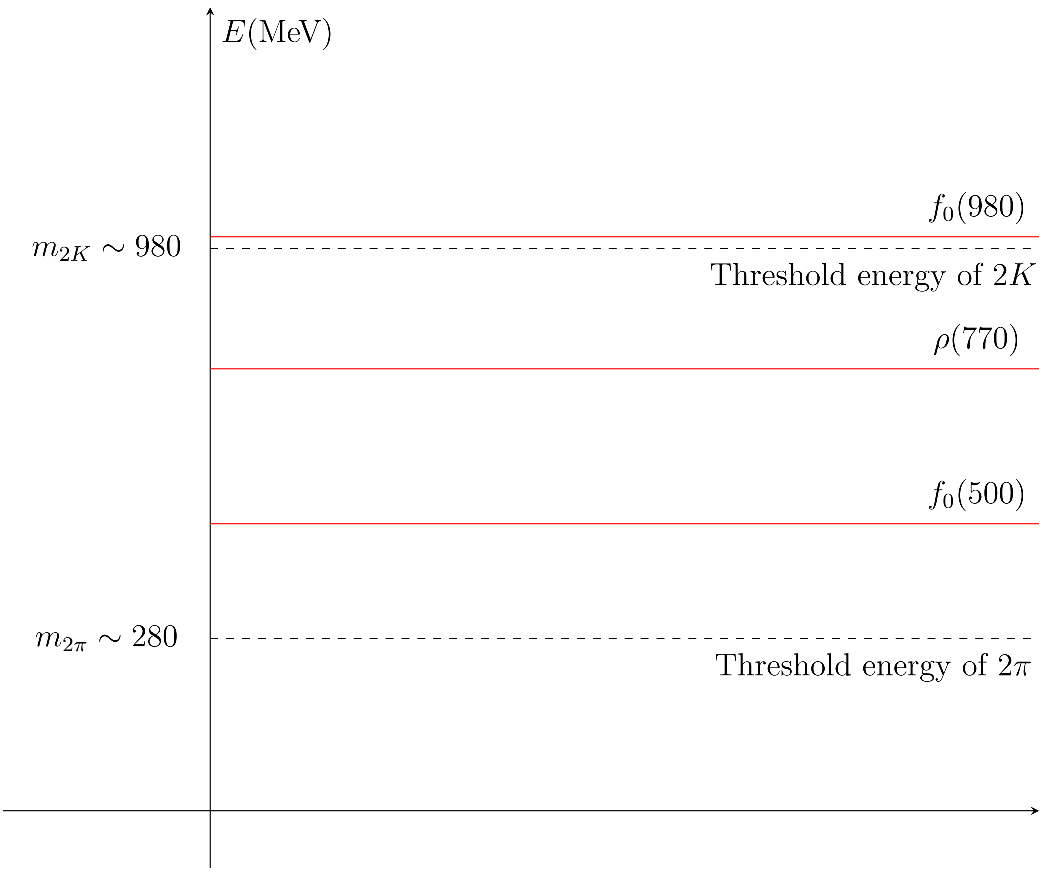

Figure 3: Possible decay channels available for some unstable QCD states are also shown.

From figure(3) we can observe that the $f_0(500)$ and $\rho(770)$ have enough energy to decay into 2π but not enough to decay into $2K$ i.e. into $K\bar{K}$. But the state $f_0(980)$ has enough energy to decay into $\pi\pi$ and also has enough energy to decay into $K\bar{K}$. The mechanism for the decay of $f_0(980)$ into $K\bar{K}$ is slightly more complicated than the mechanism for the decay of $f_0(980)$ into $\pi\pi$.

In the figure(4) we can see that how different laboratories creates the Hadronic resonance which is in this case $\rho(770)$

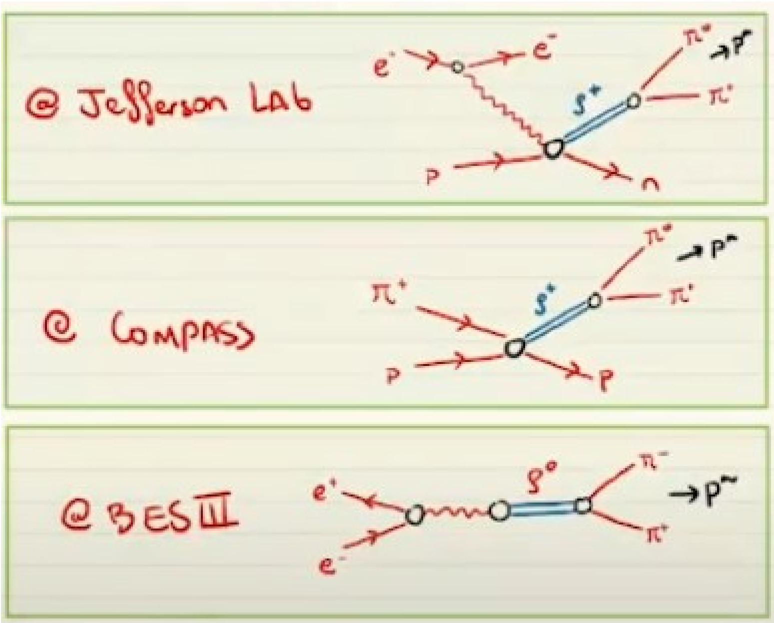

Figure 4: Different approach to create $\rho(770)$ around the different laboratories

In conclusion, we can make some remarks about the Resonances:

1. *Resonance are universal*, they are independent on the mechanism of their production.
2. *Their presence is less obvious in some experiment*, i.e. if their producing coupling is small, it is easier to miss them.
3. *Resonance states must decay into few body states.* Thus, the physics of resonances will also drive into physics of mechanism of few bodies.