MAGNETIC MOMENT OF CHARMED BARYON

Patrick Robbe for **Emi KOU (LAL)**

Workshop on electromagnetic dipole moments of unstable particles, 3-4 October 2019 at LAL

MAGNETIC MOMENT OF ELEMENTARY PARTICLES

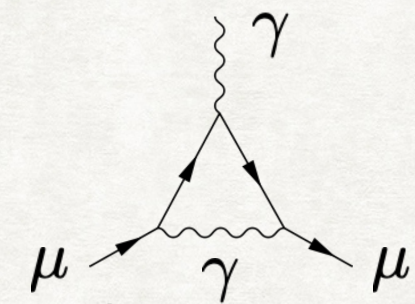
LEPTON, PROTON AND QUARK

- The spin 1/2 particle such as leptons (electron, muon…) have a magnetic moment of the form

$$\mu = \frac{g}{2}\frac{|e|Q}{2m}$$

$g_{electron}=2.00231930436182 \pm (2.6\times10^{-13})$

where Q and m are the charge and mass of the particle.



- The g factor is 2 at the classic level while it is slightly modified by the quantum effect. This correction is called anomalous magnetic moment and defined as a=(g-2)/2.

- There is a longstanding question of muon anomalous magnetic moment: the experiment is 3.6 sigma away from experiment (hint of new physics?)

$a_\mu^{exp.}=11659\,2091(54)(33) \times 10^{-11}$.

$a_\mu^{the.}=116591803(1)(42)(26) \times 10^{-11}$

3.6σ effect!

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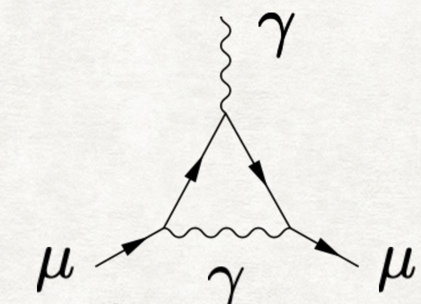
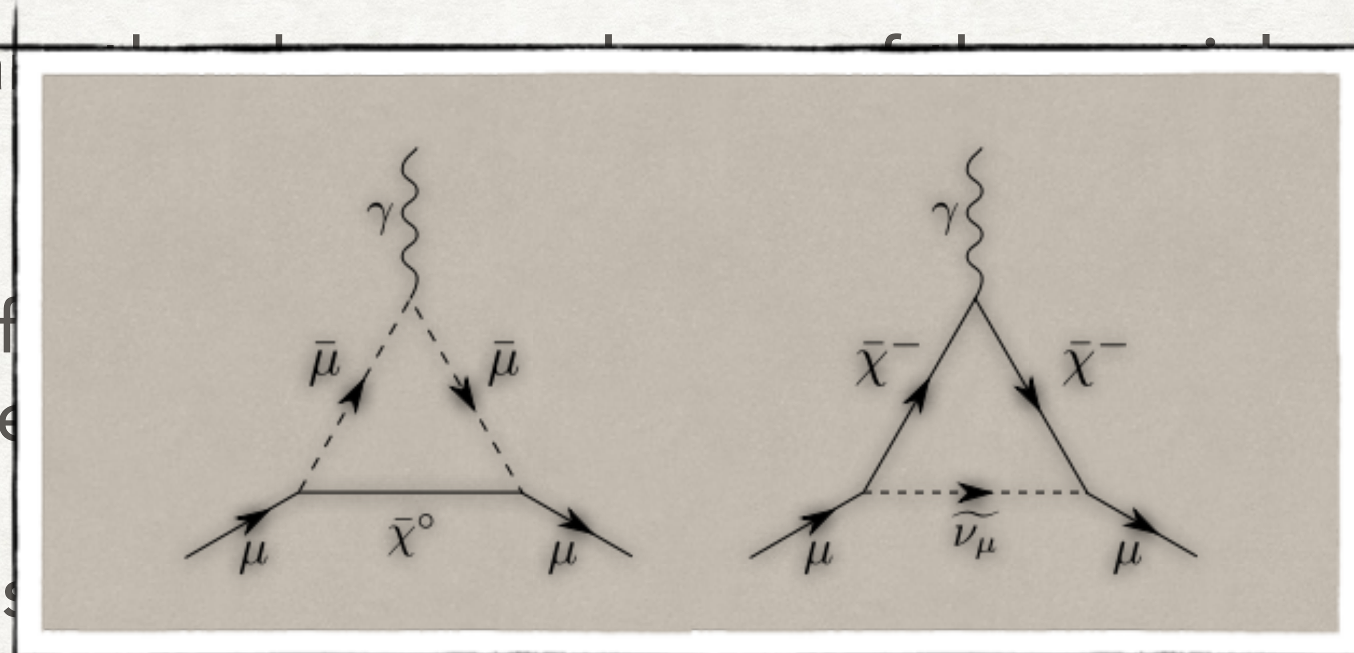


where Q and m a



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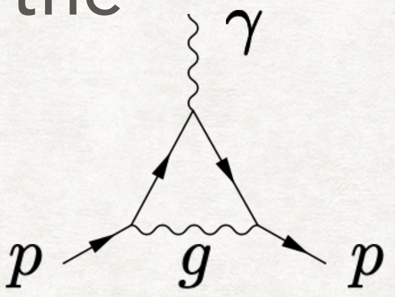
MAGNETIC MOMENT OF ELEMENTARY PARTICLES

LEPTON, PROTON AND QUARK

- The proton magnetic moment is also measured very precisely. But how do we interpret this result?

g_{proton}=5.585694702(17)

- If we consider the proton to be a fundamental particle, the magnetic moment can be written as



$$\mu = \frac{g_P}{2} \frac{|e|}{2m_P}$$

- g>>2 can be understood by a large strong interaction effect?

- The proton is not a fundamental particle. So this may not be the solution…

μ_M=lel/2M_P is called the nuclear magneton

PROTON MAGNETIC MOMENT IN QUARK MODEL

- In quark model, magnetic moment of proton is a sum of the magnetic moment of the constituent quark (up-up-down) with fully symmetric spin configuration.

$$\mathbf{M} = \sum_q \mathbf{M}_q \qquad \mathbf{M}_q = \mu \frac{e_q}{e} \sigma_q$$

μ=|e|/2M_q

where q is the constituent quark and σ is the spin operator

$$\Psi^{\text{proton}}_{\text{spin+flavor}} = [2\,u\uparrow u\uparrow d\downarrow - u\downarrow u\uparrow d\uparrow - u\uparrow u\downarrow d\uparrow + 2\,u\uparrow d\downarrow u\uparrow - u\downarrow d\uparrow u\uparrow - u\uparrow d\uparrow u\downarrow + 2\,d\downarrow u\uparrow u\uparrow - d\uparrow u\downarrow u\uparrow - d\uparrow u\uparrow u\downarrow]/\sqrt{18},$$

- Then the magnetic moment of proton is computed as

$$\begin{aligned}\mu_p &= \langle \phi_P | \mathbf{M}_u + \mathbf{M}_u + \mathbf{M}_d | \phi_P \rangle \\ &= \frac{1}{18}(4 \times 3(2e_u - e_d) + 6 \times e_d)\mu \\ &= \mu = \frac{|e|}{2m_q}\end{aligned}$$

Similar to the previous result but now, the denominator is not proton mass but quark mass!

Using the constituent quark mass m_q=1/3 m_P, we find g_q=1.86

PROTON MAGNETIC MOMENT IN QUARK MODEL

- In addition, since it is known that the large portion of the proton spin is actually carried by the gluons, gluon contributions to the magnetic moment has to be considered.
- On the other hand, the quark model can predict the relation of proton and neutron/Lambda magnetic moment without quark mass dependence

$$\mu_N = -\frac{2}{3}\mu_p, \qquad \mu_\Lambda = -\frac{1}{3}\mu_p$$

g_{proton} = 5.585694702(17)
$g_{neutron}$= - 3.82608545(90)
g_{lambda}= - 1.226(8)

which is satisfied well by the experiment.

- In any case, the proton magnetic moment is an input for various theoretical computations, it is important to measure it very precisely.

CHARMED BARYON MAGNETIC MOMENT

- Proposal to measure directly MDM of charm baryons discussed during the workshop

- It will be the first direct measurement of the magnetic moment of the charmed baryon.

- Different from light baryon, spin is known to be carried mostly by the heavy quark (charm quark) —> direct connection to the charm quark (anomalous) magnetic moment.

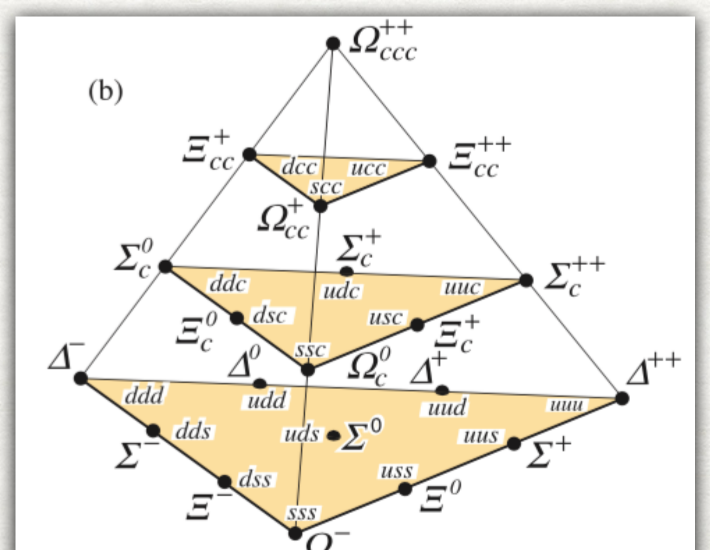
- LHCb are producing many new results on charmed baryon (e.g. discovery of doubly charged charmed baryon!) and charmed baryon spectroscopy is becoming very interesting.

BARYON SPECTROSCOPY
CHARMED BARYONS

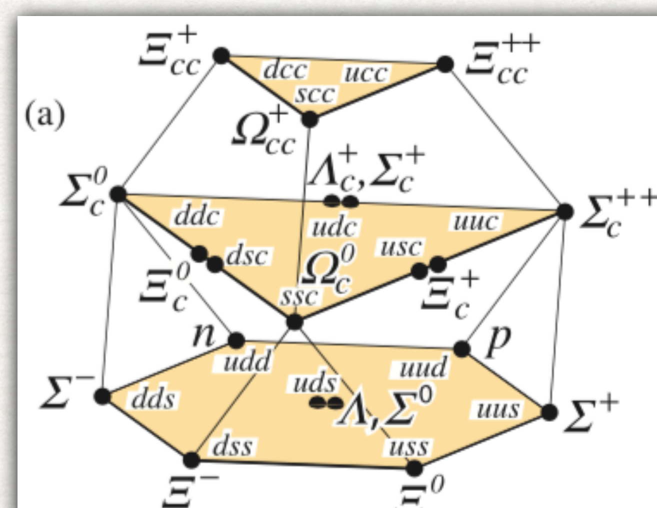
- Let us now include charm quark. SU(4) symmetry for 3 quark states

$$4 \otimes 4 \otimes 4 = 20_s \oplus 20_s \oplus 20_a \oplus 4_a$$

- Considering charmed baryons, this results in 6 spin 3/2 baryons and 9 spin 1/2 baryons.
- Different from the light baryons, not only Λ_c (*udc*) and Σ_c^+ (*udc*), but also Ξ_c^+ (*usc*) and Ξ_c^0 (*dsc*) are no longer degenerated.
- New names are NOT given to these particles but to distinguish them, they are sometimes called (Ξ_{c1}, Ξ_{c2}) or (Ξ_c, Ξ_c').



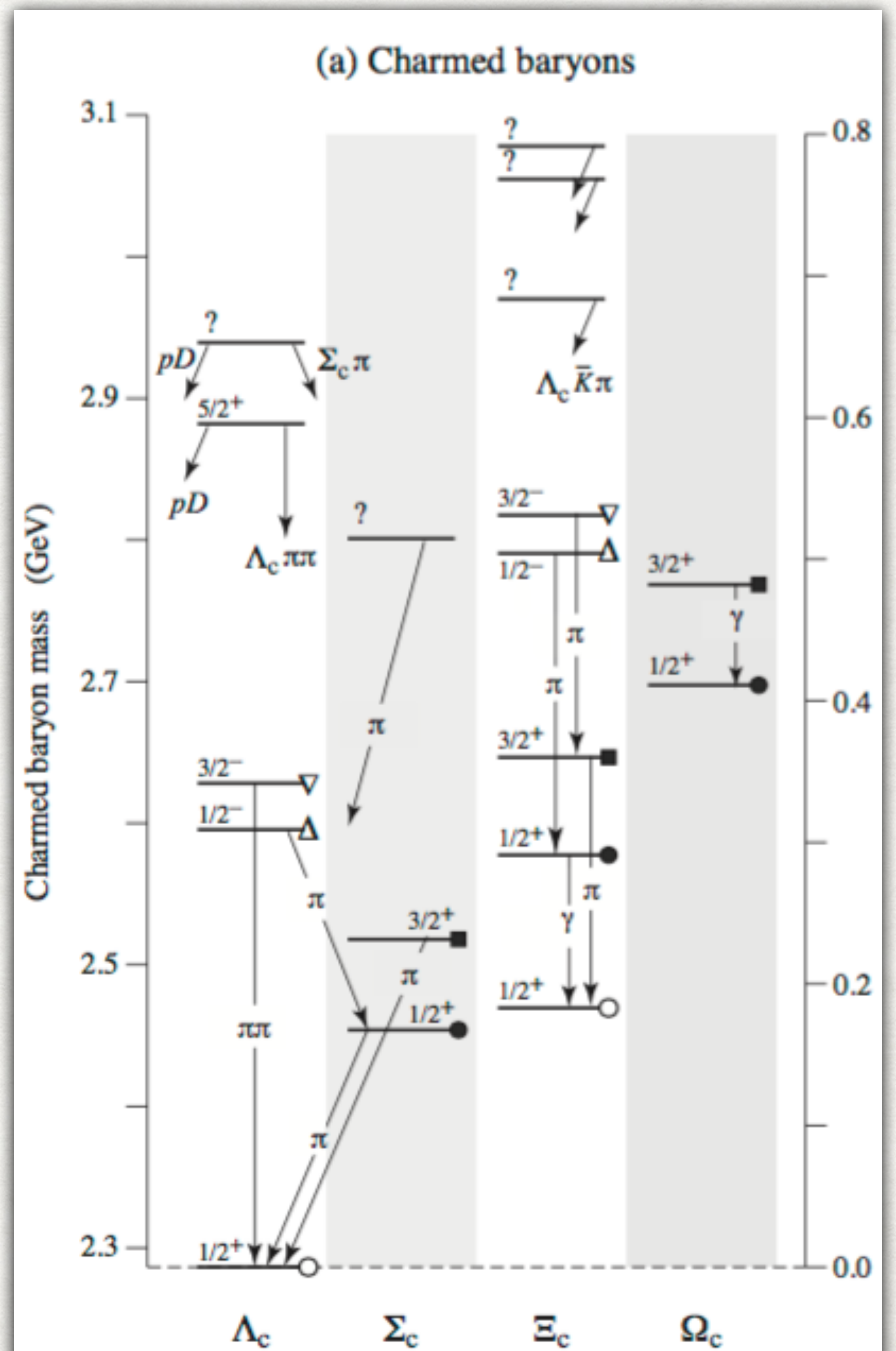
J=3/2 totally-symmetric decuplet



J=1/2 mixed-symmetry octet

QUESTION OF TWO Ξ_c STATES

Ξ_{c1}^+, Ξ_{c2}^+???



At heavy quark limit :

- ○: the anti-symmetric 1/2 ($\Lambda_c, \Xi_{c1}^+, \Xi_{c1}^0$)
- ●: the symmetric 1/2 ($\Sigma_c^0, \Xi_{c2}^+, \Xi_{c2}^0$)
- ■: the symmetric 3/2 ($\Sigma_c^{0*}, \Xi_c^{+*}, \Xi_c^{0*}$)

But this has never been confirmed…
The observed state can be a mixture of Ξ_{c1} and Ξ_{c2}. How can we distinguish?

We show below that
magnetic moment, which measures directly the quark spin-configuration, is the most powerful tool to distinguish different charmed baryon states!

Λ_C MAGNETIC MOMENT

- We compute the Λ_c (*udc*, spin anti-symmetric state) magnetic moment in the quark model. The result turns out that Λ_c magnetic moment is equal to the charm quark magnetic moment.

$$\mu_{\Lambda_c} = \langle \phi_{\Lambda_c} | \mathbf{M}_u + \mathbf{M}_d + \mathbf{M}_c | \phi_{\Lambda_c} \rangle$$

$$= \mu_c$$

- Using the definition

$$\mu_{\Lambda_c} \left(= \frac{g_{\Lambda_c}}{2} \frac{|e|Q_c}{2m_P} \right) = \mu_c \left(= \frac{g_c}{2} \frac{|e|Q_c}{2m_c} \right)$$

the measurement of $g_{\Lambda c}/2$ can be translated to the charm quark magnetic moment $g_c/2$

$$\frac{g_{\Lambda_c}}{2} = \frac{m_{\Lambda_c}}{m_c} \frac{g_c}{2}$$

- If the measured $g_{\Lambda c}/2$ is far from $m_{\Lambda c}/m_c$~1.3-1.9 (m_c=1.2-1.8 GeV) then, that is an indication of large anomalous magnetic moment of charm quark.

- Nevertheless, the quantitative statement is model-dependent (interactions of heavy quark and photons inside the hadron, ...).

$$\frac{\mu(\Lambda_c^+)}{\mu_N} = 0.37\text{–}0.42,$$

Brown mock argument…

OTHER CHARMED BARYON MAGNETIC MOMENT

- Spin anti-symmetric state

~0.39N.M .

$$\mu_{\Xi_c^{0,+}} = \mu_c$$

which is the same as Λc magnetic moment

Corrections to the relation
Savage et al PLB326 ('94)
Banuls et al PRD61 ('00)

- Spin symmetric state

$$\mu_{\Sigma_c^+} = -\frac{1}{3}\mu_c + \frac{2}{3}\mu_u + \frac{2}{3}\mu_d, \quad \mu_{\Sigma_c^0} = -\frac{1}{3}\mu_c + \frac{4}{3}\mu_d$$

~0.54N.M .

@SU(3) limit
$\mu_{\Sigma c}=\mu_{\Xi c'}$

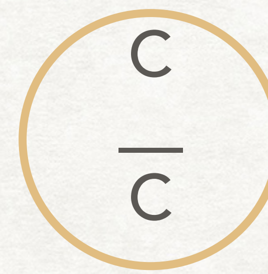
~– 1.46N.M.

$$\mu_{\Xi_c'^+} = -\frac{1}{3}\mu_c + \frac{2}{3}\mu_u + \frac{2}{3}\mu_s, \quad \mu_{\Xi_c'^0} = -\frac{1}{3}\mu_c + \frac{2}{3}\mu_d + \frac{2}{3}\mu_s$$

If heavy quark limit is correct and Ξc (Ξc') state is purely anti-symmetric (symmetric) state, we would observe
$\mu_{\Lambda c}=\mu_{\Xi c^0} \gg \mu_{\Xi c^{0\prime}}$

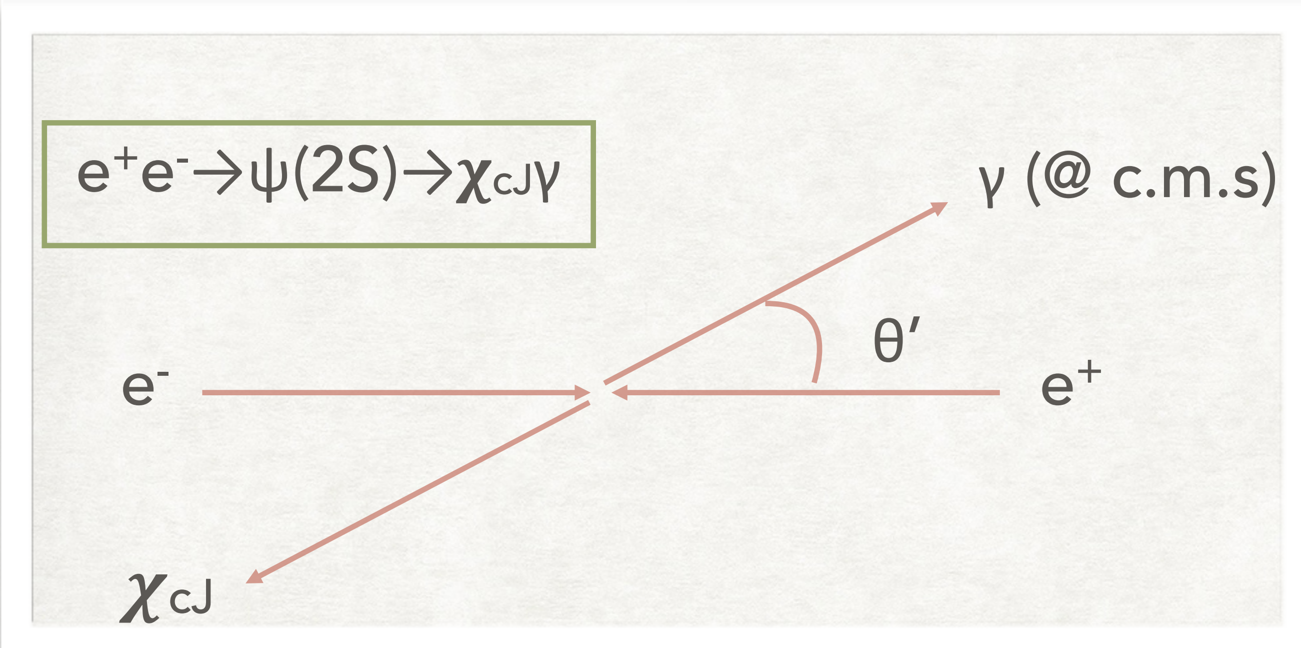
PREDICTING Λ_c MAGNETIC MOMENT WITH BESIII RESULT

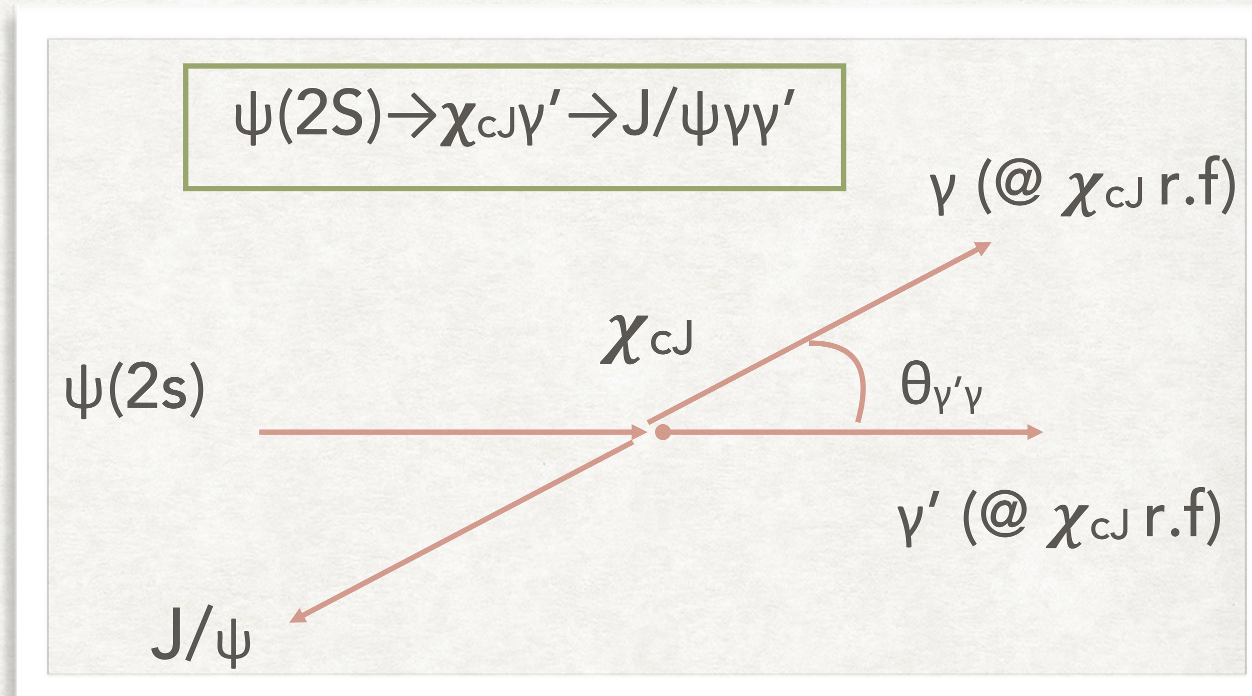
Karl et al PR D13 '76

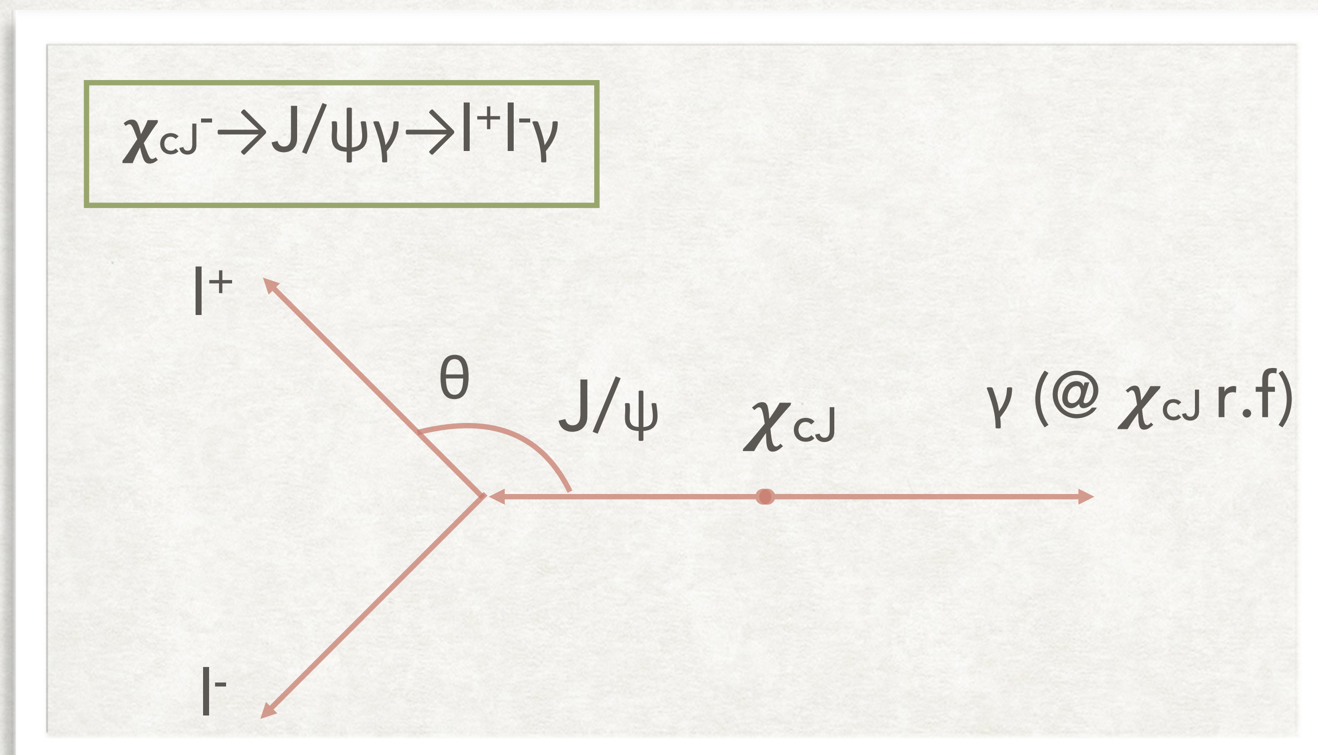


$$c: \left(\frac{\vec{r}}{2}, \frac{\vec{v}}{2}, \vec{\sigma_1}\right) \qquad \bar{c}: \left(-\frac{\vec{r}}{2}, -\frac{\vec{v}}{2}, \vec{\sigma_2}\right)$$

The charm quark magnetic moment can be determined by the charmonium radiative decays







5 angles to disentangle different contributions

$(\theta, \varphi, \theta', \theta_{\gamma'\gamma}, \varphi_{\gamma'\gamma})$

PREDICTING Λ_C MAGNETIC MOMENT WITH BESIII RESULT

a_i^J, b_i^J = helicity amplitudes

arXiv: 1701.01197 (also see CLEO 0910.0046)

TABLE I. Fit results for $a^J_{2,3}$ and $b^J_{2,3}$ for the process of $\psi(3686) \to \gamma_1\chi_{c1,2} \to \gamma_1\gamma_2 J/\psi$; the first uncertainty is statistical, and the second is systematic. The $\rho^J_{a_{2,3}b_{2,3}}$ are the correlation coefficients between $a^J_{2,3}$ and $b^J_{2,3}$.

χ_{c1}	$a^1_2 = -0.0740 \pm 0.0033 \pm 0.0034$, $b^1_2 = 0.0229 \pm 0.0039 \pm 0.0027$ $\rho^1_{a_2b_2} = 0.133$
χ_{c2}	$a^2_2 = -0.120 \pm 0.013 \pm 0.004$, $b^2_2 = 0.017 \pm 0.008 \pm 0.002$ $a^2_3 = -0.013 \pm 0.009 \pm 0.004$, $b^2_3 = -0.014 \pm 0.007 \pm 0.004$ $\rho^2_{a_2b_2} = -0.605$, $\rho^2_{a_2a_3} = 0.733$, $\rho^2_{a_2b_3} = -0.095$ $\rho^2_{a_3b_2} = -0.422$, $\rho^2_{b_2b_3} = 0.384$, $\rho^2_{a_3b_3} = -0.024$

theory

$b^1_2/b^2_2 = 1.35 \pm 0.72,$ ←1.000±0.015

$a^1_2/a^2_2 = 0.617 \pm 0.083.$ ←0.676±0.071

Extracting anomalous magnetic moment

error from charm mass mc=1.5±0.3 GeV

$$1+\kappa = -\frac{4m_c}{E_{\gamma_2}[\chi_{c1} \to \gamma_2 J/\psi]}a^1_2$$

$$= 1.140 \pm 0.051 \pm 0.053 \pm 0.229, \quad = \frac{g_c}{2}$$

PREDICTING Λ_C MAGNETIC MOMENT

- Using the BES III data, we can predict magnetic moment of Λc

$$g_c/(2m_c) = 0.76 \pm 0.05\ \text{GeV}^{-1} \rightarrow \mu_{\Lambda c} = (0.48 \pm 0.03)\mu_N$$

without charm mass ambiguity.

This value should be compared with theoretical predictions (where charm quark mass is often obtained from other observable)

$$\frac{\mu(\Lambda_c^+)}{\mu_N} = 0.37\text{–}0.42,$$

which implies a slightly higher charm anomalous magnetic moment (g_c>2?).

Higher precision measurements on BOTH at a few % precision desired!

magnetic moment of Λc

&

charm radiative decays

CONCLUSIONS

- Charm quark magnetic moment has never been measured directly.
- A new idea to measure the magnetic moment of charmed baryon $\mu_{\Lambda c}$, using the bent-crystal is proposed (a hight precision expected). $\mu_{\Lambda c}$ can be translated to the magnetic moment of charm quark, μ_{c}.
- We showed that the measurement of various charmed baryon, such as Ξ_c can provide important information on the charmed baryon spectroscopy.
- Charmonium radiative decay can indirectly provide the charm quark magnetic moment. Using BESIII result, we made an estimate on $\mu_{\Lambda c}$. We found that the obtained value of $\mu_{\Lambda c}$ is slightly higher than the theory predictions.
- Thus, we conclude that a few % level precision for both Λ_c polarisation and the radiative charmonium decays are desired.
- We are currently working on LHCb measurement of polarisation and weak parameter of Λ_c, which is a crucial factor for $\mu_{\Lambda c}$ determination.

BARYON SPECTROSCOPY

LIGHT BARYONS

- Let us start with the light baryons. SU(3) symmetry for 3 quark states

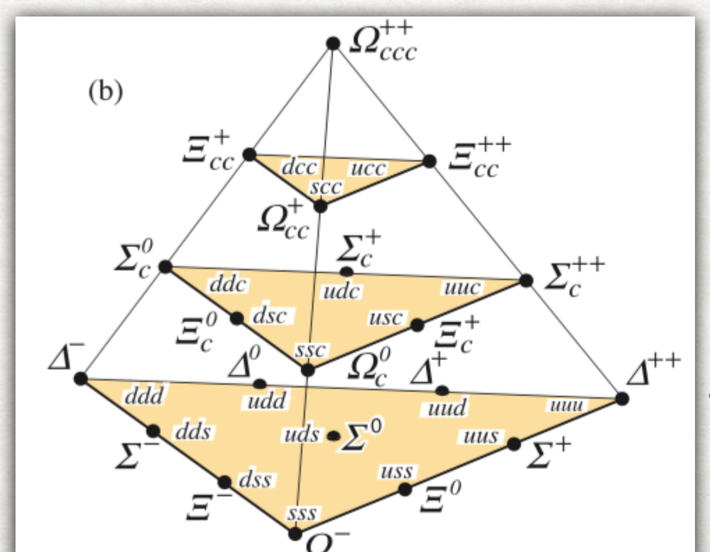
$$3 \otimes 3 \otimes 3 = 10_s \oplus 8_s \oplus 8_a \oplus 1_a$$

where s and a corresponds to symmetric and anti-symmetric of flavour, e.g.

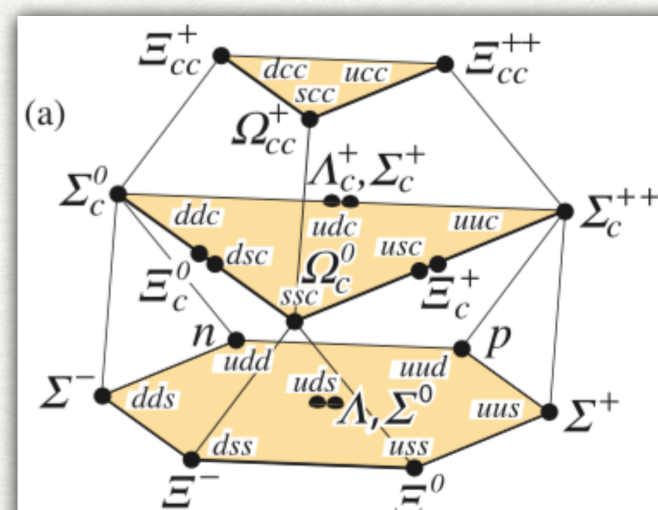
$$Symmetric: \qquad uuu, ddd, \frac{1}{\sqrt{2}}\left[ud + du\right]u, \frac{1}{\sqrt{2}}\left[us + su\right]u \cdots$$

$$Anti-Symmetric: \qquad \frac{1}{\sqrt{2}}\left[ud - du\right]u, \frac{1}{\sqrt{2}}\left[us - su\right]u \cdots$$

- This results in 10 spin 3/2 baryons and 8 spin 1/2 baryons



J=3/2
totally-symmetric
decuplet



J=1/2
mixed-symmetry
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where s and a corresponds to symmetric and anti-symmetric of flavour, e.g.

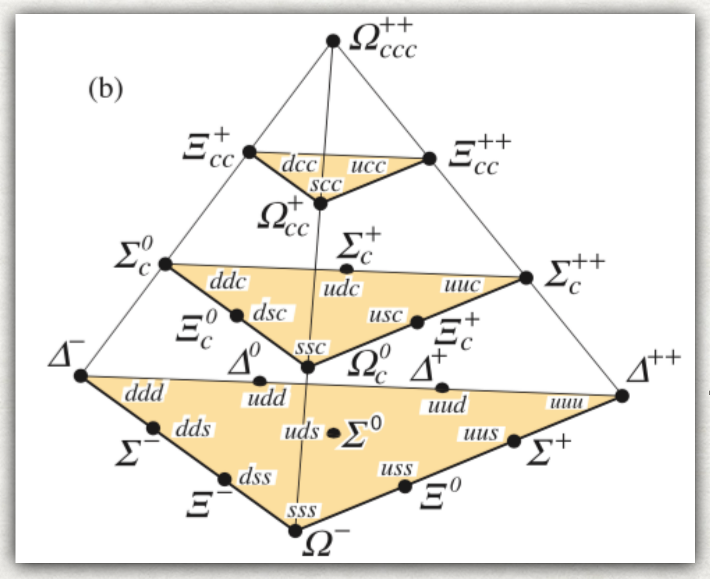
NOTE ON OCTET STATES:

8s and 8a states are mixed.

The qqq’ sates (like proton=uud), multiplying with the spin symmetry, they turn out to have exactly the same wave function.

For Λ and Σ^0 (uds states), the wave function is different: Λ is anti-symmetric and Σ^0 is symmetric.

- This



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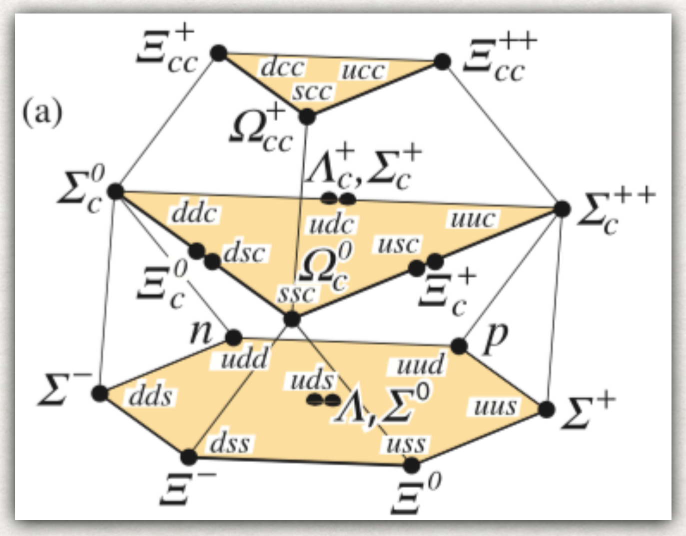

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