Baryonic Decays

Rong -Gang Ping, Mo Xiao-Hu

1 baryonic decays

1.1 Theoretical framework

Exclusive decays of J/ψ into baryon anti-baryon ($B\bar{B}$) have been investigated by many authors in the framework of perturbative QCD (pQCD) [1, 2, 3, 4], for recent review see Ref. [5]. The dominant dynamical mechanism is $c\bar{c}$ annihilation into the minimal number of gluons allowed by symmetries and subsequent creation of light quark-antiquark pairs forming the final state hadrons. The pQCD calculation is based on the factorization scheme, i.e., the non-perturbative factor of the hadronic properties is described by the wavefunctions, and the hard process is described by pQCD approach as shown in Fig. 1.1. The decay amplitude is expressed as a convolution of a hard scattering amplitude and a factor that involves the charmonium wave functions for the initial state and the baryonic wave for the final state. As shown in [6], the charmonium wave function can be organized into a hierarchy according to the scaling with the velocity of the c quark in the charmonium. The Fock expansions of the charmonium states start as:

$$\begin{aligned}
|J/\psi\rangle &= \underbrace{|c\bar{c}_1(^3S_1)\rangle}_{\mathcal{O}(1)} + \underbrace{|c\bar{c}_8(^3P_J)\,g\rangle}_{\mathcal{O}(v)} + \underbrace{|c\bar{c}_8(^3S_1)\,gg\rangle}_{\mathcal{O}(v^2)} + \ldots, \\
|\ \eta_c\ \rangle &= \underbrace{|c\bar{c}_1(^1S_0)\rangle}_{\mathcal{O}(1)} + \underbrace{|c\bar{c}_8(^1P_1)\,g\rangle}_{\mathcal{O}(v)} + \underbrace{|c\bar{c}_8(^1S_0)\,gg\rangle}_{\mathcal{O}(v^2)} + \ldots, \\
|\ \chi_{cJ}\rangle &= \underbrace{|c\bar{c}_1(^3P_J)\rangle}_{\mathcal{O}(1)} + \underbrace{|c\bar{c}_8(^3S_1)\,g\rangle}_{\mathcal{O}(v)} + \ldots,
\end{aligned} \tag{1}$$

where the subscripts at the $c\bar{c}$ pair specify whether it is in a colour-singlet (1) or colour-octet (8) state; $\mathcal{O}(1)$, $\mathcal{O}(v)$ and $\mathcal{O}(v^2)$ are the orders to which the corresponding Fock states contribute, once evaluated in a matrix element.

As shown in Ref [7], the P-wave charmonium decays into baryon anti-baryon pair are suppressed by a factor of $1/M$ relative to the S-wave charmonium decays. For the charmonium decays into $B\bar{B}$, the decay amplitude can be expressed by:

$$\mathcal{M} \sim f_c\phi_c(x) \otimes f_N\phi_N(x) \otimes f_{\bar{N}}\phi_{\bar{N}} \otimes T_H(x), \tag{2}$$

where T_H is the hard perturbative part, and f_i and ϕ_i are the decay constant and the hadronic wave function for charmonium and baryon/anti-baryon, respectively. It is easy to use the power counting on (2) to compare the S-wave charminium and P-wave charmonium, as well as the color singlet and octet contributions the decay width. For vector charmonia decays into $B\bar{B}$, the decay amplitudes are dependent on the large scale M as:

$$\begin{aligned}
\mathcal{M}_S^{(1)} &\sim M\frac{f_c^{(1)}}{M}\left(\frac{f_N}{M^2}\right)^2 \sim \frac{1}{M^4} \\
\mathcal{M}_S^{(8)} &\sim M\frac{f_c^{(1)}}{M^2}\left(\frac{f_N}{M^2}\right)^2 \sim \frac{1}{M^5}.
\end{aligned} \tag{3}$$

For example in case of J/ψ decays into $B\bar{B}$, the color octet contribution is suppressed by energy scale $1/M$. Therefore, the color octet contribution can be neglected in the decay of a S-wave. However, for P-wave

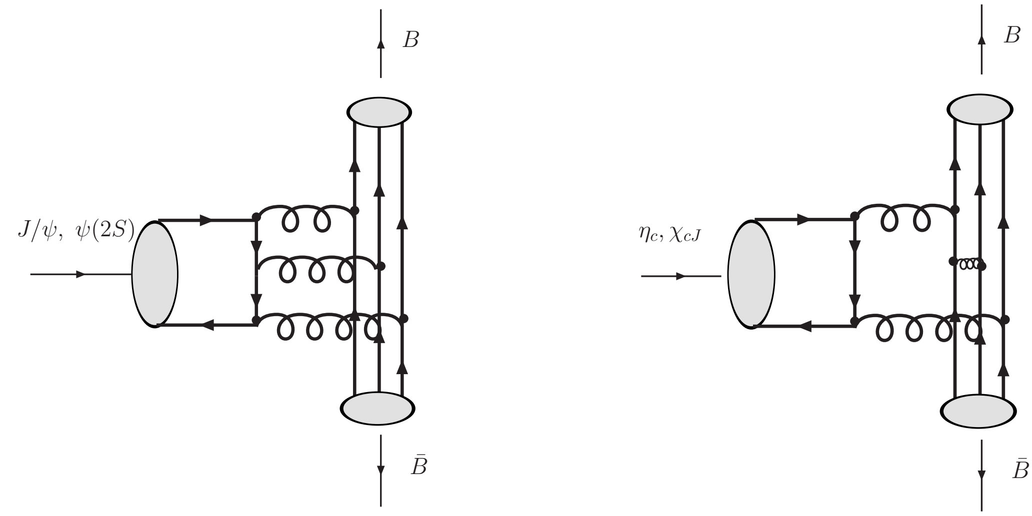

Figure 1: The lowest-order Feynman graphs for J/ψ or ψ' (left) and η_c or χ_{cJ} decays into a baryon-antibaryon pair.

charmonium decays the color octet contribution can not be neglected. For example, the amplitudes of $\chi_{cJ} \to B\bar{B}$ are dependent on the energy scale as:

$$\mathcal{M}_P^{(1)} \sim M\frac{f_c^{(1)}}{M^2}(\frac{f_N}{M^2})^2 \sim \frac{1}{M^5}$$
$$\mathcal{M}_P^{(8)} \sim M\frac{f_c^{(1)}}{M^2}(\frac{f_N}{M^2})^2 \sim \frac{1}{M^5}. \tag{4}$$

For evaluation of the decay width, the hadronic information on decay constants of charmonium can be determined by the leptonic decay width. For example:

$$\Gamma(J/\psi \to e^+e^-) = \frac{4\pi}{3}\frac{e_c^2\alpha_{em}^2 f_{J/\psi}^2}{M_{J/\psi}}. \tag{5}$$

One gets $f_{J/\psi} = 409$MeV,$f_{\psi'} = 282$MeV. The other soft physics information required is the leading-twist baryon distribution amplitude. In a recent analysis of the J/ψ and ψ' decays into baryon-antibaryon pair [8] use is made of the phenomenological proton distribution amplitude proposed in [9]

$$\Phi_{123}^p = \Phi_{AS}^B \frac{1}{2}(1 + 3x_1), \tag{6}$$

which is valid at the factorization scale $\mu_0 = 1$ GeV. This distribution amplitude goes along with the normalization parameter $f_p(\mu_0) = 6.64\times10^{-3}$ GeV^2. This distribution amplitude can be suitably generalized to the case of hyperons and decuplet baryon [8]. Based on these information, the evaluation of the $J/\psi,\ \psi' \to B\bar{B}$ via the hard process $c\bar{c} \to 3g^* \to 3(q\bar{q})$ is made in [8] and listed in Table 1. The theoretical values are good in agreement with the values with errors.

The leading-twist formation of the light hadrons in the final state has implications for their helicity configurations. As a consequence of the vector nature of QCD (and QED) time-like virtual gluons (or photons) create light, (almost) massless quarks and antiquarks in opposite helicity states, see Figure 2. To leading-twist accuracy such partons form the valence quarks of the light hadrons and transfer their helicities to them (see Figure 2). Hence, the total hadronic helicity is zero

$$\lambda_1 + \lambda_2 = 0. \tag{7}$$

The conservation of hadronic helicities is a dynamical consequence of QCD (and QED) which holds to leading-twist order. The violation of helicity conservation in a decay process signals the presence of higher-twist, higher Fock state and/or soft, non-factorizable contributions.

Table 1: Results for J/ψ and $\psi(2S)$ branching ratios for $B\overline{B}$ channels in units of 10^{-3} and 10^{-4}, respectively. The three-gluon contributions, taken from [8], are evaluated from $m_c = 1.5$ Gev, and the one-loop α_s with $\Lambda_{\rm QCD} = 210$ MeV. Unless specified data are taken from Ref. [10]. For the $J/\psi \to p\bar{p}$ we have included the recent BES measurement [11] in the average. The theoretical branching ratios are evaluated using $\Gamma(J/\psi) = 91.0 \pm 3.2\,\text{keV}$[10].

channel	$p\overline{p}$	$\Sigma^0\overline{\Sigma}^0$	$\Lambda\overline{\Lambda}$	$\Xi^-\overline{\Xi}^+$	$\Delta^{++}\overline{\Delta}^{--}$	$\Sigma^{*-}\overline{\Sigma}^{*+}$
$\mathcal{B}_{3g}(J/\psi)$	1.91	1.24	1.29	0.69	0.72	0.45
$\mathcal{B}_{\rm exp}$ [10]	2.17 ± 0.08	1.31 ± 0.10	1.54 ± 0.19	0.90 ± 0.20	1.10 ± 0.29	1.03 ± 0.13
$\mathcal{B}_{3g}(\psi(2S))$	2.50	1.79	1.79	1.11	1.07	0.80
$\mathcal{B}_{\rm exp}$ [10]	2.65 ± 0.22	2.1 ± 0.7	2.5 ± 0.7	1.5 ± 0.7	1.28 ± 0.35	1.10 ± 0.40

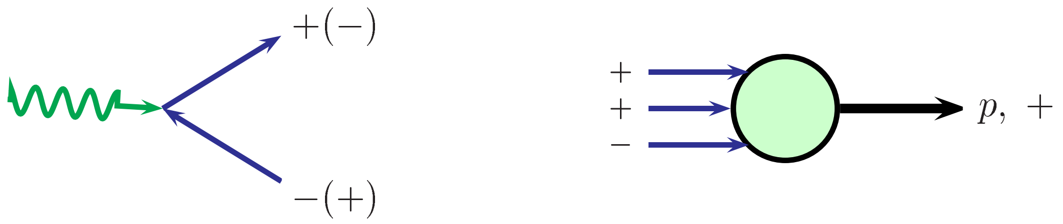

Figure 2: Helicity configurations in the creation of a light $q\bar{q}$ pair (left) and for a leading-twist parton–proton transition (right).

We note that hadronic helicity conservation does also not hold in η_c and χ_{c0} decays into baryon–antibaryon pairs where, in the charmonium rest frame, angular momentum conservation requires $\lambda_B = \lambda_{\overline{B}}$. A systematic investigation of higher-twist contributions to these processes is still lacking despite some attempts of estimating them, for a review see [12]. Recent progress in classifying higher-twist distribution amplitudes and understanding their properties [13, 14] now permits such analyses. The most important question to be answered is whether or not factorization holds for these decays to higher-twist order. It goes without saying that besides higher-twist effects, the leading-twist forbidden channels might be under control of other dynamical mechanisms such as higher Fock state contributions or soft power corrections.

The colour-singlet contribution to the decays $\chi_{cJ} \to p\bar{p}$ $(J = 1, 2)$ has been investigated by many authors [3, 12, 15, 16]. Employing the proton distribution amplitude (Eq. 6) or a similar one, one again finds results that are clearly below experiment, which again signals the lack of the colour-octet contributions. An analysis of the $\chi_{c1(2)}$ decays into the octet and decuplet baryons along the same lines as for the pseudoscalar meson channels [6] has been carried through by Wong [7]. The branching ratios have been evaluated from the baryon wave functions and the same colour-octet χ_{cJ} wave function as in [6]. Some of the results obtained in [7] are shown and compared to experiment in Table 2. As can be seen from the table the results for the $p\bar{p}$ channels are in excellent agreement with experiment while the branching ratios for $\Lambda\overline{\Lambda}$ channels are much smaller than experiment [17] although the errors are large. A peculiar fact has to be noted: the experimental $\Lambda\overline{\Lambda}$ branching ratios are larger than the proton–antiproton ones although there is agreement within two standard deviations.

The present analyses of the χ_{cJ} decays suffer from the rough treatment of the colour-octet charmonium wave function. As we mentioned before a reanalysis of the decays into the PP and $B\overline{B}$ channels as well as an extension to the VV ones is required. Our knowledge of the colour-octet wave function has been improved recently due to the intense analyses of inclusive processes involving charmonia, e.g. [18]. This new information may be used to ameliorate the analysis of the $\chi_{cJ} \to PP, B\overline{B}$ decays and, perhaps, to reach a satisfactory quantitative understanding of these processes. We finally want to remark that the colour-octet contribution does not only play an important role in the χ_{cJ} decays into PP and $B\overline{B}$ pairs but potentially also in their two-photon decays [19, 20, 21].

The leading-twist forbidden $\chi_{c0} \to B\overline{B}$ decays have sizeable experimental branching ratios, see Table 2. There is no reliable theoretical interpretation of these decays as yet. The only proposition [30] is the use of a diquark model, a variant of the leading-twist approach in which baryons are viewed as being composed of quarks and quasi-elementary diquarks. With vector diquarks as constituents one may overcome the helicity sum rule (7). The diquark model in its present form, however, contends with difficulties. Large momentum transfer data on the Pauli form factor of the proton as well as a helicity correlation parameter for Compton scattering off protons are in severe conflict with predictions from the diquark model.

Table 2: Comparison of theoretical and experimental branching ratios for various χ_{cJ} decays into pairs of light hadrons. The theoretical values have been computed within the modified perturbative approach, colour-singlet and -octet contributions are taken into account ($B_2^\pi = B_2^\eta = B_1^K = 0$, $B_2^K = -0.1$, baryon wave functions. The branching ratios are quoted in units of 10^{-3} for the mesonic channels and 10^{-5} for the baryonic ones. Data taken from [10]. The values listed for $p\bar{p}$ branching rates do not include the most recent values $\left(27.4^{+4.2}_{-4.0} \pm 4.5\right) \cdot 10^{-5}$, $\left(5.7^{+1.7}_{-1.5} \pm 0.9\right) \cdot 10^{-5}$ and $\left(6.9^{+2.5}_{-2.2} \pm 1.1\right) \cdot 10^{-5}$ measured by BES [32] for χ_c0, χ_{c1} and χ_{c2} respectively.

process	theory	experiment
$\mathcal{B}(\chi_{c0} \to p\,\bar{p})$	–	22.4 ± 2.7
$\mathcal{B}(\chi_{c1} \to p\,\bar{p})$	6.4 [7]	7.2 ± 1.3
$\mathcal{B}(\chi_{c2} \to p\,\bar{p})$	7.7 [7]	6.8 ± 0.7
$\mathcal{B}(\chi_{c0} \to \Lambda\,\overline{\Lambda})$	–	47 ± 16
$\mathcal{B}(\chi_{c1} \to \Lambda\,\overline{\Lambda})$	3.8 [7]	26 ± 12
$\mathcal{B}(\chi_{c2} \to \Lambda\,\overline{\Lambda})$	3.5 [7]	34 ± 17

In experimental aspects, the test of the color octet contribution needs a comparison between a reliably theoretical calculation and measurements of the decay width or other observables, such as the information of helicity amplitudes and angular distributions and so on. More experiments on the charmonium decays into baryon anti-baryon pair are expected for determining the color octet wave function. Another interesting measurement is the angular distribution for the process $e^+e^- \to J/\psi$ or $\psi' \to B_8\bar{B}_8$, which takes the form:

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha\cos^2\theta, \tag{8}$$

where θ is the angle between the out-going baryon and the e^+e^- beam. Table 3 summarizes the measured angular distribution parameters and comparison with theoretical predictions. In the limit of the helicity conservation, the $\alpha = 1$ is predicted. The available data in Table 3 shows a larger violation of the helicity conservation takes please for $J/\psi \to \Sigma^0\bar{\Sigma}^0$ and $\Xi^-\bar{\Xi}^+$ modes. The violation has been modeled as a constituent quark[23, 28] and/or hadron mass effect[29], final state interactions [31], both the effects are part of the $\mathcal{O}(v^2)$ and high-twist/power corrections. Also electromagnetic effects in α have been investigated.

1.2 SU(3) flavor symmetry breaking effects

For J/ψ baryonic decay at the level of $SU(3)$ symmetry only the decay

$$J/\psi \to B_1\bar{B}_1, B_8\bar{B}_8, B_{10}\bar{B}_{10}$$

are allowed, with the same decay amplitudes for a given decay family if electromagnetic contributions are neglected. However, MarkII collaboration first published experimental results showing a large SU(3) flavor symmetry breaking takes place in the J/ψ decays into a baryonic pair [33], especially, into octe-decplet

Table 3: Angular distribution parameter α for $J/\psi \to B\bar{B}$ decays. They are assumed to be the form of $dN/d\cos\theta \propto 1 + \alpha\cos^2\theta$.

Decay mode	Measured value of α	Calculated value of α Ref. [22]	Ref. [23]
$J/\psi \to p\bar{p}$	0.68 ± 0.06[24]	1	0.69
$J/\psi \to \Lambda\bar{\Lambda}$	0.65 ± 0.11[25]	1	0.51
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	-0.24 ± 0.20[25]	1	0.43
$J/\psi \to \Xi^-\bar{\Xi}^+$	-0.13 ± 0.59[26]	1	0.27
$\psi' \to p\bar{p}$	0.67 ± 0.16[27]	1	0.80

baryon pairs, then confirmed by DM2 [34] and MarkIII [35] collaboration. Table 4 summarizes the DM2 results on the J/ψ SU(2) or SU(3) forbidden decays. For the $J/\psi \to \Lambda\bar{\Lambda}\pi^0$, it seems that the large contamination from $J/\psi \to \Sigma\bar{\Lambda}\pi^0$ would lead to a small branching fraction. These SU(3) flavor symmetry decays will be studied at BESII/BESIII.

Table 4: Summary of J/ψ SU(2) and SU(3) forbidden decay modes measured.

Decay Mode	Number of events	Branching fraction ($\times 10^{-4}$)
	SU(3) forbidden decay modes	
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$	74 ± 8	$3.0 \pm 0.3 \pm 0.8$
$J/\psi \to \Sigma(1385)^+\bar{\Sigma}^-$	77 ± 9	$3.4 \pm 0.4 \pm 0.8$
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	80 ± 9	$5.9 \pm 0.7 \pm 1.5$
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	24 ± 5	$3.2 \pm 0.7 \pm 1.5$
	SU(2) forbidden decay modes	
$J/\psi \to \Lambda\bar{\Lambda}\pi^0$	19 ± 4	$2.2 \pm 0.5 \pm 0.5$
$J/\psi \to \Sigma(1385)^0\bar{\Lambda}$	13	$< 2.0 (90\% CL)$
$J/\psi \to \Sigma^0\bar{\Lambda}$	11	$< 0.9 (90\% CL)$
$J/\psi \to \Delta^+\bar{p}$	50	$< 1.0 (90\% CL)$

As discussed in literatures, the SU(3) flavor symmetry can be broken in several ways:

- One photon processes, i.e. $c\bar{c} \to \gamma \to B_{10}\bar{B}_8$. Because the direct product $8 \otimes \bar{10}$ contains an octet contribution, it is possible via the octet component of the photon. It is also via the processes $c\bar{c} \to gg\gamma \to B_{10}\bar{B}_8$, which represents a direct electromagnetic decay. As calculated in pQCD framework the ratio R of this decay amplitude to that of the three-gluon decay is about a few percent, $R_{QCD} = -4\alpha/(5\alpha_s)$ [36], and also in the framework of vector meson dominance, $R_{VMD} = 24\alpha/(5\alpha_s)$.

- A second SU(3) breaking mechanism arises from the mass difference of light and strange quarks. The decay chain $c\bar{c} \to (u\bar{u}+d\bar{d}+s\bar{s})_1 \to \alpha(u\bar{u}+d\bar{d})_{1\oplus 8}+\beta(s\bar{s})_{1\oplus 8} \to B_{10}\bar{B}_8$ can occur if the coupling α and β differ. The mass breaking can equivalently be described by an octet [37] or 27-plet representation to the J/ψ wave function [34].

- The third mechanism possibly arises from the intermediate states. As pointed by Genz et al. [38] that an intermediate $q\bar{q}$ state could lead to the apparent SU(3) breaking. A generalization to multi-quark intermediate states would also make the contribution of a 27-plet possible. If the decay amplitudes are decomposed into the contributions from one-photon (D), octet SU(3) breaking (D'), and 27-plet terms (D"), the ratios of branching fractions for J/ψ decays into octe-duplet baryon pairs are given by

$$
\begin{aligned}
R_1 &= \frac{B(\Xi(1530)^0\bar{\Xi}^0)}{B(\Sigma(1385)^+\bar{\Sigma}^-)} \propto \left|\frac{2D+D'+\frac{3}{2}D"}{2D+D'-D"}\right|^2, \\
R_2 &= \frac{B(\Xi(1530)^-\bar{\Xi}^+)}{B(\Sigma(1385)^-\bar{\Sigma}^+)} \propto \left|\frac{D'+\frac{3}{2}D"}{D'-D"}\right|^2, \\
R_3 &= \frac{B(\Sigma(1385)^+\bar{\Sigma}^-)-B(\Sigma(1385)^-\bar{\Sigma}^+)}{B(\Xi(1530)^0\bar{\Xi}^0)-B(\Xi(1530)^-\bar{\Xi}^+)} \propto \frac{|2D+D'-D"|^2-|D'-D"|^2}{|2D+D'+\frac{3}{2}D"|^2-|D'+\frac{3}{2}D"|^2}.
\end{aligned} \tag{9}
$$

If octet dominance ($D' >> D''$) would predict that $R_1 = R_2 = R_3 = 1$, in contradiction with the measurements $R_1 = 1.3 \pm 0.6, R_2 = 2.8 \pm 1.0$ and $R_3 = -0.1 \pm 0.3$. The more sophisticated model of Körner [39], which allows for strong mass breaking effects and final state dependent electromagnetic amplitudes but neglects a 27-plet contribution, runs into similar problems. While a model allowing electromagnetic contributions is ruled out, some electromagnetic component seems to be required, sin $B(J/\psi \to \Xi^0(1530)\bar{\Xi}^0) \neq B(J/\psi \to \Xi(1530)^-\bar{\Xi}^+)$. In the framework of the given model, the data can well be described if both electromagnetic and strong isospin breaking effects are taken into account.

1.3 Searching for CP violation in baryonic decays

The decays of $J/\psi \to B_8B_8$ (B_8: octet baryon) can be used to search for the electric dipole momentum (EDM) of baryons. The non-zero values of EDM indicate that CP symmetry is violated. As shown in Ref. [40], for $J/\psi \to B(p_1)\bar{B}(p_2)$ the decay amplitudes can be parameterized as

$$
\mathcal{M} = \epsilon^\mu \bar{u}(p_1)[\gamma_\mu(a+b\gamma_5)+(p_{1\mu}-p_{2\mu})(c+id\gamma_5)]v(p_2) \equiv \epsilon^\mu A_\mu, \tag{10}
$$

where ϵ^μ is the polarization of J/ψ. If CP violation, $d = 0$.

In experimental aspect, the decay of $J/\psi \to \Lambda\bar{\Lambda}$ is a good laboratory to searcher for the EDM of Λ, since this channel can be well reconstructed with a small background and large data sample ($B(J/\psi \to \Lambda\bar{\Lambda}) = (1.54 \pm 0.19) \times 10^{-3}$). The polarization of Λ ($\bar{\Lambda}$) particle are measured by analyzing subsequent $\Lambda(\mathbf{s}_1) \to p(\mathbf{q}_1)\pi^-$, $\bar{\Lambda}(\mathbf{s}_2) \to \bar{p}(\mathbf{q}_2)\pi^+$ decays with density matrices $\rho_\Lambda = 1+\alpha_+\mathbf{s}_1\cdot\mathbf{q}_1/|\mathbf{q}_1|$ and $\rho_{\bar{\Lambda}} = 1-\alpha_-\mathbf{s}_2\cdot\mathbf{q}_2/|\mathbf{q}_2|$. Experimental observables O can be constructed from $\mathbf{p}, \mathbf{q}_i$ and the e beam direction $\mathbf{k}$. The expectation value of O is given by

$$
< O >= \frac{\sqrt{1-4m^2/M^2}}{2M\Gamma(J/\psi \to \Lambda\bar{\Lambda})8\pi}\frac{1}{(4\pi)^3}\int d\Omega_p d\Omega_{q_1} d\Omega_{q_2} O Tr\{R_{ij}\rho_{ji}\rho_\Lambda\rho_{\bar{\Lambda}}\}, \tag{11}
$$

where $R_{ij} = A_iA_j^*$ and ρ_{ij} are the density matrices for J/ψ decays into $\Lambda\bar{\Lambda}$ and J/ψ production form e^+e^-, respectively. The CP-odd observable A and CPT-even observable are constructed as:

$$
\begin{aligned}
A &= \theta(\hat{p}\cdot(\hat{q}_1\times\hat{q}_2)) - \theta(-\hat{p}\cdot(\hat{q}_1\times\hat{q}_2)) \\
B &= \hat{p}\cdot(\hat{q}_1\times\hat{q}_2),
\end{aligned} \tag{12}
$$

where $\theta(x)$ is 1 if $x > 0$ and is zero if $x < 0$. The expectation values can be expressed as:

$$
\begin{aligned}
< A > &= -\frac{\alpha_-^2\beta^2}{96M\Gamma(J/\psi \to \Lambda\bar{\Lambda})}M^2[2mRe(da^*)+(M^2-4m^2)Re(dc^*)] \\
< B > &= -\frac{48}{27\pi} < A > .
\end{aligned} \tag{13}
$$

The quantity $< A >$ is equal to

$$
< A >= \frac{N^+ - N^-}{N^+ + N^-}, \tag{14}
$$

where $N^\pm$ indicate events with $\mathrm{sgn}[\mathbf{p}\cdot(\mathbf{q_1}\times\mathbf{q_2})] = \pm$, respectively.

The EDM d_Λ of Λ is related to the quantity $< A >$ by the Lagrangian:

$$L_{\text{dipole}} = i\frac{d_\Lambda}{2}\bar{\Lambda}\sigma_{\mu\nu}\gamma_5\Lambda F^{\mu\nu},$$

where $F^{\mu\nu}$ is the field strength of the electromagnetic field. Exchanging a photon between Λ and a c quark , the CP violating $c-\Lambda$ interaction is expressed by

$$L_{c-\Lambda} = -\frac{2}{3M^2}ed_\Lambda(p_1^\mu - p_2^\mu)\bar{c}\gamma_\mu c\bar{\Lambda}i\gamma_5\Lambda$$

From these relations one has $d = -\frac{2.5}{3M^2}ed_\Lambda$, thus

$$|< A >| = \begin{cases} 5.6\times 10^{-3}d_\Lambda/(10^{-16}ecm), & \text{if the } a \text{ term dominates} \\ 1.25\times 10^{-2}d_\Lambda/(10^{-16}ecm), & \text{if the } c \text{ term dominates} \end{cases} \tag{15}$$

The experimental upper bound on $1.5\times 10^{-16}e$ cm[10]. If d_Λ indeed has a value close to its experimental upper bound, the asymmetry $|< A >|$ can be large as 10^{-2}. So $< A >$ can be used to improve bound on d_Λ. If 10^{10} J/ψ can be produced, one can improve the upper limit bound on d_Λ by more than an order of magnitude. The same analysis can be easily applied to J/ψ to Σ, Ξ, etc.

Quantitative predictions for CP violation in hyperon decays indicating that $A = \frac{\alpha_\Lambda+\alpha_\Lambda}{\alpha_\Lambda-\alpha_\Lambda}$ should be in the range $(-2\times 10^{-5} \sim -1\times 10^{-4})$. Present experimental results dose not have a sufficient sensitivity to observe such a small effect, BESIII provide an opportunity to search for this quality. As shown by DM2 collaboration, the decay of $J/\psi \to \Lambda\bar{\Lambda}$ can be used to look CP violation by test of the correlation of p and $\bar{p}$ momentum in the mother system frame [41]. The differential cross-section of the $J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$ decay can be expressed as:

$$\frac{d\Gamma}{d\cos\theta d\Omega' d\Omega"} \propto 2\left|\frac{A_{++}}{A_{--}}\right|\sin^2\theta[1-\alpha_\Lambda\alpha_{\bar{\Lambda}}(\cos\theta'\cos\theta" - \sin\theta'\sin\theta"\cos(\phi'-\phi"))] \\ +(1+\cos^2\theta)(1+\alpha_\Lambda\alpha_{\bar{\Lambda}}\cos\theta'\cos\theta"), \tag{16}$$

where α_Λ ($\alpha_{\bar{\Lambda}}$) is the Λ ($\bar{\Lambda}$) decay constant. $A_{\lambda_1\lambda_2}$ and θ are the helicity amplitude and polar angle of the out-going Λ for the $J/\psi \to \Lambda\bar{\Lambda}$, respectively. The angular variables of Ω' and $\Omega"$ are defined as shown in Fig. 3. From this equation, the quantity $\alpha_\Lambda\alpha_{\bar{\Lambda}}$ can be obtained experimentally.

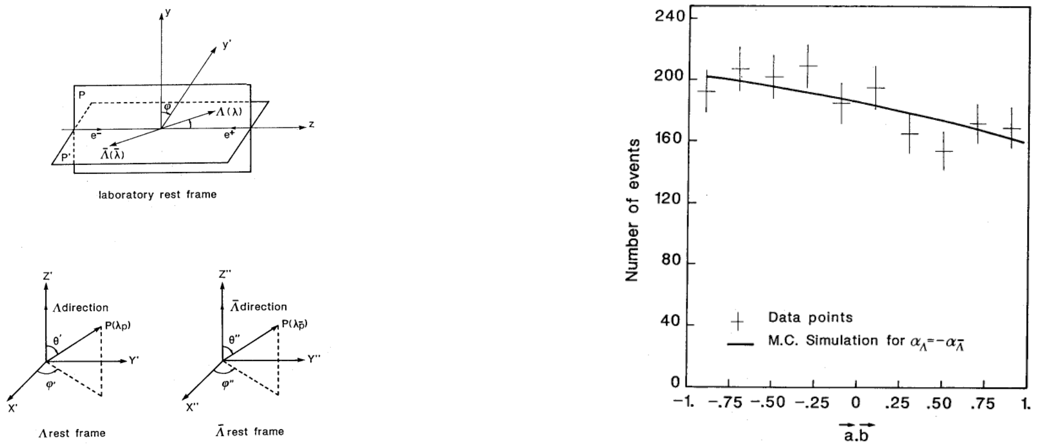

Figure 3:

As Tornqvist [42] demonstrated that the decay $\eta_c, J/\psi \to \Lambda\bar{\Lambda}$ are experimental realization of the Bell's conceptual proposition to test Quantum Mechanics versus local hidden variable theories. The initial state is well known and due to parity symmetry breaking, the Λ decay works as a spin analyser. The proton direction plays the same part that the direction of external polarimeter in classical experiments [43]. Then the important quantity is the scalar product of p and $\bar{p}$ in the Λ and $\bar{\Lambda}$ rest frame. The differential cross-section of the $\eta_c \to \Lambda\bar{\Lambda}$ decay is directly proporthonal to $\vec{a}\cdot\vec{b}$. So it is the most sensitive test of Quantum Mechanics since this scalar product can be compared to Bell's inequality. Unfortunately, this decay has not yet been observed and only an upper limits ($< 2\times 10^{-3}$) exists. For the $J/\psi \to \Lambda\bar{\Lambda}$, Tornqvist reformulated the differential cross-section as:

$$\frac{d\Gamma}{d\cos\theta d\Omega' d\Omega"} \propto 2(1-\frac{p_\Lambda^2}{E_\Lambda^2}\sin^2\theta)(1-\alpha_\Lambda^2 a_n b_n) + \frac{p_\Lambda^2}{E_\Lambda^2}\sin^2\theta[1-\alpha_\Lambda^2(\vec{a}\cdot\vec{b}-2a_x b_x)], \tag{17}$$

where $\vec{a}$ and $\vec{b}$ are the proton and antiproton momentum, respectively in the Λ ($\bar{\Lambda}$) rest frame, x is the direction orthogonal to the $\Lambda\bar{\Lambda}$ direction and to the e^+e^- beam axis and $\vec{n}$ is an axis defined to take into account the suppression of 0-spin projection in the J/ψ decay. The terms containing $a_n b_n$ or $a_x b_x$ only reduce the sensitivity of the test since they do not depend on the nature of the theory, and they play the same role as hidden parameters [42]. The contribution of the $\vec{a}\cdot\vec{b}$ term is important for the test of Quantum Mechanics. Unfortunately p_Λ^2/E_Λ^2 at J/ψ is only equal to 0.48 and α_Λ^2 to 0.412, which reduce the contribution of the $\vec{a}\cdot\vec{b}$ term in experimental measurement.

As DM2 collaboration measured, the $\vec{a}\cdot\vec{b}$ distribution is plotted in Fig. 3 and compared with that expected from standard physics (Quantum Mechanics and CP invariance). The agreement is very good by taking the PDG value $\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$. Fixing the α_Λ parameter to its standard value (0.642), the fit to the $\vec{a}\cdot\vec{b}$ distribution yields the value of $\alpha_{\bar{\Lambda}}$, which gives value of the asymmetry decay parameter:

$$A = \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}} = 0.01 \pm 0.10$$

with observed 1077 events for the $J/\psi \to \Lambda\bar{\Lambda}$. The precision of this measurement dose not permit to conclude to CP violation. With 10^{10} J/ψ events, the sensitivity is expected to be 8×10^{-4}.

The measurement of the correction between the proton and antiproton in $J/\psi \to \Lambda\bar{\Lambda}$ decay is associated with the test of Bell's inequality. For example, in the $\eta_c \to \Lambda\bar{\Lambda} \to p\bar{p}\pi^+\pi^-$ decay, the spin correction between the two nucleon predicted by Quantum Mechanics can be expressed by [42]:

$$I(\vec{a},\vec{b}) \propto 1 + \alpha^2 \vec{a}\cdot\vec{b}, \tag{18}$$

while a hidden measurement of Λ polarization before the decay would reduce the slope to $\alpha^2/3$, i.e.

$$I(\vec{a},\vec{b}) \propto 1 + \frac{\alpha^2}{3}\vec{a}\cdot\vec{b}. \tag{19}$$

Using invariance under rotations and reflections, one can derive special bound for Bell's inequality:

$$|E(\theta)| \leq 1 - \frac{2}{\pi}\theta,\ 0 \leq \theta \leq \pi.$$

Figure 1.3 shows the distribution in the angle θ between two pions as predicted by Quantum Mechanics and the area bounded by Bell's inequality.

1.4 Searching exotic states in baryonic decays

As well known, besides conventional quark states, QCD theory also predicts the existence of multiquark states, hybrid states and other exotic states. Searching for such exotic states has been attempted for a long time, but none is established experimentally. One of the difficulty to identify exotic states is to search for their signature properties to distinguish them from the common states or get information about their mixing. So it is important for experimental experts to collaborate closely with theoretical physicist. As our knowledge about common hadronic structure, hadronic spectroscopy will continue to be a key tool to search for N^* states (see the section of "Baryon spectroscopy") and exotic states. Various models and methods have been used to predict the spectrum of hybrid mesons/baryons, such as the bag model, QCD sum rule, the flux tube model, and so on. Though each model assumes a particular description of exited glue, fortunately

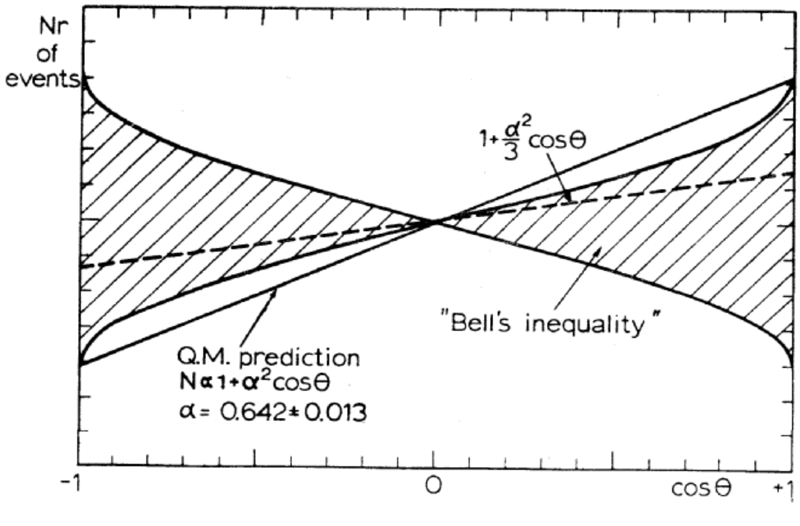

Figure 4: The distribution in the angle θ between the π^+ and the π^- as predicted by Quantum Mechanics (solid line), and if a "hidden" Λ polarization measurement is done before the decay (dashed line). The shaded area gives the domain where the inequality is satisfied.

they often reach similar conclusion regarding the quantum numbers and approximate masses of these states. For instance, the predictions on the light hybrid mesons are in good agreement with each other, with the so-called exotic number $J^{PC} = 1^{-+}$ and the mass about 1.5-2.0 GeV. In baryon sector, the Roper resonance $N^*(1440)$ has been suggested to be a potential candidate of hybrid baryons for a long time.

As shown in Ref. [44], BEPCI/BEPCII provides an excellent place for studying Roper resonance. Using 58×10^6 J/ψ decays, the $N^*(1440)$ is clear seen with statical significance of 11σ. For identification of Roper resonance as a hybrid state, the transitional information of amplitudes play an important role in partial wave analysis in the future. As demonstrated in Ref. [45], If the Roper resonance is assigned as a pure hybrid state, numerical results show that the ratio $\Gamma(J/\psi^{(\Lambda)} \to \bar{p}N^*)/\Gamma(J/\psi^{(\Lambda)} \to \bar{p}p) < 2\%$, and $\Gamma(J/\psi^{(\Lambda)} \to \bar{N}^*N^*)/\Gamma(J/\psi^{(\Lambda)} \to \bar{p}p) < 0.2\%$, and their angular distribution parameters are $\alpha_* = 0.42 \sim 0.57$ and $\alpha_{**} = (-0.1) - (-0.9)$, respectively. However, when the Roper resonance is assumed to be a common $2S$ state, the results are quite different, with $\Gamma(J/\psi^{(\Lambda)} \to \bar{p}N^*)/\Gamma(J/\psi^{(\Lambda)} \to \bar{p}p) = 2.0 \sim 4.5$, and $\Gamma(J/\psi^{(\Lambda)} \to \bar{N}^*N^*)/\Gamma(J/\psi^{(\Lambda)} \to \bar{p}p) = 3.2 \sim 22.0$, and with the angular distribution parameter $\alpha_* = 0.22 \sim 0.70, \alpha_{**} = 0.06 \sim 0.08$. This implies that, not only the dynamics of three gluons and created quarks , but also the structure of the final cluster state , i.e. $|qqq\rangle$ or $|qqqg\rangle$, play important roles in the evaluation of the amplitudes in these decay processes. So it is suggestive that an accurate measurement of the decay widths and angular distributions of these channels may provide us a novel tool to probe the structure of the Roper resonance. If the Roper resonance is assumed as a mixture of a pure quark state $|qqq\rangle$ with a hybrid state $|qqqg\rangle$ modeled with a mixing parameter δ, the results show that the hybrid constituent make a large contribution to the decay width of J/ψ decay into $\bar{p}N^*(1440)$ and $\bar{N}^*(1440)N^*(1440)$.

It goes without saying that the search for the pentaquark state $\Theta(1540)^+$ in J/ψ and ψ' decays into $p\bar{n}K^0_SK^-$ and $\bar{p}nK^0_SK^+$. With 14 million ψ' and 58 million J/ψ events accumulated at the BESII detector. No $\Theta(1540)$ signal is observed, and upper limits are set for $\mathcal{B}(\psi' \to \Theta\bar{\Theta} \to K^0_SpK^-\bar{n} + K^0_S\bar{p}K^+n) < 0.84 \times 10^{-5}$ and $\mathcal{B}(J/\psi \to \Theta\bar{\Theta} \to K^0_SpK^-\bar{n} + K^0_S\bar{p}K^+n) < 1.1 \times 10^{-5}$ at the 90% confidence level [46]. By far there have been a number of other high statistics experiments, none of which have found any evidence for the Θ^+; and all attempts to confirm the two other claimed pentaquark states have led to negative results. As reviewed by Particle Data Group 2006, *"Pentaquarks in general, and Θ^+, in particular, do not exist, appears compelling."*

Recently, some threshold enhancements involved baryons are observed at BESII, for example $p\bar{p}$ threshold enhancement at the $J/\psi \to \gamma p\bar{p}$ [47] and $p\bar{\Lambda}$ or $\bar{p}\Lambda$ threshold enhancement in J/ψ and ψ' decays to $pK^-\bar{\Lambda}+c.c.$

final states [48]. Whether these enhancements are the tail of the new multi-quark states, or molecular states or other effects, such as final state interaction effects and so on, are expected to test in other experiments and give more information for theoretical studies on their structure. Anyhow, the BEPCII/BESII is expected to provide more opportunities to search for new exotic states and glueball and throw lights on the understanding of the strong interaction theory.

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