The baryon spectroscopy from J/ψ decays

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J/ψ decay at Beijing Electron-Positron Collider (BEPC) is well known as the best place for looking for glueballs. But in fact it is also an excellent place for studying N^* and hyperon physics. For $J/\psi \to N\bar{N}\pi$ and $N\bar{N}\pi\pi$, the πN and $\pi\pi N$ systems are limited to be pure isospin 1/2 due to isospin conservation. This is a big advantage in studying N^* resonances from J/ψ decays, compared with the πN and γN experiments which suffer difficulty on the isospin decomposition of 1/2 and 3/2. There are also plenty other decay modes of J/ψ involving baryon-antibaryon pairs plus mesons which can be used to study N^* and hyperon resonances, *e.g.*, looking for the "missing" N^* states from $J/\psi \to \bar{p}p\omega$, $\bar{p}p\eta'$, $pK^-\bar{\Lambda}$, etc.; studying $N^*(1535) \to \eta p$ from $J/\psi \to \bar{p}p\eta$ and studying $\Lambda(1405) \to \Sigma\pi$ from $J/\psi \to \Lambda\bar{\Sigma}^-\pi^+$. It provides a new way to study the internal structure of baryon resonances. The newest progress and outlook in this field are presented.

1. STATUS OF BARYON SPECTROSCOPY

There are two basic questions for the baryon spectroscopy: (1) what is a baryon composed of ? and (2) what are the forces between its constituents? For the first question, we know there are three valence quarks, sea quarks and gluons inside a baryon, but we are not sure whether the three valence quarks are constituent or current quarks, whether they are well separated from each other or combined into a diquark cluster plus a single quark; whether the sea quarks are in the form of $q\bar{q}$ soup or mesons; whether the gluons are particle-like or flux-tubes, whether they are constituent or only virtual fields. For the second question, we know at short distance between quarks the force can be described by one gluon exchange; at medium range, some people now believe it is necessary to introduce meson exchange force; at long distance, the most commonly used force in quark models is the infinitely large linear (kr) confinement potential. But in reality, the infinitely large confinement potential is obviously wrong. For such potential, a quark in a hadron cannot be separated from other quarks or antiquark in the same hadron, while in real world a quark can be easily separated from others by hadronic decays. For a physical baryonic state, the bag size of quarks should have fluctuation at different time. For the time of smaller bag size, there should be three constituent quarks; for the time of larger bag size, an additional constituent $q\bar{q}$ should be pull out from sea quarks. Especially for spatial excited baryonic states, the bag size should be larger than the spatial ground baryonic states, and hence they should have more $(qqq)(\bar{q}q)$ components. How to describe the strong force is still a problem. After more than twenty years of QCD, such basic questions have still not solved. The situation is obvious not satisfactory. The physics of nucleon resonance excitation continues to provide a major challenge to hadron physics.

The main source of information for the baryon internal structure is their mass spectrum, various production and decay rates. Our present knowledge of this aspect came almost entirely from partial-wave analyses of πN total, elastic, and charge-exchange scattering data of more than twenty years ago[1]. Only very recently, a new generation of experiments on N^* physics with electromagnetic probes has been started at new facilities such as CEBAF at JLAB, ELSA at Bonn, GRAAL at Grenoble, MAMI at Mainz. Some nice results on $\Delta \rightarrow p\gamma$ [2], $N^*(1535) \rightarrow p\gamma$[3] and $\gamma p \rightarrow K^+\Lambda$[4] *etc.* have been produced.

On theoretical side, Chiral Perturbation Theory is not amenable to N^* physics, lattice QCD has only recently begun to contribute to this field in a very limited scope[5]. Most of the theoretical work on the nucleon excitation spectrum has been based on phenomenological models. Among these models, the most systematic and successful ones are the constituent quark models (CQM) within a nonrelativistic[6] or relativistic framework[7], and the chiral constituent quark models (CCQM)[8]. Both CQM and CCQM assume three constituent quarks for a baryon. The difference is that CQM assumes one-gluon-exchange force between quarks while the CCQM includes meson-exchange force in addition. A relative new approach is a collective constituent model for the nucleon, in which the resonances are interpreted as rotations and vibrations of a symmetric top with a prescribed distribution of the charge and magnetization[9].

Despite the over all success, none of these models has been able to explain the properties of $N^*(1440)$, $N^*(1535)$ and $\Lambda^*(1405)$ without difficulty. In the simple three-quark picture of baryons, $N^*(1440)$ should be the first radial excitation state of the nucleon; $N^*(1535)$ should be the first orbital angular momentum (L=1) excitation state of the nucleon; while $\Lambda^*(1405)$ should be the L=1 excitation state of the hyperon, *i.e.*, (uds)-baryon. The failure of the three-quark models in explaining properties of these lowest spatial excited baryonic states is natural since these spatial excited states are more sensitive to the long-range force between quarks while the three-quark models assume an improper kr confinement potential. Additional constituents seem to be needed. These spatial excited states have been suggested to be hybrid (qqqg) baryon[10] and/or meson-nucleon bound states[11].

Another problem for above models is that they predict many N^* states which have not been observed in $\pi N \rightarrow \pi N$ reactions. A possible explanation is that the "missing" states are weakly coupled to πN and mainly coupled to other channels such as ρN, ωN, $\pi\Delta$, or $K\Lambda$[12]. However, some models, such as the diquark-quark cluster model[13], predict a fewer number of excited states due to the reduced numbers of degrees of freedom.

To examine the structure of the low-lying spatial excited baryon states and to search for the "missing" N^* states are a few key issues for the present electromagnetic production experiments [14].

2. ADVANTAGES OF STUDYING BARYON SPECTROSCOPY FROM J/ψ DECAYS

J/ψ decay at Beijing Electron-Positron Collider (BEPC) is well known as the best place for looking for glueballs. But in fact it is also an excellent place for studying N^* and hyperon physics. The advantages of studying baryon spectroscopy from J/ψ decays are as the following.

(1) $J/\psi \to N\bar{N}\pi$ and $N\bar{N}\pi\pi$ provide a natural isospin $I = 1/2$ filter for the πN and $\pi\pi N$ systems due to isospin conservation.

Although the existence of the $N^*(1440)$ and $N^*(1535)$ is well-established, their properties, such as mass, width and decay branching ratios etc., still suffer large experimental uncertainties[1]. A big problem in extracting information on these N^* resonances from πN and γN experiments is the isospin decomposition of 1/2 and 3/2 for πN and $\pi\pi N$ systems[15]. We expect that the results from J/ψ decays will provide better determination of the properties of these N^* resonances.

(2) Interference between N^* and $\bar{N}^*$ bands in $J/\psi \to N\bar{N}\pi$ Dalitz plots may help to distinguish some ambiguities in the partial wave analysis of πN two-body channel alone from πN and γN experiments.

(3) The branching ratios for our interested channels from J/ψ decay are quite large[1], cf. Table 1.

Table 1
Branching ratios (BR$\times 10^3$) for some interested channels

$p\bar{n}\pi^-$	$p\bar{p}\pi^0$	$p\bar{p}\pi^+\pi^-$	$p\bar{p}\eta$	$p\bar{p}\eta'$	$p\bar{p}\omega$	$\Lambda\bar{\Sigma}^-\pi^+$	$pK^-\bar{\Lambda}$
2.0 ± 0.1	1.1 ± 0.1	6.0 ± 0.5	2.1 ± 0.2	0.9 ± 0.4	1.3 ± 0.3	1.1 ± 0.1	0.9 ± 0.2

With present available 7.8 million J/ψ events and forthcoming 50 millions more at BES in next two years, we expect to get the best determination of properties for $N^* \to \pi N$ and $\pi\pi N$ from $p\bar{n}\pi^-$, $p\bar{p}\pi^0$ and $p\bar{p}\pi^+\pi^-$ channels; we will get the largest data sample for studying $\Lambda^*(1405) \to \Sigma\pi$ from $\Lambda\bar{\Sigma}^-\pi^+$ channel; We can search for the "missing" N^* states and study known N^* states decaying into ηN, $\eta' N$, ωN and $K\Lambda$ etc.
(4) The process $J/\psi \to \bar{p}N^*$ or $p\bar{N}^*$ provides a new way to probe the internal quark-gluon structure of the N^* resonances.

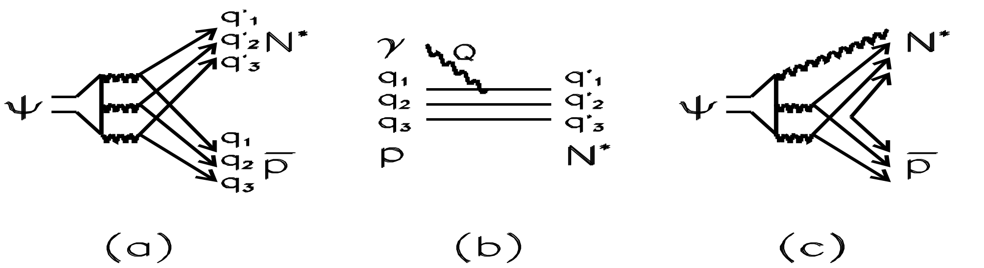

Figure 1. Diagrams for N^* production from J/ψ decays for 3-quark (qqq) N^* (a) and hybrid (qqqg) N^* (c), and from γN reaction (b).

In the simple three-quark picture of baryons, the process can be described by Fig.1(a). In this picture, three quark-antiquark pairs are created independently via a symmetric three-gluon intermediate state; the quarks and antiquarks have momenta of very similar magnitude. This is quite different from the $\gamma p \to N^*$ process, cf. Fig.1(b), where the photon couples to only one quark and unsymmetric configuration of quarks is favored with $q_1' = q_1 + Q$. Therefore the processes $J/\psi \to \bar{p}N^*$ and $\gamma p \to N^*$ should probe different aspects of the quark distributions inside baryons.

The J/ψ decay is a glue-rich process. A hybrid N^* can be produced via diagram Fig.1(c) and is expected to have larger production rate than a pure three-quark N^*[16].

3. RECENT PROGRESS ON N^* PHYSICS FROM J/ψ DECAYS

There was very little information[1,17] available on N^* resonances from J/ψ decays before the Hadron99 Conference. The BES Collaboration just started the N^* program from J/ψ decays[18]. Based on 7.8 million J/ψ events collected at BEPC, the events for $J/\psi \to p\bar{p}\pi^0$ and $p\bar{p}\eta$ have been selected and reconstructed. A partial wave analysis of $J/\psi \to p\bar{p}\eta$ data has been performed. Two $J^P = \frac{1}{2}^-$ resonances, $N^*(1535, S_{11})$ and $N^*(1650, S_{11})$, are observed. For $J/\psi \to p\bar{p}\pi^0$, a clear peak is observed around 1480 MeV in $p\pi^0(\bar{p}\pi^0)$ invariant mass spectrum (see Fig.2 in Ref.[18]). There are three resonances which may contribute to this peak: $N^*(1440, P_{11})$, $N^*(1520, D_{13})$ and $N^*(1535, S_{11})$[1]. A partial wave analysis of this channel is underway to get the relative production rates of these resonances and may provide better determinations of their $BR(N\pi)/BR(N\eta)$ ratio than the present PDG values. We are also going to perform detail studies of N^* and Λ^* baryons in other J/ψ decay channels listed in Table 1.

On theoretical side, we have performed a quark model calculation[19] for $J/\psi \to \bar{p}p$, $\bar{p}N^*(1440)$ and $\bar{N}^*(1440)N^*(1440)$ assuming $N^*(1440)$ to be a pure three-quark radial excitation state. The basic amplitude corresponding to Fig.1(a) is taken from Ref.[20]:

$$\begin{aligned}
& \langle q_i, s_i, q_i', s_i', i = 1,2,3|\hat{T}|J/\psi^{(\Lambda)}\rangle \\
= \; & C_0[\prod_{i=1}^{3} \delta^4(\frac{1}{3}P_\psi - q_i - q_i')]\epsilon_\psi^{(\Lambda)\lambda}[g_{\mu\lambda}g_{\nu\rho} + g_{\nu\lambda}g_{\mu\rho} + g_{\rho\lambda}g_{\mu\nu}] \\
& \cdot\bar{u}(q_1', s_1')\gamma^\mu v(q_1, s_1)\bar{u}(q_2', s_2')\gamma^\nu v(q_2, s_2)\bar{u}(q_3', s_3')\gamma^\rho v(q_3, s_3) \qquad (1)
\end{aligned}$$

where $\epsilon_\psi^{(\Lambda)}$ is the polarization four-vector of J/ψ with the helicity value Λ, P_ψ is the four-vector momentum of J/ψ, $q_i', s_i'(q_i, s_i)$ are the four-vector momenta and spin z-projection of quarks (anti-quarks), respectively. We have put all color matrix elements, QCD strong coupling constant at J/ψ energy, J/ψ decay constants, etc., into a single overall constant C_0 which should have the same value for $\bar{p}p$, $J/\psi \to \bar{p}N^*$ and $\bar{N}^*N^*$. As a reasonable approximation[20], each intermediate virtual gluon is assumed to have 1/3 of the momentum available in J/ψ decay. The only difference between quark wave functions of the proton and $N^*(1440)$ is their spatial parts, which we assume to be simple harmonic-oscillator eigenfunctions with the oscillator parameter $\alpha = m\omega$ in the range of $0.12 \sim 0.18 GeV^2$. Taking $\alpha = 0.15 GeV^2$, we have for numerical results

$$\frac{d\Gamma(J/\psi^{(\pm)} \to \bar{p}p)}{d\Omega} \approx N_{\bar{p}p}(1 + \alpha_p cos^2\theta) \quad with \quad \alpha_p = 0.67; \qquad (2)$$

$$\frac{d\Gamma(J/\psi^{(\pm)} \to \bar{N}^*N^*)}{d\Omega} \approx 0.51 N_{\bar{p}p}(1 + \alpha_{**} cos^2\theta) \quad with \quad \alpha_{**} = 0.49; \qquad (3)$$

$$\frac{d\Gamma(J/\psi^{(\pm)} \to \bar{p}N^*)}{d\Omega} \approx R_{N^*/p} N_{\bar{p}p}(1+\alpha_{N^*}cos^2\theta) \quad with \quad \alpha_{N^*} = 0.49, \tag{4}$$

$$R_{N^*/p} = 0.007. \tag{5}$$

Here $N_{\bar{p}p}$ is a constant and can be fixed from the experimental branching ratio of $J/\psi \to \bar{p}p$. Our theoretical value of α_p is compatible with its measured value of (0.62 ± 0.11)[21]. We expect $\bar{N}^*N^*$ and $\bar{p}N^*(1440)$ will have a flatter angular distribution with $\alpha_{**} \approx \alpha_{N^*} \approx 0.49$.

The most intriguing result of our model calculation is the very small $R_{N^*/p}$ value. Varying the α parameter from 0.12 to $0.18 GeV^2$, the $R_{N^*/p}$ value changes from 0.004 to 0.011. However there is a clear peak around 1.48 GeV in the πN invariant mass in $J/\psi \to \bar{p}N\pi$ processes from both BES[18] and MARKII[17] experiments. If there is a substantial contribution from $N^*(1440)$ to this 1.48 GeV peak, which in our opinion is very likely, the experimental $R_{N^*/p}$ value will be at least one order of magnitude larger than our theoretical value with simple quark wavefunctions.

The situation here for the $\psi NN^*(1440)$ coupling is similar to the case for $\gamma NN^*(1440)$ where the simple quark model also gives an amplitude value about one order of magnitude smaller than experimental measurements. This is very puzzling since the two couplings have very different mechanisms: one is a strong coupling with three gluons while the other is an electro-magnetic coupling with one photon. In explaining the case of $\gamma NN^*(1440)$ coupling, two possibilities have been suggested: (1) $N^*(1440)$ is a hybrid baryon [10], and (2) $N^*(1440)$ has a large component of πN in its internal structure[11]. Since the J/ψ decay is a glue-rich process, our result here seems to support the first possibility.

To pin down this possibility, on the theoretical side, we need further improvement on quark model calculation and extension to other N^* productions, which are in progress, and study of other model possibilities; on the experimental side, a partial wave analysis of $J/\psi \to \bar{N}N\pi$ and $\bar{p}p\pi^+\pi^-$ are absolutely necessary.

4. SUMMARY AND OUTLOOK

In summary, the J/ψ decay at BEPC provides a new excellent laboratory for studying the baryon spectroscopy. On experimental side, it provides a natural isospin 1/2 filter for πN and $\pi\pi N$ systems and many interesting channels for studying N^* and Λ^* baryons; on theoretical side, it provides a new way to explore the internal structure of baryons and may help us to pin down hybrid baryon(s). Most subjects on the baryon spectroscopy at the CEBAF and other $\gamma p(ep)$ facilities can be studied here complementally.

Based on 7.8 million J/ψ events collected at BEPC, a partial wave analysis of $J/\psi \to p\bar{p}\eta$ data has been performed. Two $J^P = \frac{1}{2}^-$ resonances, $N^*(1535, S_{11})$ and $N^*(1650, S_{11})$, are observed. With the forthcoming 50 millions more J/ψ events at BEPC with the improved BES detector in next two years[22], more precise partial wave analyses can be carried out on many channels involving baryons and should offer some best determinations of N^* and Λ^* properties. A systematic theoretical and experimental study of the N^* and Λ^* production from the J/ψ decays is underway.

With the new generation of $\gamma p(ep)$ and J/ψ experiments, a new era for the baryon spectroscopy is coming!

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