1 Introduction

To understand the internal quark-gluon structure of nucleon and its excited states $N^*$’s is one of the most important tasks in nowadays particle and nuclear 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 the old generation of $\pi N$ experiments of more than twenty years ago. Considering its importance for the understanding of the nonperturbative QCD, a new generation of experiments on $N^*$ physics with electromagnetic probes (real photon and space-like virtual photon) has recently been started at new facilities such as CEBAF at JLAB, ELSA at Bonn, GRAAL at Grenoble.

The $J/\Psi$ experiment at the Beijing Electron-Positron Collider (BEPC) has long been known as the best place for looking for glueballs. But in fact it is also an excellent place for studying $N^*$ resonances. The corresponding Feynman graphs for the $N^*$ and $N^*$ production are shown in Fig. 1.

These graphs are almost identical to those describing the $N^*$ electro-production process if the direction of the time axis is rotated by $90^\circ$. The only difference is that the virtual photon here is time-like instead of space-like and couples to $NN^*$ through a real vector charmonium meson $J/\Psi$. This fact leads to a few advantages for studying $N^*$ resonances at the BEPC as the
Figure 1: Feynman graphs for $N^*$ and $\bar{N}^*$ production from $e^+e^-$ collision through $J/\Psi$ meson.

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 $\pi N$ 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. A big problem in extracting information on these $N^*$ resonances from $\pi N$ and $\gamma N$ experiments is the isospin decomposition of $1/2$ and $3/2$ for $\pi N$ and $\pi\pi N$ systems. We expect that the results from $J/\Psi$ 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 $\pi N$ two-body channel alone from $\pi N$ and $\gamma N$ experiments.

(3) The annihilation cross section of $e^+e^-$ through $J/\Psi$ is about two order of magnitude larger than that without going through $J/\Psi$ and the branching ratios for our interested channels from $J/\Psi$ decay are quite large, cf. Table 1.

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

Table 1: Branching ratios (BR×10^3) for some interested channels.

With present available 7.8 million $J/\Psi$ events at BES-I and forthcoming 50 millions more at BES-II in near future, we expect to have enough statistics to
get the best determination of properties for $N^* \rightarrow \pi N$ and $\pi\pi N$ from $p\bar{n}\pi^-$, $p\bar{p}\pi^0$ and $p\bar{p}\pi^+\pi^-$ channels; We can also search for the “missing” $N^*$ states and study known $N^*$ states decaying into $\eta N$, $\eta' N$, $\omega N$ and $K\Lambda$ etc.

(4) On theoretical side, the process $J/\Psi \rightarrow \bar{p}N^*$ or $p\bar{N}^*$ provides a new way to probe the internal quark-gluon structure of the $N^*$ resonance.

In the simple three-quark picture of baryons, the process can be described by Fig. 2(a). In this picture, three quark-antiquark pairs are created independently via a symmetric three-gluon intermediate state; the quarks and anti-quarks have momenta of very similar magnitude. This is quite different from the $\gamma p \rightarrow N^*$ process, cf. Fig. 2(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 $J/\Psi \rightarrow \bar{p}N^*$ and $\gamma p \rightarrow N^*$ should probe different aspects of the quark distributions inside baryons. This may help us to distinguish various quark models.

For a hybrid $N^*$, since the $J/\Psi$ decay is a glue-rich process, it can be produced via diagram Fig. 2(c) and is expected to have larger production rate than a pure three-quark $N^*$ resonance.

Considering these advantages, a $N^*$ program at BEPC has been proposed and started.

2 Status of $N^*$ data at BES

Based on 7.8 million $J/\Psi$ events collected at BEPC before 1996, the events for $J/\Psi \rightarrow \bar{p}p\pi^0$ and $\bar{p}p\eta$ have been selected and reconstructed.

The $\pi^0$ and $\eta$ are detected in their $\gamma\gamma$ decay mode. For selected $J/\Psi \rightarrow \bar{p}p\gamma\gamma$ events, the invariant mass spectrum of the $2\gamma$ is shown in Fig. 3. The $\pi^0$ and $\eta$ signals are clearly there.
Figure 3: $\gamma\gamma$ invariant mass spectrum after 4C fit for $J/\Psi \rightarrow \bar{p}p\gamma\gamma$.

Figure 4: Dalitz plot for $J/\Psi \rightarrow \bar{p}p\pi^0$.

Figure 5: $p\pi^0$ invariant mass spectrum for $J/\Psi \rightarrow \bar{p}p\pi^0$.

Figure 6: $p\eta$ invariant mass spectrum for $J/\Psi \rightarrow \bar{p}p\eta$. Crosses are data and histogram the fit.
Fig.4 and Fig.5 show Dalitz plot and $p\pi^0$ invariant mass spectrum for the $J/\Psi \rightarrow \bar{p}p\pi^0$. There are clear peaks around 1480 and 1650 MeV of $p\pi^0$ invariant mass.

Fig.6 shows $p\eta$ invariant mass spectrum for the $J/\Psi \rightarrow \bar{p}p\eta$. There are clear enhancement around the $p\eta$ threshold, peaks at 1540 and 1650 MeV.

We have also selected and reconstructed events for $J/\Psi \rightarrow \bar{p}n\pi^+$ and $p\bar{n}\pi^-$ channels. There are similar $p\pi$ structures as in $J/\Psi \rightarrow \bar{p}p\pi^0$ process. The data processing for other channels, such as $\bar{p}\Lambda K$, $\bar{\Lambda}pK$, $p\bar{n}\pi^+$ and $\bar{p}p\omega$, are in progress.

3 Partial wave analyses of $J/\Psi \rightarrow \bar{p}p\eta$

Because the $J/\Psi \rightarrow \bar{p}p\eta$ has the simplest possible resonance contributions, a partial wave analysis is performed for this channel first. We are mainly interested in the structures at 1540 and 1650 MeV of the $p\eta$ invariant mass. Only $J^P = \frac{1}{2}^+\ N^*$ resonances are included in the analysis, since according to the information from $\pi N \rightarrow \eta N$ and $\gamma N \rightarrow \eta N$ experiments resonances with higher spins have much smaller couplings to $p\eta$ in our interested mass range.

We use the effective Lagrangian approach\cite{9,10} for the partial wave analysis. The relevant spin-1/2 interaction Lagrangians are

$$L_{\eta PR} = -ig_{\eta PR} \bar{R} \Gamma_{\eta} R + H.c.,$$

$$L_{\Psi PR}^{(1)} = \frac{ig_{\Psi PR}}{M_R + M_P} \bar{R} \Gamma_{\mu} q^{\mu} P \Psi + H.c.,$$

$$L_{\Psi PR}^{(2)} = -g_{\Psi PR} \bar{R} \Gamma_{\mu} P \Psi + H.c.$$\hspace{1cm}(3)

where $R$ is the generic notation for the resonance with mass $M_R$, $P$ for proton with mass $M_P$ and $\Psi$ for $J/\Psi$ with four-momentum $q$. The operator structures for the $\Gamma$, $\Gamma_{\mu}$ and $\Gamma_{\mu\nu}$ are

$$\Gamma = 1, \quad \Gamma_{\mu} = \gamma_{\mu}, \quad \Gamma_{\mu\nu} = \gamma_5 \sigma_{\mu\nu},$$

$$\Gamma = \gamma_5, \quad \Gamma_{\mu} = \gamma_5 \gamma_{\mu}, \quad \Gamma_{\mu\nu} = \sigma_{\mu\nu},$$\hspace{1cm}(5)

where $\Gamma$ and $\Gamma_{\mu}$ correspond to nucleon resonances of odd and even parities, respectively. The relative magnitudes and phases of the amplitudes are determined by a maximum likelihood fit to the data. A fit with three $N^*$ resonances is shown in Figs.6-8 for the $p\eta$, $\bar{p}p$ invariant mass spectra and the angular distribution of the proton relative to the beam direction, respectively.

The peak near the $p\eta$ threshold is fitted with a $N^*$ resonance of mass and width optimised at $M = 1540^{+15}_{-12}$ and $\Gamma = 178^{+20}_{-22}$ MeV, respectively.
data favor $J^P = \frac{1}{2}^-$ over $\frac{1}{2}^+$. A fit with $J^P = \frac{1}{2}^+$ instead gives likelihood value $\ln L$ worse by 16.0 than for $\frac{1}{2}^-$ assignment (Our definition of $\ln L$ is such that it increases by 0.5 for a one standard deviation change in one parameter). The statistical significance of the peak is above 6.0$\sigma$. It is obviously the $S_{11}N^*(1535)$ resonance. It makes the largest contribution $(84 \pm 5)\%$ to the $p\bar{p}\eta$ final states. The errors here and later include both statistics and systematic errors from the fit.

The second peak around 1650 MeV is also fitted with a $J^P = \frac{1}{2}^-$ resonance $N^*(1650)$. Its mass optimises at $M = 1648^{+18}_{-16}$ MeV with $\Gamma = 150$ MeV fixed to PDG value. Its width cannot be well determined by our data due to a correlation with the parameters used for the third resonance. It contributes $(11 \pm 3)\%$ to the $p\bar{p}\eta$ final states.

A small improvement to the fit is given by including an additional $J^P = \frac{1}{2}^+$ resonance, which optimises at $M = 1834^{+46}_{-55}$ MeV with $\Gamma = 200$ MeV fixed. The statistical significance of the peak is only 2.0$\sigma$. We have tried $J^P = \frac{1}{2}^-$ instead $\frac{1}{2}^+$, the fit is worse.

An interesting result is that the $\mathcal{L}^{(2)}_{\Psi PR}$ term given by Eq.(3) makes insignificant contribution for both $N^*(1535)$ and $N^*(1650)$. If we drop this kind of couplings for both resonances, the likelihood value for the fit is only worse by
0.8 for 4 less free parameters. This kind of couplings should vanish for the real photon coupling to $NN^*$. Why it also vanishes for the $\Psi NN^*$ coupling needs to be understood. A theoretical calculation assuming pure $L(2)$ $\Psi$ coupling without $L(1)$ $\Psi$ coupling failed to reproduce the basic feature of the $J/\Psi \rightarrow \bar{p}p\eta$ data. This is consistent with our observation that the $L(1)$ $\Psi$ coupling dominates for both $N^*(1535)$ and $N^*(1650)$.

In the Vector Meson Dominance (VMD) picture, the virtual photon couples to the $NN^*$ through vetor mesons, and the electro-magnetic $NN^*$ transition form factors $g_{\gamma^*NN^*}$ can be expressed in terms of photon-meson coupling strengths $C_{\gamma V}$ and meson-$NN^*$ vertex form factors $g_{VNN^*}$:

$$g_{\gamma^*NN^*}(q^2) = \sum_j \frac{m_j^2 C_{\gamma V_j}}{m_j^2 - q^2 - im_j \Gamma_j} g_{V NN^*}(q^2)$$

with

$$C_{\gamma V} = \sqrt{\frac{3(\Gamma_{V \rightarrow e^+e^-})}{\alpha m_V}}.$$  \hspace{1cm} (7)

At $q^2 = M_{\Psi}^2$, the $J/\Psi$ meson dominates. The terms from other vector mesons are negligible. From our PWA results here and other relevant information from PDG, we can deduce the transition form factor for the time-like virtual photon to $PN^*(1535)$ as

$$|g_{\gamma^*pN^*}(q^2 = M_{\Psi}^2)| = 2.8 \pm 0.5,$$

which is related to the more familiar helicity amplitude $A^{P}_{1/2}$ for $N^* \rightarrow \gamma P$ by

$$|A^{P}_{1/2}|^2 = \left( \frac{g_{\gamma pN^*}(q^2 = 0)}{M_{N^*} + M_P} \right)^2 \frac{(M_{N^*}^2 - M_P^2)}{2M_P}.$$  \hspace{1cm} (9)

4 Summary and outlook

In summary, the $J/\Psi$ decay at BEPC provides a new excellent laboratory for studying the $N^*$ resonances. On experimental side, it provides a natural isospin 1/2 filter for $\pi N$ and $\pi\pi N$ systems and many interesting channels for studying $N^*$ and hyperon resonances; 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). Almost all subjects on the $N^*$ resonances at the CEBAF and other $\gamma p(ep)$ facilities can be studied here complementally with the virtual time-like photon.
Based on 7.8 million $J/\psi$ events collected at BEPC, a partial wave analysis of $J/\psi \rightarrow pp\eta$ data has been performed. Two $J^P = \frac{1}{2}^-$ resonances, $N^*(1535, S_{11})$ and $N^*(1650, S_{11})$, are observed. Now we are collecting more $J/\Psi$ events with the improved BES detector. With the forthcoming 50 millions more $J/\Psi$ events in near future, more precise partial wave analyses can be carried out on many channels involving $N^*$ resonances and should offer some best determinations of $N^*$ properties. A systematic theoretical and experimental study of the $N^*$ and hyperon production from the $J/\psi$ decays is underway.

There is also a plan to upgrade the BEPC to BEPC2 which will increase the luminosity by an order of magnitude. This will provide us more precise data for the study of the $N^*$ resonances from $J/\Psi$ decays and also enable us to extend the $N^*$ program to a higher energy at the $\Psi'$ resonance which now suffers low statistics for the $N^*$ study.

With the new generation of $\gamma p(e)p$, $J/\psi$ and $\Psi'$ experiments, a new era for the baryon spectroscopy is coming.

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