Over sixty million $J/\psi$ events have been collected by the BES Collaboration at the Beijing Electron-Positron Collider (BEPC). $J/\psi$ decays provide an excellent place for studying excited nucleons and hyperons – $N^*$, $\Lambda^*$, $\Sigma^*$ and $\Xi^*$ resonances, as well as meson resonances, including possible glueballs and hybrids. Physics objectives, recent results and future prospects of light hadron spectroscopy at BEPC are presented.

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1. Introduction

The Institute of High Energy Physics at Beijing runs an electron-positron collider (BEPC) with a general purpose solenoidal detector, the BEijing Spectrometer (BES)\cite{1}, which is designed to study exclusive final states in $e^+e^-$ annihilations at the center of mass energy from 2000 to 5600 MeV. In this energy range, the largest cross sections are at the $J/\psi(3097)$ and $\psi'(3686)$ resonant peaks. Up to now, the BES has collected about 65 million $J/\psi$ events and 18 million $\psi'$ events. From $J/\psi$ and $\psi'$ decays, both meson spectroscopy and baryon spectroscopy can be studied.

Three main processes which play very important role for the light hadron spectroscopy are $\psi$ hadronic decay into baryons and anti-baryons, $\psi$ radiative decay, and $\psi$ hadronic decay into mesons. In the following three sections, I will outline the physics objectives and summarize recent results for each of them. Future prospects are given in the final section.

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2. $N^*$ and hyperons from $J/\psi$ decays

Baryons are the basic building blocks of our world. If we cut any piece of object smaller and smaller, we will finally reach the nucleons, i.e., the lightest baryons, and we cannot cut them smaller any further. So without mention any theory, we know that the study of baryon structure is at the forefront of exploring microscopic structure of matter. From theoretical point of view, since baryons represent the simplest system in which the three colors of QCD neutralize into colorless objects and the essential non-Abelian character of QCD is manifest, understanding the baryon structure is absolutely necessary before we claim that we really understand QCD.

Spectroscopy has long proved to be a powerful tool for exploring internal structures and basic interactions of microscopic world. Ninety years ago detailed studies of atomic spectroscopy resulted in the great discovery of Niels Bohr’s atomic quantum theory [2]. Forty to sixty years later, still detailed studies of nuclear spectroscopy resulted in Nobel Prize winning discoveries of nuclear shell model [3] and collective motion model [4] by Aage Bohr et al. Comparing with the atomic and nuclear spectroscopy at those times, our present baryon spectroscopy is still in its infancy [5]. Many fundamental issues in baryon spectroscopy are still not well understood [6]. The possibility of new, as yet unappreciated, symmetries could be addressed with accumulation of more data. The new symmetries may not have obvious relation with QCD, just like nuclear shell model and collective motion model.

Joining the new effort on studying the excited nucleons, $N^*$ baryons, at new facilities such as CEBAF at JLAB, ELSA at Bonn, GRAAL at Grenoble and SPRINGS at JASRI, we also started a baryon resonance program at BES [7], at Beijing Electron-Positron Collider (BEPC). The $J/\psi$ and $\psi'$ experiments at BES provide an excellent place for studying excited nucleons and hyperons – $N^*$, $\Lambda^*$, $\Sigma^*$ and $\Xi^*$ resonances [8]. The corresponding Feynman graph for the production of these excited nucleons and hyperons is shown in Fig. 1 where $\psi$ represents either $J/\psi$ or $\psi'$.

![Feynman graph](image_url)

Fig. 1. $\bar{p}N^*$, $\bar{\Lambda}\Lambda^*$, $\bar{\Sigma}\Sigma^*$ and $\bar{\Xi}\Xi^*$ production from $e^+e^-$ collision through $\psi$ meson.
Comparing with other facilities, our baryon program has advantages in at least three obvious aspects:

1. We have pure isospin 1/2 $\pi N$ and $\pi \pi N$ systems from $J/\psi \rightarrow \bar{N}N\pi$ and $\bar{N}N\pi\pi$ processes due to isospin conservation, while $\pi N$ and $\pi\pi N$ systems from $\pi N$ and $\gamma N$ experiments are mixture of isospin 1/2 and 3/2, and suffer difficulty on the isospin decomposition;

2. $\psi$ mesons decay to baryon-antibaryon pairs through three or more gluons. It is a favorable place for producing hybrid ($qqg$) baryons, and for looking for some “missing” $N^*$ resonances which have weak coupling to both $\pi N$ and $\gamma N$, but stronger coupling to $g^3N$;

3. Not only $N^*$, $\Lambda^*$, $\Sigma^*$ baryons, but also $\Xi^*$ baryons with two strange quarks can be studied. Many QCD-inspired models\cite{9,10} are expected to be more reliable for baryons with two strange quarks due to their heavier quark mass. More than thirty $\Xi^*$ resonances are predicted where only two such states are well established by experiments. The theory is totally not challenged due to lack of data.

BES started data-taking in 1989 and was upgraded in 1998. The upgraded BES is named BESII while the previous one is called BESI. BESI collected 7.8 million $J/\psi$ events and 3.7 million $\psi'$ events. BESII has collected 58 million $J/\psi$ events.

![Fig. 2. left: $p\pi^0$ invariant mass spectrum for $J/\psi \rightarrow \bar{p}p\pi^0$; right: $p\eta$ invariant mass spectrum for $J/\psi \rightarrow \bar{p}p\eta$. BESI data.](image_url)
mass spectra are shown in Fig. 2 with clear peaks around 1500 and 1670 MeV for $p\pi^0$ and clear enhancement around the $p\eta$ threshold, peaks at 1540 and 1650 MeV for $p\eta$. Partial wave analysis has been performed for the $J/\psi \to \bar{p}p\eta$ channel [7] using the effective Lagrangian approach [11, 12] with Rarita-Schwinger formalism [13, 14, 15, 16] and the extended automatic Feynman Diagram Calculation (FDC) package [17]. There is a definite requirement for a $J^P = \frac{1}{2}^-$ component at $M = 1530 \pm 10$ MeV with $\Gamma = 95 \pm 25$ MeV near the $\eta N$ threshold. In addition, there is an obvious resonance around 1650 MeV with $J^P = \frac{1}{2}^-$ preferred, $M = 1647 \pm 20$ MeV and $\Gamma = 145^{+80}_{-45}$ MeV. These two $N^*$ resonances are believed to be the two well established states, $S_{11}(1535)$ and $S_{11}(1650)$, respectively. In the higher $\eta N$ mass region, there is a evidence for a structure around 1800 MeV; with BESI statistics we cannot determine its quantum numbers.

![Fig. 3. left: missing mass spectrum against $p\pi^-$ for $J/\psi \to \bar{n}p\pi^-$; right: $p\pi^- & \bar{n}\pi^-$ invariant mass spectrum for $J/\psi \to \bar{n}p\pi^-$. Preliminary BESII data](image)

With 58 million new $J/\psi$ events collected by BESII of improved detecting efficiency, we have one order of magnitude more reconstructed events for each channel. We show in Figs. 3 and 4 preliminary results for $J/\psi \to p\bar{n}\pi^-$ and $J/\psi \to pK^-\Lambda + h.c.$ channels, respectively.

For $J/\psi \to p\bar{n}\pi^-$ channel, proton and $\pi^-$ are detected. With some cuts of backgrounds, the missing mass spectrum shows a very clean peak for the missing antineutron with negligible backgrounds; The $N\pi$ invariant mass spectrum of 28,904 reconstructed events from half BESII data looks similar to the $p\pi$ invariant mass spectrum for $J/\psi \to p\bar{n}\pi^0$ as in Fig. 3, but with much higher statistics. Besides two very clear peaks around 1500 and 1670 MeV, the peak around 2020 MeV becomes clearer. This could be a “missing”
For the decay $J/\psi \rightarrow \bar{N}N^*(2020)$, the orbital angular momentum of $L = 0$ is much preferred due to the suppression of the centrifugal barrier factor for $L \leq 1$. For $L = 0$, the spin-parity of $N^*(2020)$ is limited to be $1/2^+$ and $3/2^+$. This may be the reason that the $N^*(2020)3/2^+$ shows up as a peak in $J/\psi$ decays while no peak shows up for $\pi N$ invariant mass spectra in $\pi N$ and $\gamma N$ production processes which allow all $1/2^\pm, 3/2^\pm, 5/2^\pm$ and $7/2^\pm$ $N^*$ resonances around 2.02 GeV to overlap and interfere with each other there.

For $J/\psi \rightarrow \bar{p}K^-\Lambda$ and $\bar{p}K^+\Lambda$ channels, there are clear $\Lambda^*$ peaks at 1.52 GeV, 1.69 GeV and 1.8 GeV in $pK$ invariant mass spectrum, and $N^*$ peaks near $K\Lambda$ threshold and 1.9 GeV for $K\Lambda$ invariant mass spectrum. The SAPHIR experiment at ELSA also observed a $N^*$ peak around 1.9 GeV for $K\Lambda$ invariant mass spectrum from photo-production.

We are also reconstructing $J/\psi \rightarrow \bar{p}\rho\omega, pK\Sigma, \bar{p}p\pi^+\pi^-$ and other channels. Partial wave analyses of various channels are in progress.

### 3. $J/\psi$ radiative decays

There are three main physics objectives for $J/\psi$ radiative decays:

1. Looking for glueballs and hybrids. As shown in Fig. 5 after emitting a photon, the $c\bar{c}$ pair is in a $C = +1$ state and decays to hadrons dominantly through two gluon intermediate states. Simply counting the power of $\alpha_s$ we know that glueballs should have the largest production rate, hybrids the second, then the ordinary $q\bar{q}$ mesons.
(2) Completing $q\bar{q}$ meson spectroscopy and studying their production and decay rates, which is crucial for understanding their internal structure and confinement.

(3) Extracting $gq \leftrightarrow q\bar{q}$ coupling from perturbative energy region of above 3 GeV to nonperturbative region of 0.3 GeV. This may show us some phenomenological pattern for the smooth transition from perturbative QCD to strong nonperturbative QCD.

Up to now, we have mainly worked on glueball searches. One thing worth noting is that the $J/\psi$ radiative decay has a similar decay pattern as $0^{-+}$, $0^{++}$ and $2^{++}$ charmoniums, i.e., $\eta_c$, $\chi_{c0}$ and $\chi_{c2}$, as it should be, since all of them decay through two gluons. The $4\pi$, $\bar{K}K\pi\pi$, $\eta\pi\pi$ and $\bar{K}K\pi$ seem to be the most favorable final states for the two gluon transition at $1 \sim 3$ GeV. The branching ratios for $J/\psi$ radiative decay to these four channels are listed in Table 1. The sum of them is about half of all radiative decays. If glueballs exist, they should appear in these four channels. Therefore BES Collaboration has performed partial wave analyses (PWA) of these four channels\cite{20,21,22,23} based on BESI data. The main results have been summarized in Ref. \cite{25}. Mesons with large branching ratios in the $J/\psi$ radiative decays are a very broad $\eta(2190)$ for $0^{-+}$, a broad $f_2(1950)$ for $2^{++}$, $f_0(1500)$, $f_0(1710-1770)$ and $f_0(2100)$ for $0^{++}$.

![Fig. 5. ψ radiative decays to (a) glueball, (b) hybrid, and (c) q̅q meson.](image)

Table 1. Branching ratios for the four largest $J/\Psi$ radiative decay channels (BR×10^{-3})

| Channel                  | BR×10^{-3} |
|--------------------------|------------|
| $\gamma 4\pi$           | 14.4 ± 1.8 |
| $\gamma \bar{K}K\pi\pi$ | 9.5 ± 2.7  |
| $\gamma \eta\pi\pi$    | 6.1 ± 1.0  |
| $\gamma \bar{K}K\pi$   | 6.0 ± 2.1  |

With BESII data, all signals become clearer. For example, Fig. 6 shows the comparison of BESI and BESII data for $J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$. For BESII data, we have performed partial wave analysis for the $\gamma \bar{K}K$ and $\gamma \pi^+\pi^-$ channels\cite{26}, where the main result is that $f_J(1710)$ peak in these
channels is definitely due to a $0^{++}$ particle.

4. $J/\psi$ hadronic decays to mesons

There are mainly two physics objectives here:

(1) Looking for hybrids. Since $\psi$ decays to hadrons through three gluons, final states involving a hybrid as shown in Fig. 7(a) are expected to have larger production rate than ordinary $q\bar{q}$ mesons as shown in Fig. 7(b,c).

(2) Extracting $u\bar{u} + d\bar{d}$ and $s\bar{s}$ components of associated mesons, $M$, via $\Psi \rightarrow M + \omega/\phi$ as shown in Fig. 7(b,c).

![Fig. 7. $\Psi$ hadronic decays to (a) hybrids, (b) $s\bar{s}$, and (c) $n\bar{n} \equiv \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ mesons.](image)

In order to look for isoscalar $1^{-+}$ hybrid $\hat{\omega}$ decaying to $4\pi$, we have studied $J/\psi \rightarrow \omega\pi^+\pi^-\pi^+\pi^-$ process\[27\]. A peak around 1.75 GeV in the $4\pi$ invariant mass spectrum is visible. But due to low statistics, no PWA is performed. No other structure is observed.

To investigate the $u\bar{u} + d\bar{d}$ and $s\bar{s}$ components of mesons, we have studied $J/\psi \rightarrow \omega\pi^+\pi^-$, $\omega K^+K^-$, $\phi\pi^+\pi^-$ and $\phi K^+K^-$ channels. The invariant mass spectra for these channels are shown in Fig. 8 and Fig. 9, which are similar to the previous ones by MARKIII and DM2 Collaborations, but with much higher statistics.
Fig. 8. left: $\pi\pi$ invariant mass spectrum for $J/\psi \rightarrow \omega \pi^+\pi^-$; right: $K^+K^-$ invariant mass spectrum for $J/\psi \rightarrow \omega K^+K^-$. Preliminary BESII data

Fig. 9. left: $\pi\pi$ invariant mass spectrum for $J/\psi \rightarrow \phi \pi^+\pi^-$; right: $K^+K^-$ invariant mass spectrum for $J/\psi \rightarrow \phi K^+K^-$. Preliminary half BESII data

For $J/\psi \rightarrow \omega \pi^+\pi^-$, there are two clear peaks at 500 MeV and 1275 MeV in the $2\pi$ mass spectrum corresponding to the $\sigma$ and the $f_2(1275)$, respectively [28]. For $J/\psi \rightarrow \omega K^+K^-$, there is a threshold enhancement due to the $f_0(980)$ and a clear peak at 1710 MeV probably due to the $f_0(1710)$.

Preliminary results [28] of partial wave analyses indicate that (1) in the $\pi\pi$ mass spectrum of the $J/\psi \rightarrow \phi \pi^+\pi^-$ process all three peaks at 980 MeV, 1330 MeV and 1770 MeV are dominantly $0^{++}$; (2) in the $K\bar{K}$ mass spectrum of the $J/\psi \rightarrow \phi K^+K^-$ the peak at 1525 MeV is due to $f_2'(1525)$ while the $K\bar{K}$ threshold enhancement and the shoulder around 1700 MeV are due to $f_0(980)$ and $f_0(1710)$, respectively.
In summary, the $\sigma$ and $f_2(1275)$ appear clearly only in the $J/\Psi \rightarrow \omega + X$ process, the $f_2'(1525)$ appears clearly only in the $J/\Psi \rightarrow \phi + X$ process, and $f_0(980)$ and $f_0(1710-1770)$ appear clearly in both processes.

5. Future prospects

We are now working on the 58 million $J/\psi$ events collected with BESII detector in the years from 1999 to 2001. Physics results on various channels of $N^*$ and meson production are expected to be published in near future.

We have been taking $\psi'(3686)$ data since last year and hope to reach more than 20 million $\psi'$ events in next year. The data of $\psi'$ decays will extend our study on $N^*$ and meson resonances to a broader energy range.

A major upgrade of the collider to BEPCII is planned to be finished in about 4 years. A further two order of magnitude more statistics is expected to be achieved. Such statistics will enable us to perform partial wave analyses of plenty important channels for both meson spectroscopy and baryon spectroscopy from the $J/\psi$ and $\psi'$ decays. We expect BEPCII to play a very important role in many aspects of light hadron spectroscopy, such as hunting for the glueballs and hybrids, extracting $u\bar{u}+d\bar{d}$ and $s\bar{s}$ components of mesons, and studying excited nucleons and hyperons, i.e., $N^*$, $\Lambda^*$, $\Sigma^*$ and $\Xi^*$ resonances.

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