Baryon Spectroscopy at Beijing Electron Positron Collider

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BES Collaboration has collected 58 million $J/\psi$ events 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. Physics motivation, data status, partial wave analyses and future prospects are presented for the baryon resonance program at BES.

1 Physics Motivation

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 [1]. Forty to sixty years later, still detailed studies of nuclear spectroscopy resulted in Nobel Prize winning discoveries of nuclear shell model [2] and collective motion model [3] by Aage Bohr et al. Comparing with the atomic and nuclear spectroscopy at those times, our present baryon spectroscopy is still in its infancy [4]. Many fundamental issues in baryon spectroscopy are still not well understood [5]. 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 SPRING8 at JASRI, we also started a baryon resonance program at BES [6], 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 [7]. 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 $\psi'$.

![Figure 1: $\bar{p}N^*$, $\bar{\Lambda}\Lambda^*$, $\bar{\Sigma}\Sigma^*$ and $\bar{\Xi}\Xi^*$ production from $e^+e^-$ collision through $\Psi$ meson.](image-url)
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 (qqgg) baryons, and for looking for some “missing” $N^*$ resonances which have weak coupling to both $\pi N$ and $\gamma N$, but stronger coupling to $g^3 N$;

(3) Not only $N^*$, $\Lambda^*$, $\Sigma^*$ baryons, but also $\Xi^*$ baryons with two strange quarks can be studied. Many QCD-inspired models \cite{8,9} 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.

2 Data Status

The BEijing Spectrometer (BES) is a conventional solenoidal magnet detector that is described in detail in Ref. \cite{10}. A four-layer central drift chamber (CDC) surrounding the beampipe provides trigger information. A forty-layer cylindrical main drift chamber (MDC), located radially outside the CDC, provides trajectory and energy loss ($dE/dX$) information for charged tracks over 85% of the total solid angle. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks. Radially outside of TOF system is a 12 radiation length thick, lead-gas barrel shower counter (BSC) operating in the limited streamer mode. This device covers $\sim 80\%$ of the total solid angle and measures the energies of electrons and photons.

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 50 million $J/\psi$ events.

![Figure 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)

Based on 7.8 million $J/\psi$ events collected at BESI before 1996, the events for $J/\Psi \rightarrow \bar{p}p\pi^0$ and $\bar{p}p\eta$ have been selected and reconstructed with $\pi^0$ and $\eta$ detected in their $\gamma\gamma$ decay mode \cite{6}. The
corresponding $p\pi^0$ and $p\eta$ invariant 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 $p\eta$.

Figure 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

Figure 4: left: $pK$ invariant mass spectrum for $J/\psi \to pK\Lambda$; right: $K\Lambda$ invariant mass spectrum for $J/\psi \to pK\Lambda$. Preliminary BESII data

With 50 million new $J/\psi$ events collected by BESII of improved detecting efficiency, we expect to have one order of magnitude more reconstructed events for each channel. We show in Figs. 3 and 4 preliminary results for $J/\psi \to \bar{n}\pi\pi^-$ [11] and $J/\psi \to pK^-\Lambda + h.c.$ [12] channels, respectively. For $J/\psi \to \bar{n}\pi\pi^-$ 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 $J/\psi \to p\bar{p}\pi^0$ as in Fig. 2 but with much higher statistics. For
$J/\psi \to pK^-\Lambda$ 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.

We are also reconstructing $J/\psi \to \bar{p}p\omega$, $\bar{p}p\pi^+\pi^-$ and other channels. The $\bar{p}p\omega$ channel suffers larger background and the $\bar{p}p\pi^+\pi^-$ suffers the complication of $\pi\pi$ S-wave interaction $^4$.$^5$.$^6$.

3 Partial wave analyses

In order to get more useful information about properties of the baryon resonances, such as their $J^{PC}$ quantum numbers, mass, width, production and decay rates, etc., partial wave analyses (PWA) are necessary.

The basic procedure for our partial wave analyses is the standard maximum likelihood method:

1. construct amplitudes $A_i$ for each i-th possible partial waves;
2. from linear combination of these partial wave amplitudes, get the total transition probability for each event as $w = |\sum_i c_i A_i|^2$ with $c_i$ as free parameters to be determined by fitting data;
3. maximize the following likelihood function $L$ to get $c_i$ parameters as well as mass and width parameters for the resonances.

$$L = \prod_{n=1}^{N} \frac{w_{\text{data}}}{\int w_{\text{MC}}},$$

where $N$ is the number of reconstructed data events and $w_{\text{data}}$, $w_{\text{MC}}$ are evaluated for data and Monte Carlo events, respectively.

For the construction of partial wave amplitudes, we assume the effective Lagrangian approach $^4$.$^5$, with Rarita-Schwinger formalism $^5$.$^6$.$^7$. In this approach, there are three basic elements for constructing amplitudes: particle spin wave functions, propagators and effective vertex couplings; the amplitude can be written out by Feynman rules for tree diagrams.

For example, for $J/\psi \to \bar{N}N^*(3/2^+) \to \bar{N}(k_1, s_1)N(k_2, s_2)\eta(k_3)$, the amplitude can be constructed as

$$A_{3/2^+} = \bar{u}(k_2, s_2)k_2\mu P_{3/2}^{\mu\nu}(c_1 g_{\nu\lambda} + c_2 k_1\nu\gamma\lambda + c_3 k_1\nu k_1\lambda)\gamma_5 v(k_1, s_1)\psi^\lambda$$

where $u(k_2, s_2)$ and $v(k_1, s_1)$ are $1/2$-spinor wave functions for $N$ and $\bar{N}$, respectively; $\psi^\lambda$ the spin-1 wave function, i.e., polarization vector, for $J/\psi$. The $c_1$, $c_2$ and $c_3$ terms correspond to three possible couplings for the $J/\psi \to \bar{N}N^*(3/2^+)$ vertex. The $c_1$, $c_2$ and $c_3$ can be taken as constant parameters or with some smooth vertex form factors in them if necessary. The spin $3/2$ propagator $P_{3/2}$ for $N^*(3/2^+)$ is

$$P_{3/2}^{\mu\nu} = \frac{\gamma \cdot p + M_{N^*}}{M_{N^*}^2 - p^2 - iM_{N^*}\Gamma_{N^*}} \left[ g^{\mu\nu} - \frac{1}{3} \gamma^\mu \gamma^\nu - \frac{2p^\mu p^\nu}{3M_{N^*}^2} + \frac{p^\mu \gamma^\nu - p^\nu \gamma^\mu}{3M_{N^*}} \right]$$

with $p = k_2 + k_3$.

Other partial wave amplitudes can be constructed similarly $^5$. Programing these amplitudes and maximum likelihood method to fit the data is straightforward, but very tedious. Now we are extending the automatic Feynman Diagram Calculation (FDC) package $^{20}$ to work for our partial wave analyses of baryon resonance channels. Using the extended FDC package, we have performed a partial wave analysis of the $\bar{p}p\eta$ channel $^3$ of BESI data and are now working on more channels.

For the $\bar{p}p\eta$ channel, 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 \( p\eta(\bar{p}\eta) \) mass region, there is a evidence for a structure around 1800 MeV; with BESI statistics we cannot determine its quantum numbers.

For the \( S_{11}(1535) \) propagator, we tried both constant and energy-dependent width. The Breit-Wigner mass is not sensitive at all to these two choices. The Breit-Wigner width differs by 10 MeV for these two choices: \( \Gamma = 90 \pm 20 \) MeV for the case of a constant width and \( \Gamma = 100 \pm 20 \) MeV for the case of an energy-dependent width assuming 50% to \( \eta N \) and 50% to \( \pi N \). The pole position \( (M, \Gamma/2) \) is \( (1530, 45) \) MeV and \( (1512, 46) \) MeV for assuming constant width and the energy-dependent width, respectively.

Preliminary partial wave analysis [11] of BESII data on \( \bar{n}p\pi^- \) channel gives a similar result on \( N^*(1535) \) with much smaller error bars. The outstanding narrow peak around 1.5 GeV in the \( \pi N \) invariant mass spectrum demands \( N^*(1535) \) to be narrow (width definitely less than 120 MeV) rather model independently, while PDG gives a width of 100 \( \sim \) 250 MeV.

4 Future prospects

BESII just finished data-taking for the 50 million \( J/\psi \) events in last May. We are now working on partial wave analyses of \( J/\psi \rightarrow p\bar{n}\pi^- \), \( p\bar{p}\omega \) channels to study \( N^* \) resonances, and \( pK^\pm\Lambda \), \( \bar{p}K^\mp\Lambda \) channels to study \( \Lambda^* \) resonances as well as \( N^* \rightarrow \Lambda K \). As next step, we are going to investigate \( \Lambda\Sigma^-\pi^+ \), \( pK^-\Sigma^0 \) channels to study \( \Sigma^* \) resonances; and \( K^-\Lambda\Xi^+ \), \( K^+\Lambda\Xi^- \) channels to study \( \Xi^* \) resonances. These channels are relative easy to be reconstructed by BES. For example, for \( K^-\Lambda\Xi^+ \), we can select events containing \( K^- \) and \( \Lambda \) with \( \Lambda \rightarrow p\pi^- \), then from missing mass spectrum of \( K^-\Lambda \) we should be able to identify the very narrow \( \Xi^+ \) peak. We will investigate more complicated channels when we get more experienced and more manpower. Meanwhile more theoretical efforts are needed for better partial wave analyses and extraction of physics from our experimental results [21].

A major upgrade of the collider to BEPC2 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 from not only \( J/\Psi \) but also \( \Psi' \) decays which will allow us to study heavier baryon resonances, e.g., for mass up to 2.36 GeV for \( \Xi^* \) resonances. We expect BEPC2 to play a very important unique role in studying excited nucleons and hyperons, i.e., \( N^* \), \( \Lambda^* \), \( \Sigma^* \) and \( \Xi^* \) resonances, and make important discoveries for understanding microscopic structure of matter.

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