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N^* Production from e^+e^- Annihilations

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Abstract: Up to now, the N^* production from e^+e^- annihilations has been studied only around charmonium region. Charmonium decays to N^*s are analogous to (time-like) EM form factors in that the charm quark annihilation provides a nearly pointlike (ggg) current. Complementary to other sources, such as πN, eN and γN reactions, this new source for N^* spectroscopy has a few advantages, such as an isospin filter and a low spin filter. The experimental results on N^* from e^+e^- annihilations and their phenomenological implications are reviewed. Possible new sources on N^* production from e^+e^- annihilations are discussed.

Key words: N^* spectrum; electron-positron annihilation; hadron structure

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1 Introduction

Historically the study of spectroscopy at various microscopic levels of matter proves to be a powerful tool to explore the relevant structures and interactions. About a hundred years ago, the study of atomic spectroscopy revealed the quantum physical picture for atoms and played an important role for the development of quantum mechanics. Around the middle of last century, the study of nuclear spectroscopy led to the two Nobel prize-winning works: nuclear shell model and collective motion model. With the quark model developed in the early 1960s, it became clear that the hadrons are not elementary particles, but composed of quarks and antiquarks. In the classical quark model, a baryon is composed of three quarks and a meson is composed of one quark and one antiquark. The only stable hadron is the proton which was proposed to be composed of two u-quarks and one d-quark. Since then, the protons were used as targets to be bombarded by pion, electron, photo beams to explore the spectroscopy of excited nucleons, N^* resonances[1–4].

With accumulation of half century on the N^* spectroscopy, two outstanding problems appeared for the classical simple 3q constituent quark model. The first outstanding problem is that the mass-order for the lowest excited states is reversed. In the simple 3q constituent quark model, the lowest spatially-excited baryon is expected to be a (uud) N^* state with one quark in orbital angular momentum $L=1$ state, and hence should have negative parity. Experimentally, the lowest negative parity N^* resonance is found to be $N^*(1535)$[4], which is heavier than $N^*(1440)$ of positive parity. The second outstanding problem is that in many of its forms the classical 3q quark model predicts a substantial number of missing N^* states' around 2 GeV/c^2, which have not so far been observed[5].

The first problem suggests that we should go beyond the simple 3q quenched quark model. It can be reconciled by taking these N^*s as meson-baryon dynamically generated states[6–11] or considering large 5-quark components in them[12–14].

For the second problem, non-observation of these missing N^* states' does not necessarily mean that they do not exist. Their couplings to πN and γN may be too weak to be observed by presently available πN and γN experiments[5]. Other production processes should be explored. Joining the effort on studying the excited nucleons, N^* baryons, BES started a baryon resonance program[15] at Beijing Electron-Positron Collider (BEPC) just before the start of new century. The J/ψ and $\psi(2S)$ experiments at BES provide an excellent place for studying excited nucleons and hyperons – N^*, Λ^*, Σ^* and Ξ^* resonances[16–17].

In the following, the major experimental results on N^* from e^+e^- annihilations for last 20 years and some of their interesting phenomenological implications are reviewed.

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2 N^* production from $c\bar{c}$ decays

Since 2001, BES/BESII/BESIII Collaborations have published their results on N^* production from $J/\psi \to p\bar{p}\eta$[18], $p\bar{n}\pi^- + c.c.$[19], $p\bar{p}\pi^0$[20], $pK^-\bar{\Lambda} + c.c.$[21], $\bar{n}K_S^0\Lambda$[22], $p\bar{p}\omega$[23], $p\bar{p}\phi$[24], $p\bar{p}\pi^0\eta$[25], and $\psi(2S) \to p\bar{p}\eta$[26], $p\bar{n}\pi^- + c.c.$[27], $p\bar{p}\pi^0$[28], $\bar{p}K^+\Sigma^0$[29], and $\chi_{cJ} \to p\bar{n}\pi^-$[30], $p\bar{n}\pi^-\pi^0$[30], $\bar{p}K^+\Lambda$[29], and $\psi(3770) \to p\bar{p}\pi^0$[31]. Some interesting insights on the N^*s have been gained through this novel source of information.

In Fig. 1, the invariant mass data corrected by Monte Carlo(MC) simulated efficiency and divided by phase space versus $p\pi^-$ (or $\bar{p}\pi^+$) invariant mass for $J/\psi \to p\bar{n}\pi^- + c.c.$ and $\psi(2S) \to p\bar{n}\pi^- + c.c.$ are shown together for a comparison. Similarly, in Fig. 2, $p\pi^0$ (or $\bar{p}\pi^0$) invariant mass for $J/\psi \to p\bar{p}\pi^0$ and $\psi(2S) \to p\bar{p}\pi^0$ are presented. Compared with $N\pi$ invariant mass spectrum from πp or γp reactions, an obvious phenomen is that there are more N^* peaks meanwhile without the strong Δ peak. This is because ψ annihilates into a baryon-antibaryon pair through three gluons and conserves isospin. The $N\pi$ recoiling an anti-proton is limited to be isospin 1/2. So the charmonium annihilation provides a nice isospin filter. Due to the non-presence of the strong Δ peak in other reactions, the $N^*(1440)$ peak was observed for the first time directly from πN invariant mass spectrum. Besides several well known N^* resonances around 1 520 MeV and 1 670 MeV, three new N^* resonances above 2 GeV were found through delicate partial wave analyses. They are $N^*(2040)\,3/2^+$[20], $N^*(2300)\,1/2^+$ and $N^*(2570)\,5/2^-$[28]. An additional advantage of this reaction is that it not only selects isospin 1/2 states but also suppresses high spin states due to the short range interaction involved in the $c\bar{c}$ annihilation that generates the $N\pi$ system. The suppression of higher spin states greatly simplifies partial wave analysis.

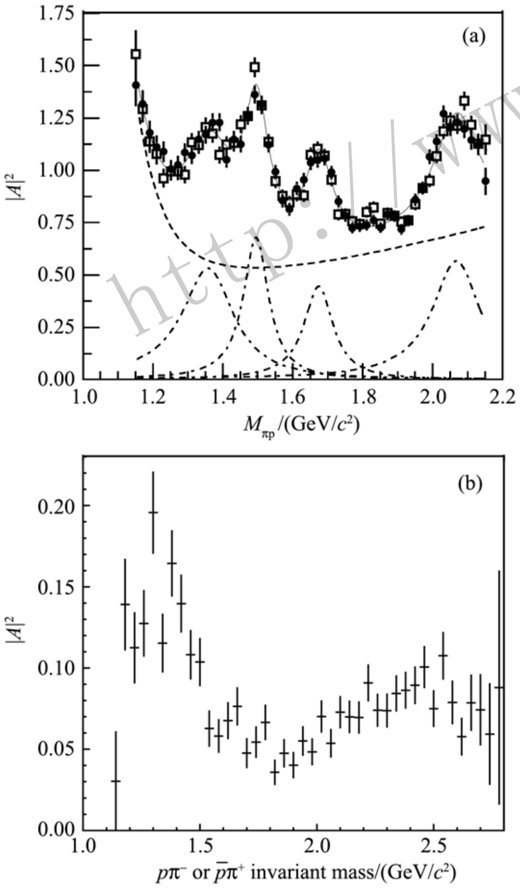

Fig. 1 Invariant mass data corrected by MC simulated efficiency and divided by phase space versus $p\pi^-$ (or $\bar{p}\pi^+$) invariant mass for $J/\psi \to p\bar{n}\pi^- + c.c.$[19] (a) and $\psi(2S) \to p\bar{n}\pi^- + c.c.$[27] (b).

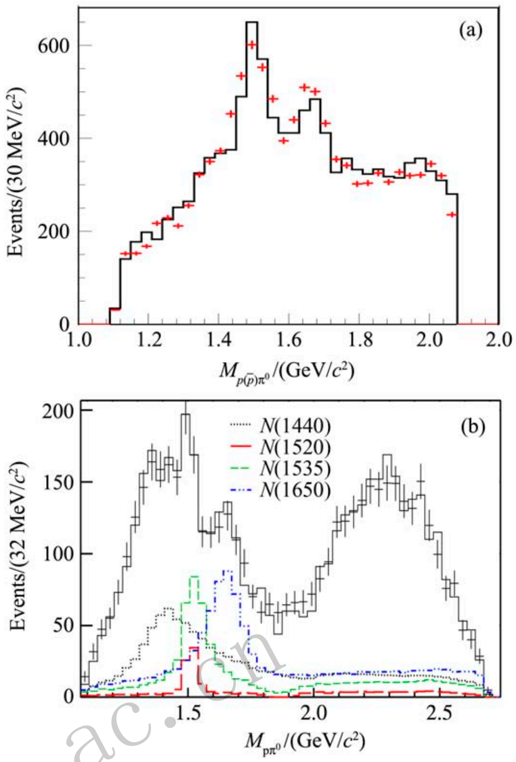

Fig. 2 (color online) $p\pi^0$ (or $\bar{p}\pi^0$) invariant mass for $J/\psi \to p\bar{p}\pi^0$[20] (a) and $\psi' \to p\bar{p}\pi^0$[28] (b).

Another interesting phenomen is that the $N^*(1440)$ is produced much stronger from $\psi(2S)$ than from J/ψ. There are two common features for $\psi(2S)$ and $N^*(1440)$: 1) they are supposed to be radial excitation of J/ψ and nucleon, respectively, in the simple quenched quark model; 2) they were found experimentally to have large coupling to $\sigma J/\psi$ and σN, respectively. In unquenched quark models, radial excitations like to pull out $q^2\bar{q}^2\,(0+)$ from sea, hence favor transition between each other. This unquenched picture not only gives a natural explanation of much enhanced $N^*(1440)$ production from $\psi(2S)$ than J/ψ, may also explain the long-standing $\rho\pi$ puzzle[17] from $\psi(2S)$ and

J/ψ decays, *i.e.*, $\psi(2S)$ tends to decay into $\rho(2S)\pi$ while J/ψ tends to decay into $\rho\pi$. CLEO Collaboration also studied $\psi(2S)\to p\bar{p}\pi^0$ channel and got a similar strong $N^*(1440)$ peak[32]. There is no obvious $N^*(1440)$ produced in the $e^+e^-\to p\bar{p}\pi^0$ reaction with e^+e^- energy around $\psi(3770)$[31].

In Fig. 3, the Dalitz plot and corresponding invariant mass spectra are presented for $J/\psi\to pK^-\bar{\Lambda}$ and $\bar{p}K^+\Lambda$ channels[21]. There are clear Λ^* peaks at 1.52 GeV, 1.69 GeV and 1.8 GeV in pK invariant mass spectrum, and N^* peaks near $K\Lambda$ threshold, 1.9 GeV and 2.05 GeV for $K\Lambda$ invariant mass spectrum. The N^* peak near $K\Lambda$ threshold is most probably due to $N^*(1535)$. Combined with information on $N^*(1535)$ from $J/\psi\to p\bar{p}\eta$[18] as well as COSY data on $pp\to pK^+\Lambda$, a large coupling to $K\Lambda$ was found for the $N^*(1535)$[13]. This supports it to be a $K\Sigma$-$K\Lambda$ dynamically generated state with large hidden strangeness component. Extending this picture from strangeness to charm and beauty, super-heavy N^* with hidden charm[33–34] or hidden beauty[35] were predicted to exist around 4.3 GeV and 11 GeV, respectively. Two super-heavy N^* states with hidden charm were later discovered by LHCb experiment[36] from Λ_b decays. They are named as $P_c(4380)$ and $P_c(4450)$, respectively. Their meson partners Z_c states were also discovered by BESIII Collaboration[37–38] and other experiments as reviewed in Refs. [39–40].

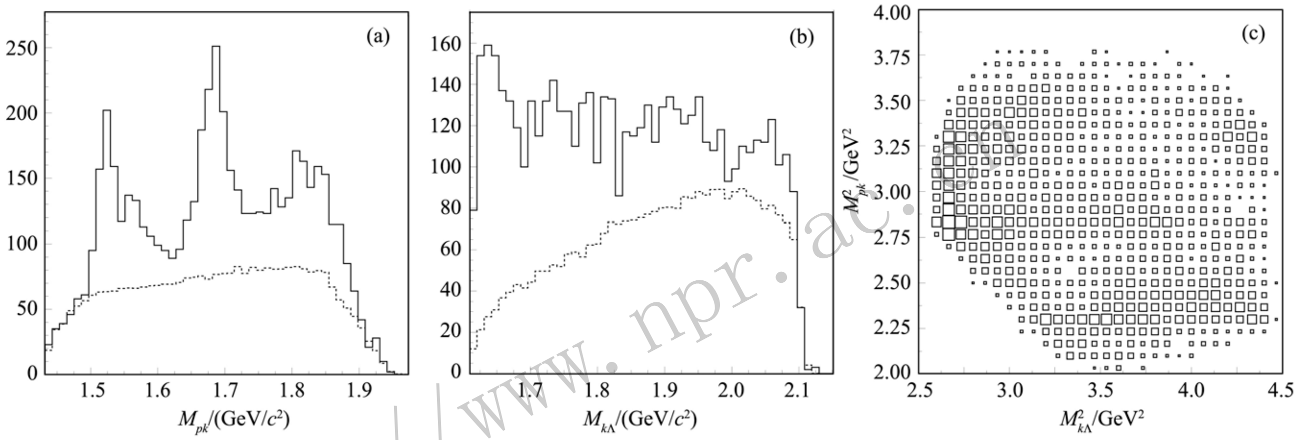

Fig. 3　pK (a) and $K\Lambda$ (b) invariant mass spectra for $J/\psi\to pK^-\bar{\Lambda}+c.c.$, compared with phase space distribution; (c) Dalitz plot for $J/\psi\to pK^-\bar{\Lambda}+c.c.$.[21].

While a popular explanation for $P_c(4380)$ and $P_c(4450)$ is that they are molecular states of $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$, respectively[40–41], their strange partners are proposed to be $N^*(1875)$ and $N^*(2080)$ as $K\Sigma^*$ and $K^*\Sigma$ molecule, respectively[42–43]. Very interestingly, three peaks were observed just around $K\Sigma$, $K\Sigma^*$ and $K^*\Sigma$ thresholds in the ΛK_S invariant mass spectrum from the BESII data on $J/\psi\to\bar{n}K^0_S\Lambda+c.c.$[22], as shown in Fig. 4, *i.e.*, $N^*(1535)$, $N^*(1875)$ and $N^*(2080)$. Now with an order of magnitude higher

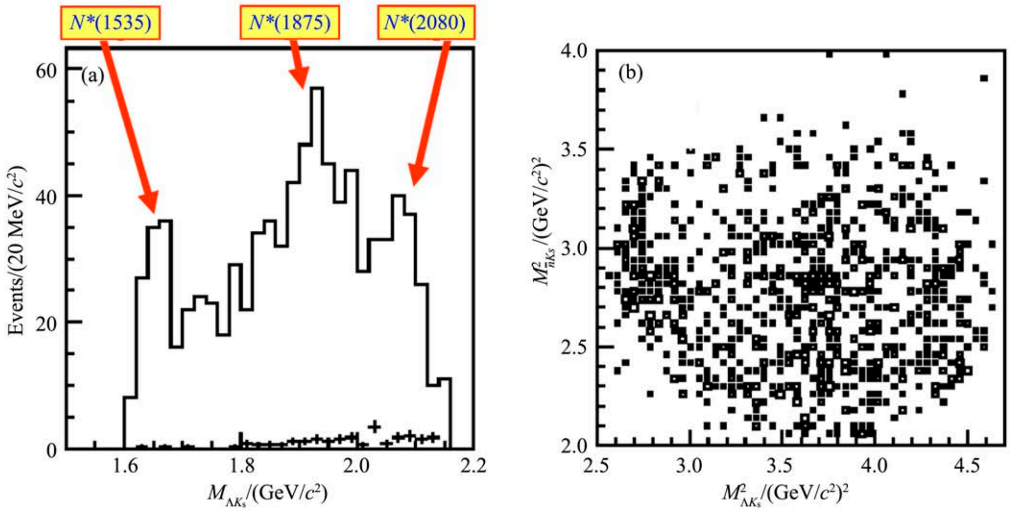

Fig. 4　(color online) ΛK_S invariant mass (a) and Dalitz plot (b) for $J/\psi\to\bar{n}K^0_S\Lambda+c.c.$[22].

statistics on this channel at BESIII, partial wave analysis should be performed to determine the quantum numbers of these three peaks.

3 Hyperon production and prospects

Besides N^* resonances, some hyperon resonances were also studied by BESIII from $J/\psi \to \Lambda\bar{\Lambda}\gamma$[44], and $\psi(2S) \to \bar{p}K^+\Sigma^0$[29], $\Lambda\bar{\Sigma}^{\pm}\pi^{\mp} + c.c.$[45], $\psi(2S) \to K^-\Lambda\bar{\Xi}^+ + c.c.$[46].

Two typical invariant mass plots for hyperon resonances are shown in Fig. 5. Clear resonance peaks are observed for Σ^* and Ξ^* resonances. There is a clear Σ^* peak around 1 580 MeV which can be fitted well with the 1-star $\Sigma(1580)3/2^-$ resonance of PDG[4]. In 2012, by analyzing $K^-p \to \pi^0\Lambda$ data by the Crystal Ball experiment at BNL[47], we also found some evidence for a $\Sigma^*(3/2^-)$ resonance around 1 542 MeV[48]. A $\Sigma^*(3/2^-)$ around 1 560 MeV was expected by unquenched quark model[14].

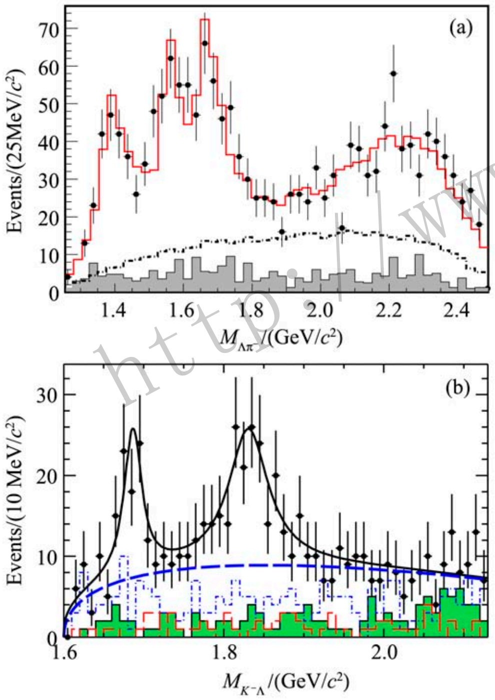

Fig. 5 (color online) $\Lambda\pi^-$ invariant mass for $\psi(2S) \to \Lambda\bar{\Sigma}^{\pm}\pi^{\mp}$[45] (a) and $K^-\Lambda$ invariant mass for $\psi(2S) \to K^-\Lambda\bar{\Xi}^+ + c.c.$[46] (b).

For e^+e^- annihilations at energies above $\Lambda_c\bar{\Lambda}_c$ threshold, the Λ_c decays provide a new source on the N^* and hyperon spectroscopy. Recently, Belle Collaboration observed a very narrow Λ^* peak around 1670 MeV in the pK invariant mass spectrum in $\Lambda_c^+ \to pK^-\pi^+$[49]. This is consistent with a previous observation of a very narrow $\Lambda^*(1670)\,1/2^-$ from analyzing $K^-p \to \Lambda\eta$ data[50]. If it is confirmed, it would be a natural candidate of $[ud]ss\bar{s}$ pentaquark state which can only decay to $\Lambda\eta$ through strongly suppressed D-wave decay. It is important to check its existence through $\Lambda\eta$ invariant mass spectrum of $\Lambda_c^+ \to \Lambda\eta\pi^+$. For e^+e^- annihilations at energies above $\Lambda_b\bar{\Lambda}_b$ threshold at super-B or super-Z factories, its Λ_b decays would provide a much cleaner source than LHCb experiment to look for super-heavy N^* and hyperon resonances with hidden-charm.

With further accumulation on charmonium decays, there are many more interesting channels can be explored, such as $\bar{\Omega}\Xi\bar{K}$, $\bar{\Xi}\Xi\pi$, $\bar{\Lambda}\Lambda\gamma$, $\bar{\Sigma}\Lambda\gamma$, $\bar{\Sigma}\Sigma\gamma$, $\bar{\Xi}\Xi\gamma$, *etc.*, with $\Omega \to \Lambda K^-$ and $\Xi \to \Lambda\pi$. While CEBAF at JLab has advantage for studying radiative decays of N^* and Δ^* with the largest data samples for $\gamma^{(*)}p \to N^*/\Delta^*$, BESIII may have advantage to study radiative decays of Λ^*, Σ^* and Ξ^* with much clean data samples due to the isospin filter effect of charmonium decays. To complete N^*, Λ^*, Σ^*, Ξ^* spectra and establish the lowest Λ^*, Σ^*, Ξ^* and Ω^* with partial wave analysis, a super τ-charm factory may be needed.

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正负电子湮灭过程的核子激发态 N^* 产生

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摘要： 目前，正负电子湮灭过程的核子激发态N^*产生的实验数据主要来自于粲偶素能区。粲偶素衰变到核子激发态过程类似于其类时电磁形状因子测量过程，正反粲夸克短程湮灭提供了近乎于点源的胶子强子化过程。与γN，eN，πN反应互补，这一新的N^*产生源具有同位旋和低自旋筛选的优势。综述了正负电子湮灭过程的核子激发态N^*产生的实验情况和相关的唯象进展，同时讨论未来发展的一些新方向，如正负电子湮灭过程的核子激发态N^*产物的一些新来源等。

关键词： 核子激发态；正负电子湮灭；强子结构

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