ROPER RESONANCE $N^*(1440)$ FROM CHARMONIUM DECAYS*

Bing-Song Zou

Department of Physics and High Energy Physics Center
Tsinghua University
Beijing 100084, China

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The Roper resonance $N^*(1440)$ was discovered by David Roper in 1964 through sophisticated partial-wave analyses of πN scattering data. However, the first direct observation of the Roper resonance peak in the πN invariant mass spectrum was only realized 40 years later from the charmonium decay $J/\psi \to \bar{p}n\pi^+ + \text{c.c.}$ at the Beijing Electron–Positron Collider. Further observations of the Roper resonance production from various charmonium decays helped reveal its multiquark nature, with a large σN component.

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1. Direct observation of $N^*(1440)$ from charmonium decays

Although the Roper resonance $N^*(1440)$ was discovered by David Roper a long time ago [1] in 1964 through sophisticated partial-wave analyses of πN scattering data, its first direct observation in the πN invariant mass spectrum was only realized 40 years later from the charmonium decay $J/\psi \to \bar{p}n\pi^+ + \text{c.c.}$ at the Beijing Electron–Positron Collider [2]. For the πN and $\pi\pi N$ systems produced from πN and γN reactions, they are a mixture of isospin $1/2$ and $3/2$ with similar strengths, and hence suffer difficulty in the isospin decomposition. In the πN invariant mass spectrum, the $N^*(1440)$ peak is buried underneath the overwhelming Δ peak and cannot be seen directly. For the $c\bar{c} \to \bar{N}N\pi$ and $\bar{N}N\pi\pi$ processes, the πN and $\pi\pi N$ systems are expected to be dominantly isospin $1/2$ due to the isospin-conserving gluon annihilation mechanism [3]. Due to the isospin filter effect, the $N^*(1440)$ peak is clearly visible in the πN invariant mass spectra in various charmonium decays: $J/\psi \to p\bar{n}\pi^- + \text{c.c.}$ [2], $p\bar{p}\pi^0$ [4], and $\psi(2S) \to p\bar{n}\pi^- + \text{c.c.}$ [5], $p\bar{p}\pi^0$ [6], and $\chi_{c0} \to p\bar{n}\pi^-$ [7], as shown in Fig. 1,

Fig. 2, and Fig. 3, respectively. The fitted constant mass and width forthe $N^*(1440)$ are consistent with its pole values from the PDG [8] obtained mainly from sophisticated partial-wave analyses of πN scattering data from the past 60 years.

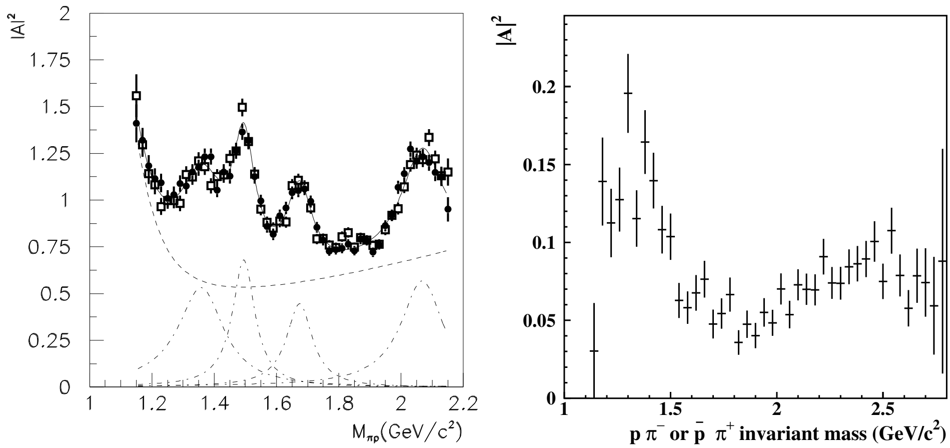

Fig. 1. Invariant mass data corrected by MC simulated efficiency and divided by phase space *versus* $p\pi^-$ (or $\bar{p}\pi^+$) invariant mass for $J/\psi \to p\bar{n}\pi^- + \text{c.c.}$ [2] (left) and $\psi' \to p\bar{n}\pi^- + \text{c.c.}$ [5] (right).

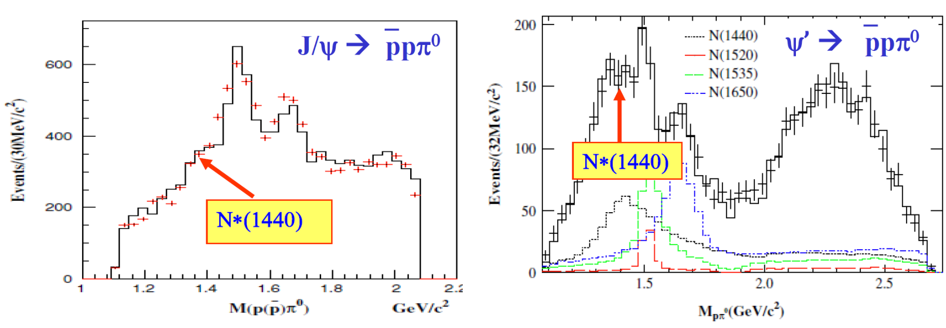

Fig. 2. $p\pi^0/\bar{p}\pi^0$ invariant mass for $J/\psi \to p\bar{p}\pi^0$ [4] (left) and $\psi' \to p\bar{p}\pi^0$ [6] (right).

Later it was found that the $N^*(1440)$ peak can also be seen in the $n\pi^+$ invariant mass spectrum of the $pp \to pn\pi^+$ reaction [9, 10] and in the πN invariant mass spectrum of the isoscalar $NN\pi$ final state obtained from some combination of the $pp \to NN\pi$ reactions [11, 12], where the Δ contribution was suppressed.

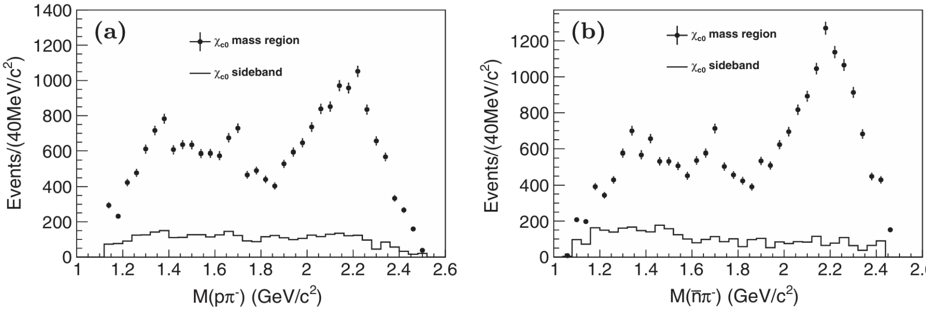

Fig. 3. The invariant mass distributions for (a) $p\pi^-$ and (b) $\bar{n}\pi^-$ of $\chi_{c0} \to p\bar{n}\pi^-$ [7].

2. Implication on the nature of $N^*(1440)$

An interesting phenomenon is that the $N^*(1440)$ is produced much stronger from $\psi(2S)$ than from J/ψ as shown in Figs. 1 and 2. This has an important implication.

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 $\bar{q}^2q^2(0^{++})$ from the 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, but may also explain the long-standing $\rho\pi$ puzzle [13] 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 $\rho\pi$. The CLEO Collaboration also studied the $\psi(2S) \to \bar{p}p\pi^0$ channel and got a similar strong $N^*(1440)$ peak [14]. There is no obvious $N^*(1440)$ produced in the $e^+e^- \to p\bar{p}\pi^0$ reaction with e^+e^- energy around $\psi(3770)$ [15].

An effective field study with lattice QCD constraints [16] also shows that the Roper resonance is best described as a resonance generated dynamically through strongly coupled meson–baryon channels with a σN component dominant. For a σN bound state, its major decay channels are expected to be πN and $\pi\Delta$, which couple to σN by one pion exchange and have larger phase space. Since σ is a resonance with a broad width, the σN bound state can also decay directly to $\pi\pi N$ through the σ decay. Note that due to the binding energy of the molecule as well as the kinetic energy of σ inside the molecule, the $\pi\pi N$ decay width through the decay of σ inside the σN molecule can be much smaller than the decay width of a single free

σ meson. A similar effect was pointed out by the authors of Refs. [17, 18] in their studies of $d^*(2380)$ as a $\Delta\Delta$ molecule, which gets a decay width smaller than the decay width of a single free Δ state. This kind of effect was also observed by the study of other hadronic molecules [19–21]. The expected decay pattern is supported by the information from PDG [8].

It would be expected that a similar scenario happens for $\Upsilon(1S, 2S) \to \bar{N}N\pi$ with the $N^*(1440)$ produced much stronger from $\Upsilon(2S)$ than from $\Upsilon(1S)$ since the $\Upsilon(2S)$ has a large coupling to $\sigma\Upsilon(1S)$ [8]. It is worth checking at Belle II.

The strange partners of the $N^*(1440)$, *i.e.*, $\Lambda(1600)1/2^+$ and $\Sigma(1660)1/2^+$, are clearly needed in analyzing data on $K^-p \to \pi^0\Sigma^0$ [22], $K^-p \to \pi^0\Lambda$ [23], and $K_{\mathrm{L}}p \to \pi^+\Sigma^0$ [24], respectively. They are also found to have large couplings to $\Lambda\sigma$ and $\Sigma\sigma$ [8, 25], respectively. They may be further explored by the forthcoming K_{L} beam experiment at JLab [26] and kaon beam experiments at J-PARC [27].

With more and more information accumulated for various "radial" excited hadronic resonances, a consistent picture seems to be appearing, *i.e.*, they are, in fact, largely multiquark states with a σ added to relevant ground states.

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