Study of nucleon resonances at EBAC@JLab

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Abstract. We present the dynamical origin of the $P_{11}$ nucleon resonances resulting from a dynamical coupled-channels (DCC) analysis of meson production reactions off a nucleon target, which is conducted at Excited Baryon Analysis Center (EBAC) of Jefferson Lab. Two resonance poles are found in the energy region where the Roper resonance $P_{11}(1440)$ was identified. Furthermore, the two resonance poles and the next higher resonance pole corresponding to $P_{11}(1710)$ are found to originate from a single bare state.

Keywords: Dynamical coupled-channels analysis, meson production reactions, Roper resonance

PACS: 14.20.Gk, 13.75.Gx, 13.60.Le

INTRODUCTION

The excited nucleon states (collectively referred to as $N^*$) are known to be a realization of the nonperturbative dynamics of the strong interaction. An understanding of their spectrum and structure is a fundamental challenge in the hadron physics.

The $N^*$ states, however, couple strongly to the meson-baryon continuum states and appear only as resonance states in $\pi N$ and $\gamma N$ reactions. Such a strong coupling to the continuum states influence strongly the $N^*$ properties and thus cannot be neglected in extracting information on the $N^*$ states from the data and giving physical interpretations.

To address this issue, an extensive research program of extracting the $N^*$ information through the comprehensive analysis of $\pi N$, $\gamma N$, $N(e,e')$ reactions is being conducted at Excited Baryon Analysis Center (EBAC) of Jefferson Lab. The analysis is performed with a dynamical coupled-channels (DCC) model developed in Ref. [1], within which the couplings among relevant meson-baryon channels are fully taken into account. The main objectives of EBAC are to extract spectrum of the $N^*$ states and their form factors from the analysis and provide reaction mechanism information necessary for interpreting the spectrum, structure, and dynamical origin of the $N^*$ states. In this contribution we present our recent results on the dynamical origin of the $P_{11}$ nucleon resonances.

The EBAC-DCC analysis is based on a multi-channel and multi-resonance model [1], within which the partial wave amplitudes of $M(p) + B(-p) \rightarrow M'(p') + B'(-p')$ with $MB,M'B' = (\pi N, \eta N, \pi\Delta, \sigma N, \rho N)$ are calculated by the coupled-channels equations (suppressing the angular momentum and isospin indices):

$$T_{MB,M'B'}(p,p';E) = V_{MB,M'B'}(p,p';E)$$
$$+ \sum_{M''B''} \int dq q^2 V_{MB,M''B''}(p,q;E) G_{M''B''}(q;E) T_{M''B'',M'B'}(q,p';E),$$

(1)

where $G_{MB}(q;E)$ is the Green function of the $MB$ channel, expressed as $G_{MB}(q;E) = ...$
The dressed imaginary part of the self-energy entering \[3\] up to where the self-energy of the dressed bare state in a given partial wave, respectively. The first term \(v_{MB,M'B'}(p,p')\) is the (energy-independent) meson-exchange potentials, which are derived from the effective Lagrangians making use of the unitary transformation method \[1, 2\]; the second term describes \(MB \rightarrow M'B'\) transitions through the bare \(N^*\) state, \(MB \rightarrow N^* \rightarrow M'B'\).

The \(MB \rightarrow M'B'\) amplitude (1) is a basic ingredient to construct all single and double meson production reactions with the initial \(\pi N, \gamma N, N(e,e')\) states. The hadronic and electromagnetic parameters of our current model have been fixed by the \(\pi N\) scattering \[3\] up to \(W = 2\) GeV and \(\gamma p \rightarrow \pi N\) \[4\] and \(ep \rightarrow e'\pi N\) \[5\] up to \(W = 1.6\) GeV, respectively, and the model has been applied to \(\pi N \rightarrow \pi N\) \[6\] and \(\gamma N \rightarrow \pi \pi N\) \[7\].

The resonance pole positions can be obtained as zeros of the determinant of the inverse of the dressed \(N^*\) propagator:

\[
[D^{-1}(E)]_{i,j} = (E - m_{N^*_i}^0) \delta_{i,j} - [M(E)]_{i,j}, \tag{3}
\]

where the self-energy of the dressed \(N^*\) state given by

\[
[M(E)]_{i,j} = \sum_{MB} \int q^2 dq \Gamma_{N^*_j \rightarrow MB}(q;E)G_{MB}(q,E)\Gamma_{MB \rightarrow N^*_i}(q), \tag{4}
\]

with \(\Gamma_{N^*_j \rightarrow MB}\) being the dressed \(N^*\) \(\rightarrow MB\) vertex defined in Ref. \[1\]. To search for zeros of \(\text{det}[D^{-1}(E)]\) for complex \(E\), we need to make an analytic continuation of the amplitudes. The analytic continuation method we used is described in detail in Refs. \[8, 9\] and will not be discussed here. The pole positions of all nucleon resonances below \(W = 2\) GeV extracted from the current EBAC-DCC analysis can be found in Ref. \[10\].

**P_{11} NUCLEON RESONANCES FROM EBAC-DCC ANALYSIS**

**Two-pole structure of the Roper resonance**

The \(P_{11}\) partial wave of the \(\pi N\) scattering has been investigated with a particular interest in the literatures. This is mainly due to the controversy over the dynamical origin of the mysterious Roper resonance \(N^*(1440)\). In the energy region below 2 GeV, we found three \(P_{11}\) resonance poles relevant to the observables as listed in Table 1. Furthermore, two of the three resonance poles are found to be near the Roper resonance.
energy, $E_A = 1357 - i76$ MeV and $E_B = 1364 - i105$ MeV, which are indicated as points A and B in Fig. 1, respectively.

At a first glance the reader might think the two poles are very close to each other because $|E_A - E_B| \sim 30$ MeV. However, in reality they locate in the different Riemann sheets with respect to the $\pi\Delta$ branch point and thus are “far” from each other: The pole A locates in the sheet continued analytically from the upper side of the $\pi\Delta$ cut (unphysical sheet), whereas the pole B locates in the sheet directly connected with the physical real energy axis (physical sheet). (We take branch cuts to be in parallel with the positive direction of the real energy axis as shown in Fig. 1 for the $\pi\Delta$ channel.)

The two Roper poles will not be observed as clear peaks because of the analytic structure of the complex energy plane induced by the $\pi\Delta$ branch point. Nevertheless, those poles are still close to the physical region and expected to have a non-negligible contribution to the observables. To prove this we need to make a detailed examination of the decay vertices into $\pi\pi N (= \pi\Delta, \rho N, \sigma N)$ as well as $\pi N$. This is under investigation and will be presented elsewhere.

It is noted that several groups have also reported similar two-pole structures of the Roper resonance [11, 12, 13].

### TABLE 1. $P_{11}$ resonance poles below $W = 2$ GeV from the EBAC-DCC analysis.

| Pole position (MeV) | Location on the complex-E plane $(\pi N, \eta N, \pi\pi N, \pi\Delta, \rho N, \sigma N)$ * |
|---------------------|-----------------------------------------------------------------------------------|
| A 1357 − i76        | (u,p,u,u,p,p)                                                                      |
| B 1364 − i105       | (u,p,u,p,p,p)                                                                      |
| C 1820 − i248       | (u,u,u,u,u,p)                                                                      |

* p = physical-sheet, u = unphysical-sheet
Another important finding from our analysis is about the dynamical origin of the $P_{11}$ nucleon resonances. We find that the two Roper poles (A and B in Table 1) and the next higher resonance pole corresponding to $N^*(1710)$ (C in Table 1), are generated from a single bare state as a result of its coupling to the meson-baryon continuum states. Theoretically, Eden and Taylor already pointed out four decades ago that multi-channel reactions can generate many resonance poles from a single bare state [14]. In most cases, only one of the poles appears close to the physical region. However, depending on a given reaction dynamics, more than one pole can appear to have a physical significance. Just few of such evidences were reported in the past (see e.g., Ref. [15]). Our result suggests that the $P_{11}$ nucleon resonances may be an important addition.

To examine how the three $P_{11}$ poles evolve from a single bare state dynamically, we trace the zeros of $\det[\hat{D}^{-1}(E)] = \det[E - m_{N^*}^0 - \sum_{MB} y_{MB} M_{MB}(E)]$ in the region $0 \leq y_{MB} \leq 1$, where $M_{MB}(E)$ is the $MB$-loop contribution to the $N^*$ self-energy $M(E)$ defined in Eq. (4). Each $y_{MB}$ is varied independently to find continuous evolution paths through the various Riemann sheet on which the analytic continuation method is valid.

By setting all $y_{MB}$'s to slightly positive from zero, the bare state (the filled square at $E = 1763$ MeV in Fig. 2) couples to all $MB$ channels and many poles are generated according to the discussion by Eden and Taylor [14]. One of them appears on the $\eta N$-unphysical, $\rho N$-unphysical, and $\pi \Delta$-unphysical sheet and it moves to the pole C by further varying all $y_{MB}$ to one (the dotted curve in Fig. 2).

Similarly we can trace how the two Roper poles evolve from the same bare state. It is instructive to see this by first keeping $y_{\pi \Delta}$ zero and varying the other $y_{MB}$'s from zero to one, which means that the coupling to the $\pi \Delta$ is off in the variation. With this variation we can trace another pole trajectory moving on the $\eta N$-physical and $\rho N$-physical sheet along the dashed curve in Fig. 2 from the bare position to the point D with $\text{Re}(E_D) \sim 1400$ MeV (the filled triangle in Fig. 2). It is noted that the poles on the $\eta N$-physical sheet are far from the physical real energy axis above the $\eta N$ threshold, while those are the nearest below the threshold. Therefore this another pole on the
$\eta N$-physical sheet, moving from the bare point to the point D along the dashed curve, becomes the nearest resonance pole as a result of crossing the $\eta N$ threshold. By further varying $y_{\pi\Delta} : 0 \rightarrow 1$, the trajectory splits into two trajectories: One moves to the pole A on the $\pi\Delta$ unphysical sheet and the other to the pole B on the $\pi\Delta$ physical sheet. This indicates that the coupling to the $\pi\Delta$ channel is essential for the two-pole structure of the Roper resonance. In this way, we observe that all the three $P_{11}$ resonance poles are connected to the same bare $N^*$ state at $E = 1763$ MeV.

**SUMMARY**

We have investigated the dynamical origin of the $P_{11}$ nucleon resonances extracted recently from the EBAC-DCC analysis. Our main findings are: 1) the Roper resonance is associated with the two resonance poles, and 2) the two Roper resonance poles and the next higher resonance pole corresponding to $N^*(1710)$ originate from a single bare state, indicating that in this case the naive one-to-one correspondence between the bare states and the observed resonance poles is not applied. We have demonstrated the critical role played by the non-trivial multi-channel reaction mechanisms in interpreting the dynamical origin of nucleon resonances. Our results have provided new insights in understanding the spectrum of the $N^*$ states.

**ACKNOWLEDGMENTS**

The author would like to thank B. Juliá-Díaz, T.-S. H. Lee, A. Matsuyama, T. Sato, and N. Suzuki for their collaborations at EBAC. This work was supported by the U.S. Department of Energy, Office of Nuclear Physics Division, under Contract No. DE-AC05-06OR23177 under which Jefferson Science Associates operates the Jefferson Lab.

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