ANATOMY OF ROPER RESONANCE*

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Sixty years ago, the first excited state of a proton/neutron was "born". During this time, we learned a lot about it, specifically, how unique this case is: a single resonance with two-pole positions on different Riemann sheets. Let me provide a brief history to remind the readers how development progressed. Sure, history is sometimes what never happened, described by those who were never there ...

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1. Introduction

QCD gives rise to the hadron spectrum [1, 2], and many $q\bar{q}$ and qqq have been observed [3]. Sixty years ago, the first excited state of a proton/neutron was discovered by Dave Roper in his Ph.D. work at the Massachusetts Institute of Technology and Lawrence Livermore Laboratory. That was reported in 1963 at the Siena conference in Italy by Dave Roper and his Ph.D. adviser, Bernard Feld [4]. Then, at Michael Moravcsik's request, Bernard Feld agreed that Dave Roper's name should be the only author of this *Physical Review Letters* paper [5]. That is how $N(1440)1/2^+$ resonance was "born" (Fig. 1), and as a result, this resonance is widely known informally as the "Roper" resonance [7]. During this time, the elastic $\pi^{\pm}p$ scattering database increased dramatically, but the situation with $N(1440)1/2^+$ appears stable over 50 years, as Fig. 2 and Table 1 demonstrate.

Discovered 60 years ago, the Roper resonance state has remained controversial ever since. The prominent $N(1440)P_{11}$ resonance is clearly evident in both Karlsruhe–Helsinki (KH) and GW/VPI analyses (Figs. 4–7 from Ref. [8]), but it occurs very near the $\pi\Delta$ ($W = 1350 - i\ 50$ MeV), ηN ($W = 1487 - i\ 0$ MeV), and ρN ($W = 1715 - i\ 73$ MeV) thresholds (Fig. 8 from Ref. [9]), making a Breit–Wigner (BW) fit questionable. The $N(1440)$

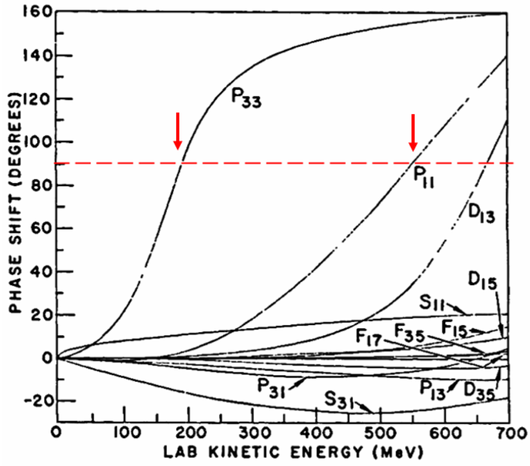

Fig. 1. Pion–nucleon phase shifts as functions of energy from 0 to 700 MeV [5]. The resonance signal is associated with a phase crossing of 90°, as shown by the red vertical arrows. The previous discovery of the $\Delta(1232)3/2^+$ in P_{33} was done by Fermi's group at the Chicago Synchrocyclotron [6], while now Roper reported his observation for the P_{11} case [5].

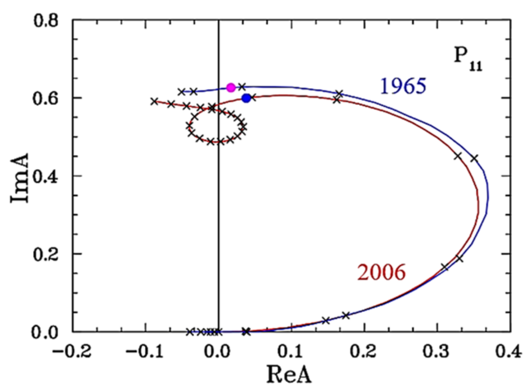

Fig. 2. Argand plots for partial-wave P_{11} amplitude from threshold (1080 MeV) to $W = 2.5$ GeV. Blue (red) solid curve corresponds to the original Roper's amplitude [7] (SAID SP06 amplitude [8]). Crosses indicate 50 MeV steps in W. Filled circles correspond to the Breit–Wigner (BW) W_R determination.

is unique in that its behavior on the real energy axis is influenced by poles on different Riemann sheets (with respect to the $\pi\Delta$ cut), as was first reported by Arndt *et al.* [10]. This happened 20 years after the Roper resonance was born. Due to the nearby $\pi\Delta$ threshold, both P_{11} poles are not far from the physical region (Fig. 3). There is a small shift between pole positions on the two sheets due to a non-zero jump at the $\pi\Delta$ cut. The conclusion is that a simple BW parametrization cannot account for such a complicated structure. This point was also emphasized by Höhler [12].

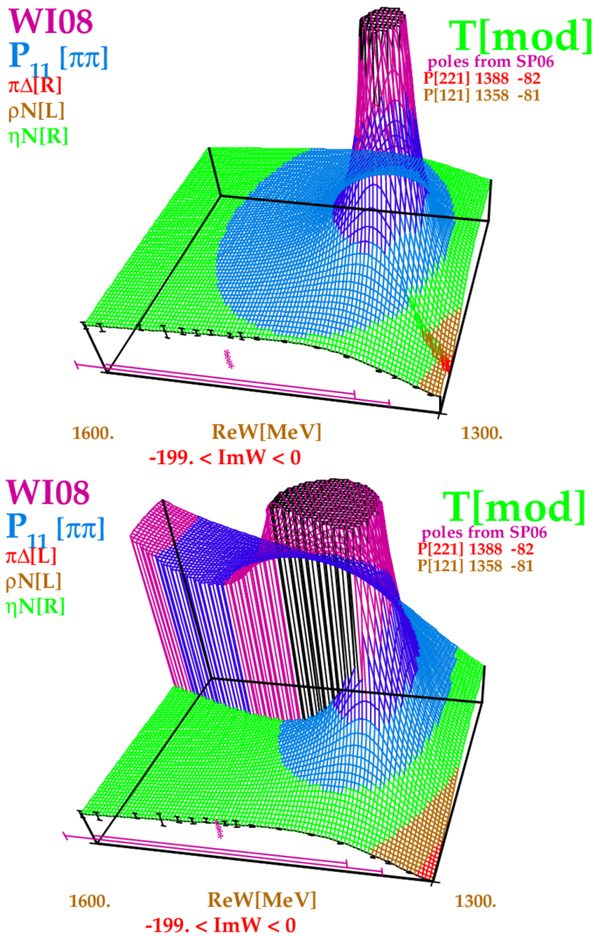

Fig. 3. Two poles for πN P_{11} for the SAID WI08 amplitude [11]. Top: the $\pi\Delta$ cut can be seen in the foreground and runs from larger to smaller values of the real part of the energy. Bottom: the $\pi\Delta$ cut is clearly visible running from smaller to larger values of the real part of the energy.

2. Two pole observation

Resonances are defined by the poles of the S-matrix, whether in scattering, production, or decay matrix elements. Recent studies of the $N(1440)1/2^+$ resonance by the Jülich [13] and ANL–Osaka (EBAC) [14] groups have confirmed the two-pole determination. An earlier study by Cutkosky and Wang came to a similar conclusion [15]. Table 1 summarizes the results of the phenomenological research conducted by several groups. One can see that the results from different treatments are in reasonable agreement.

Table 1. Pole positions from the different phenomenological studies of the $N(1440)1/2^+$ resonance. Real (W_R) and imaginary ($-2W_\mathrm{I}$) parts are listed.

Pole-1 [MeV]	Pole-2 [MeV]	Reference
$1359 - i\ 100$	$1410 - i\ 80$	[10]
$1358 - i\ 80$	$1388 - i\ 82$	[11]
$1370 - i\ 114$	$1360 - i\ 120$	[15]
$1387 - i\ 73$	$1397 - i\ 71$	[13]
$1357 - i\ 76$	$1364 - i\ 105$	[14]

3. Conclusion

Overall, most of the analyses of $N(1440)$ are based on its BW parametrization, which implicitly assumes that the resonance is related to an isolated pole on the second Riemann sheet. However, given the complicated structure found in our SAID PWA, the BW description may only be an effective parametrization that could differ across various processes. Some inelastic data indirectly support this point, giving $N(1440)$ BW masses and widths significantly different from the PDG BW values [12]. This may also cast some doubt on the recent Q^2 evaluation results [16–20], since the Q^2 dependence of the contributions from different singularities may vary. This may also suggest the need to extend the extraction of $N(1440)1/2^+$ electroexcitation amplitudes beyond the BW approximation to shed light on Q^2, the evolution of the two residues at the two-pole positions. This problem can be studied in experiments with JLab CLAS12. Combining anticipated results from CLAS6 and CLAS12 will address an important open question: whether the two Roper poles originated from a common quark core. The important step in this direction was made in Refs. [21, 22].

More details about the Roper resonance are available in this volume of *Acta Physica Polonica B.*

Finally, let me cite some words from well-known experts that I learned from: Dave Roper: *I spent a lot of time trying to eliminate the* P_{11} *resonance*, and Dick Arndt: *This is one of the mysterious resonances.*

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