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60^{th} ANNIVERSARY OF THE "ROPER RESONANCE" DISCOVERY

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The Roper resonance was discovered in L. David Roper's Ph.D. thesis research at MIT with Prof. Bernard T. Feld as advisor, with the extensive computing done at Livermore Radiation Laboratory with Dr. Michael J. Moravcsik and programmer Robert M. Wright. The basic coding was taken from the nucleon–nucleon coding of Dr. Richard A. Arndt. Despite the fact of a negative scattering length, which had led to thinking that there would be no P_{11} resonance, the computer code and large amount of data at that time insisted that the resonance existed. This article discusses some features, including the serendipity, of the discovery and of the unusual Roper resonance.

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1. Introduction

In the early 1960s, analyses of several pion–nucleon scattering experiments had hinted at a resonance in the 400–500 MeV pion laboratory kinetic-energy region (see Fig. 2). William (Bill) M. Layson and Bernard T. Feld at MIT had suggested that there might be a P_{11} resonance at a much higher energy [1].

Bill Layson and I were teaching assistants in the Junior Atomic Physics Laboratory at the Massachusetts Institute of Technology (MIT). I was impressed by his and another graduate student's comments about the thesis research work they were pursuing with Professor Bernard T. Feld. I gravitated toward particle physics phenomenology, Prof. Feld's specialty. In the fall of 1961, I asked Prof. Feld about being my Ph.D. thesis advisor; he agreed.

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Professor Feld and I soon decided to continue the work of Bill Layson. Bill had obtained a set of $\pi^- p$ partial-wave amplitudes by assuming the existence of the D_{13} and F_{15} resonances at 600 and 900 MeV pion laboratory kinetic energy, respectively.

Figure 2 is a plot of the five baryon resonances that are now known to be in the pion laboratory kinetic-energy region 0–1500 MeV.

Professor Feld felt that, with new data rapidly becoming available from experiments at new nuclear-particle accelerators, we might be able to separate out the isospin 1/2 and 3/2 partial waves by using both $\pi^- p$ and $\pi^+ p$ scattering data. (It turned out that a considerable amount of charge-exchange ($\pi^- p \to \pi^0 n$) data and polarization data was becoming available and was crucial in allowing an analysis to achieve a unique solution.) I, with great enthusiasm, set out on the arduous task of collecting all pion–nucleon scattering data, including data not yet published.

Several physicists at MIT told me that it would be impossible to fit over 1000 data with about 100 parameters to achieve a unique solution. They were wrong; there were 1,170 data and 98 variable parameters. Others told me that the analysis should be single-energy rather than energy dependent, but the PPG group at LRL (see below) had proved the efficacy of doing energy-dependent partial-wave analyses (PWAs).

2. Involvement of Lawrence Radiation Laboratory

I spent the summer of 1962 as a research assistant in the Particle Physics Group (PPG) at Lawrence Radiation Laboratory (LRL) with the PPG director being Dr. Michael J. Moravcsik (MJM). (The laboratory name was later changed to Lawrence Livermore National Laboratory.) I worked with MJM, mainly studying the $K \to 2\pi$ decay.

The PPG had developed expertise in analyzing nucleon–nucleon scattering, including a large energy-dependent Fortran computer code. When MJM learned of my Ph.D. thesis selection of pion–nucleon scattering, he realized that the nucleon–nucleon code, developed by a UC-Berkeley student and LRL employee, Richard (Dick) A. Arndt (RAA), could be converted to pion–nucleon scattering.

In September 1962, MJM sent me back to MIT with a proposal that LRL would provide the very powerful computers at LRL and a computer programmer, Robert M. Wright (RMW), to convert the NN code to πN for my thesis. Professor Feld agreed.

So, I continued gathering old, new, and not-yet-published pion–nucleon scattering data and the complex theoretical-physics equations to use in the calculations at LRL, which I forwarded by mail to RMW regularly. While I was at MIT, I had weekly meetings with Prof. Feld. MJM was in Pakistan for the 1963 school year; I exchanged weekly letters with him about the progress of the project.

I was very fortunate to have the steady advice of two of the best particle-physics phenomenologists, Feld and Moravcsik.

3. The pion–nucleon scattering analysis

The pion–nucleon scattering analysis involved two $6'' \times 18'' \times 2''$ boxes of punched cards being hauled between my office and the IBM-7094 and CD-3600/6600 computers at LRL at times when the computers were not being used to design nuclear weapons. Several nights were spent using the IBM-7094 computer at Lawrence Berkeley Laboratory.

Near the end, the computer code insisted that the P_{11} state had a resonance at about $T = 556$ MeV pion laboratory kinetic energy ($W = 1485$ MeV center-of-mass energy). The current Roper resonance (RR) mass is reported by PDG2024 to be 1440 MeV [2]. However, SAID reports it as 1485.0 [3].

For about a week, I tried to force the computer to find an equally good solution without the resonance. Finally, I gave up and reported the result to MJM; he instantly told me that I had to publish the existence of the P_{11} resonance right away before someone beat me to it, since several others were working on the same system.

The results of this pion–nucleon analysis predicted the large set of scattering data, within their error bars, that had just been measured by the Burton Moyer group at the Berkeley Bevatron. (See Fig. 1.) The analysis results were used to help decide which future experiments would best further determine the pion–nucleon scattering amplitudes.

4. Quantum physics of the Roper resonance

If you are a physicist, you can skip this section.

The Roper resonance (RR) with mass of $M = 1440/1485$ MeV and width $\Gamma = 350$ MeV is the first excited state of the neutron/proton (939.565 MeV/ 938.272 MeV). The proton is the nucleus of the hydrogen atom, with it and an electron rotating around each other. The electron mass is 0.510999 MeV.

For the strong nuclear interaction, the neutron and the proton are identical, although the free neutron has a lifetime of about 15 minutes; the proton is stable. The electric interaction has little effect in strong nuclear interactions, and the gravitational interaction is negligible; the weak interaction is involved in the decay of a free neutron and other nuclear particles.

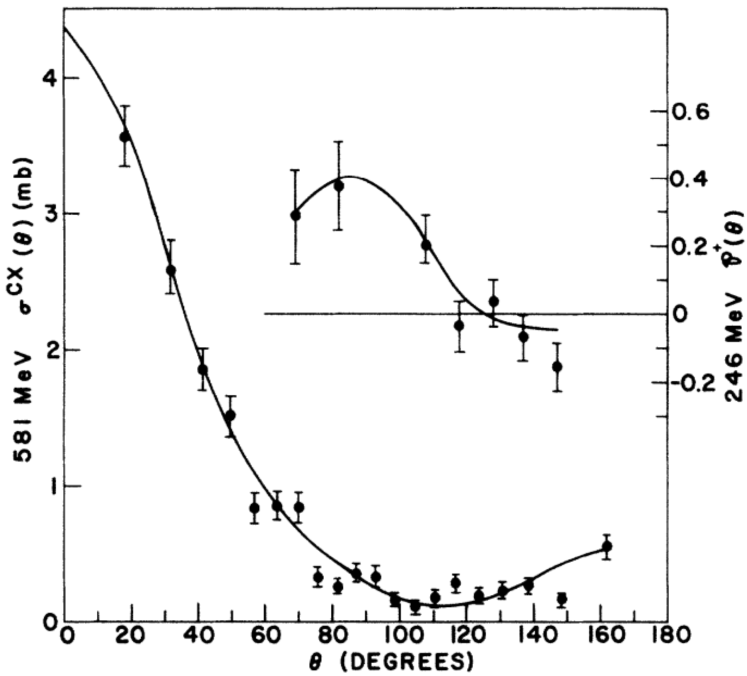

Fig. 1. Prediction of the energy-dependent phase-shift analysis *versus* some new data that were not used in the analysis. The charge-exchange differential cross section data, $\sigma^{cx}(\theta)$, are preliminary results from a recent Berkeley Bevatron experiment [4], and the π^+p polarization data, $P^+(\theta)$, are the values obtained by means of the Berkeley polarized target [5]. Figure taken from Ref. [6].

The lifetime of the RR, according to the uncertainty principle, is about $\tau \approx \hbar/\Gamma = 1.9 \times 10^{-24}$ seconds, a very small time interval. Its radius is about 0.5 fm $= 0.5 \times 10^{-15}$ meters [7], a very small length. These small numbers are why RR is a quantum particle.

The RR and many other excited states are produced in high-energy accelerators, including high-energy cosmic rays hitting molecules and ions in the Earth's atmosphere and in the vicinity of black holes and neutron stars.

After the discovery of the RR, the first excited state of the neutron/proton, four more higher-mass excited states of the n/p were discovered, as shown in Table 1! Notice that just the Roper resonance came from πN elastic scattering PWA, while the rest came from coupled channel analyses, analyses of pion photo-production, and the event $\psi(2S)$ decay.

Figure 2 is a plot of the five neutron/proton excited states' masses and widths (Table 1). Figure 3 is a plot of the five neutron/proton excited states' masses and cross sections. Resonance cross sections and resonance widths are different concepts; cross sections can be asymmetric, widths are symmetric. Cross sections are probabilities that a resonance will occur at a given energy and widths, $\Gamma \approx \hbar/\tau$, are inversely proportional to the lifetime, τ, of a resonance.

Table 1. Since RR's discovery 60 years ago [6], four higher $N1/2^+$excited states have been discovered [2].

Mass [MeV]	Width [MeV]	Date [year]
1710	140	1980
1880	300	2012
2100	260	2000
$\approx$ 2300	$\approx$ 340	2013

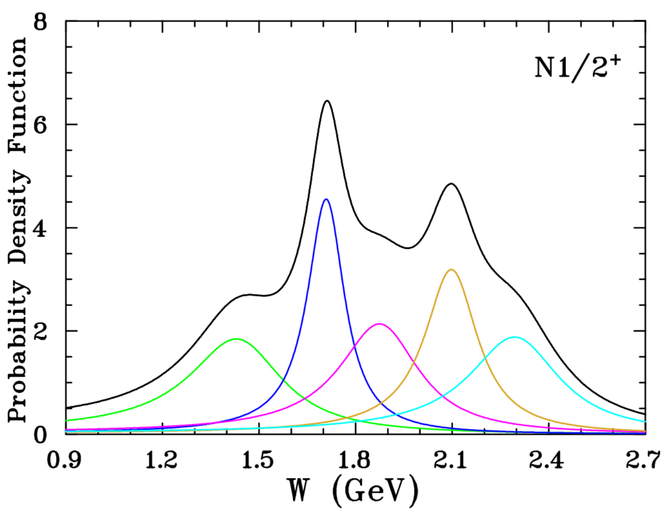

Fig. 2. The masses with widths, using the relativistic Breit–Wigner resonance equation [8], of the five neutron/proton excited states $N1/2^+$ [2]. The Roper resonance $N(1440)$ is the first one on the left (green), then $N(1710)$ (blue), $N(1880)$ (magenta), and $N(2100)$ (yellow). The one on the right $N(2300)$ (cyan) is uncertain.

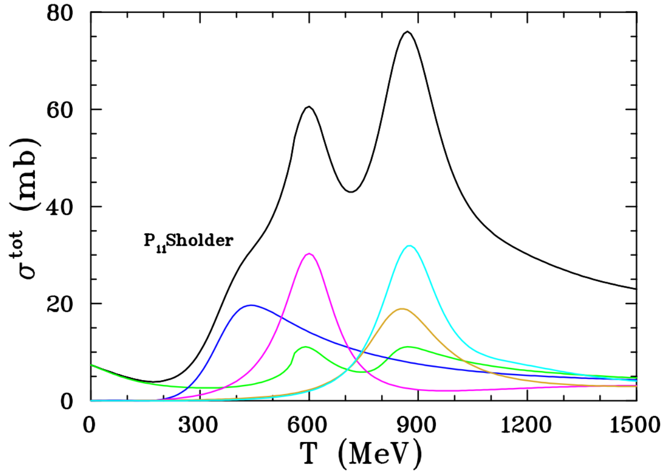

Fig. 3. The current 0–1500 MeV pion laboratory kinetic-energy region resonances' cross sections. GW SAID πN PWA results for $I = 1/2$ (black), S_{11} resonance (green), P_{11} resonance (blue), D_{13} resonance (magenta), D_{15} resonance (yellow), and F_{15} resonance (cyan) cross sections [9]. Note the unusual long-tail behavior of the P_{11} resonance.

5. Postdoctoral appointment at LRL

I was accepted as a postdoctoral appointee at LRL's PPG to begin after my Ph.D. was awarded by MIT. The thesis work was not completed by the end of the 1963 school year; so, I went back to LRL as a research assistant for the 1963 summer to complete the analysis. While at LRL, I exchanged letters with BTF about the progress of the project. (BTF mentioned the discovery of the P_{11} resonance in a talk at a 1963 summer conference in Siena, Italy [10]). When the thesis work was done, LRL flew me back to MIT to defend the thesis, which was accepted by my thesis committee.

The many letters exchanged between BTF and me and between MJM and me were saved and have been donated to the Niels Bohr Library at the American Institute of Physics.

6. Publications

At MJM's request, BTF at MIT agreed that only my name should be listed as the author of the 1964 *Physical Review Letters* paper announcing the existence of the P_{11} resonance, the first excited state of the proton/neutron. Later, two more detailed papers had BTF's and RMW's names as co-authors. MJM did not want his name on any of the papers, although he was as much my thesis advisor as BTF and had provided a large amount of computer time and much time of a programmer.

I was fortunate to have the expertise of computer experts, physicists, typesetting experts, and publication experts at LRL to help me with my research and publications during the summers of 1962 and 1963, and two years as a postdoctoral appointee.

The first published paper about the thesis work was «Evidence for a P_{11} Pion–Nucleon Resonance at 556 MeV» [6]. Two following, much more detailed, papers were «Energy Dependent Pion–Nucleon Phase-Shift Analysis» [11] and «Pion–Nucleon Phase-Shift Analysis: 0–350 MeV» [12]. Two decades later was the publication of «Pion–Nucleon Partial-Wave Analysis to 1100 MeV» [13], a Virginia-Tech Ph.D. thesis by Dr. John M. Ford.

7. Democratic origin of the Roper resonance name

Within a year of its discovery, the pion–nucleon P_{11} resonance started being called "Roper resonance" in research papers, a democratically named moniker.

"Roper resonance" is still occurring in titles of papers, 60 years after the discovery. Search for papers citing "Roper resonance", including the quotes: `https://scholar.google.com` On 28 April 2025, this search yielded 3,730 papers.

8. Serendipity of the discovery

The availability of high computing power at LRL (IBM-7094 mostly, later CDC-3600 and CDC-6600) was crucial to doing the pion–nucleon analysis. I owe large gratitude to Dr. Michael J. Moravcsik and Dr. Sidney Fernbach for making that possible. I do not know what computing facilities would have been available to me at MIT since I never did any computing there.

Several experimentalists generously let me use their data before publication. The then-recent availability of polarization data and charge-exchange cross-section data was crucial in obtaining a unique solution.

There was considerable serendipity in my being at the right places at the right times with the right people and the right amount of new crucial data, coupled with many hours collecting data, studying scattering theory, and lugging two boxes of punched cards to computers, to do pion–nucleon scattering analysis for my MIT theoretical-physics thesis and discovering the Roper resonance 60 years ago.

In 1965, I was told by a 12-year-old home-schooled boy in Utah that he had watched a BBC film about serendipitous discoveries in science that included the Roper resonance as one of the discoveries.

9. Roper-resonance mystery

For the 60 years since its discovery, the Roper resonance (RR) has been somewhat of a mystery. Many ideas have been studied in great detail about its possible structure. A recent 2019 paper by Burkert and Roberts [14] has the following conclusion: "the observed Roper is at the heart of the proton's first radial excitation, consisting of a dressed-quark core augmented by a meson cloud that reduces the core mass by approximately 20%."

The Breit–Wigner RR mass determined 60 years ago via πN PWA was 1485 MeV [6]. That is in perfect agreement with the modern determination by the SAID group and using the modern πN database, which is 1485.0 ± 1.2 MeV [3]. Figure 4 shows it on the Argand diagrams.

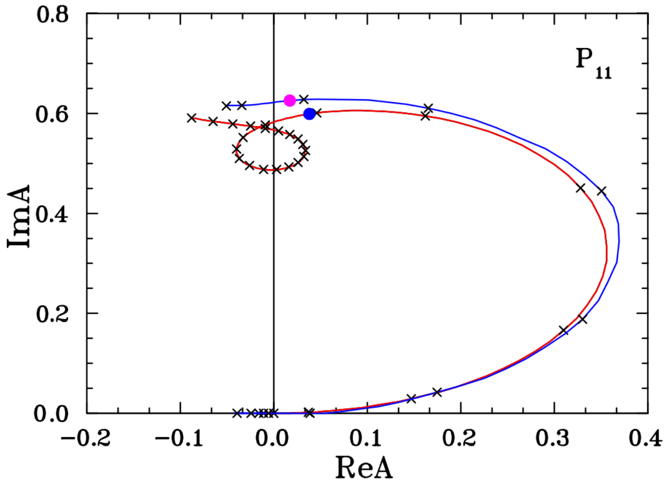

Fig. 4. Argand plots for partial-wave P_{11} amplitude from threshold (1080 MeV) to $W = 2.5$ GeV. Blue curve presents 60 years old results [11] (it was digitized), while the red curve is the recent SAID WI08 solution [9]. Crosses indicate 50 MeV steps in W. Solid circles correspond to Breit–Wigner Roper-resonance mass. Note that the diagram goes negative for a short bit at the start due to the negative real part of the scattering amplitude for about 200 MeV laboratory kinetic energy.

10. Virginia Tech and The George Washington University

The RAA-LDR pion–nucleon, nucleon–nucleon, and other particle scattering computer codes were moved from LRL to Virginia Polytechnic Institute and State University (VPI&SU), also known as Virginia Tech (VT), in 1967. (Richard A. Arndt and I were hired there as a team.) In the 1980s, we developed Internet online access to the VT scattering analyses: Scattering Analyses Interactive Dial-in (SAID).

When Richard Arndt and I retired from VT in 1998, Dick moved the VT analyses, including SAID, to the Institute for Nuclear Studies at The George Washington University in DC [15]. SAID has become the major online source for nuclear-particle scattering data and analysis results.

11. Universal mass equation [7]

A plot (Fig. 5) of the masses of the neutron and the five excited states of the neutron/proton recently led the author and Dr. Igor I. Strakovsky to postulate a universal mass equation [7]

$$M_n = \alpha \ \ln(n) + \beta\,. \qquad (1)$$

For the n/p set of the neutron and five excited states $\alpha = 698.2 \pm 14.1$ MeV and $\beta =$ mass of the neutron. (parameter α could be called the "logarithmic slope".)

Only two parameters define all seven masses of the neutron and six excited states, plus the mass of one missing state at position #6 and four predicted higher-mass excited states.

Roper and Strakovsky [7] have shown that Eq. (1) applies to dozens of equal-quantum excited-states sets besides the n/p set, and conclude that it is a universal mass equation for such quantum sets.

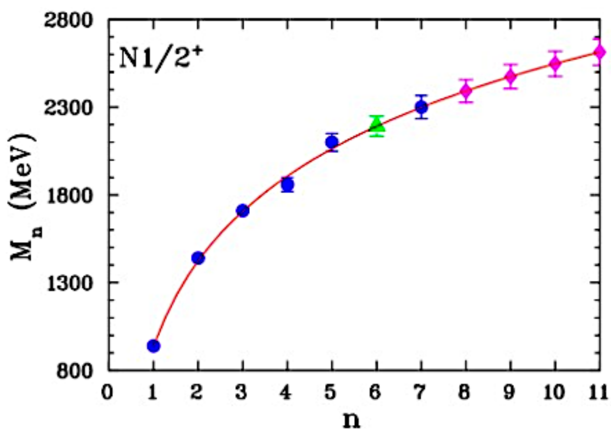

Fig. 5. Data for $N1/2^+$ (blue circles): $N(940)$, $N(1440)$, $N(1710)$, $N(1860)$, $N(2100)$, and $N(2300)$ [2]. The green triangle is the calculated mass of the missing $N(2191)$ state. Predicted states (magenta diamonds): $N(2391)$, $N(2474)$, $N(2547)$, and $N(2614)$. The solid red curve presents the best-fit. The fit parameters are $\alpha = 698.2 \pm 14.1$ MeV and $\beta = 939.6 \pm 5.4 \times 10^{-7}$ MeV.

The author is very grateful to Dr. Igor I. Strakovsky of the George Washington University for the large amount of help in preparing this document. My excellent colleague for forty-eight years, Dr. Richard Allen Arndt (1933–2010), contributed to my successes by providing computer codes, a team job at VPI&SU, and good physics advice. My wife, Jeanne Muriel Baril Roper, and daughters, Tamra Dawn Roper Oliver and Truda Gaye (Taisa) Roper, have provided constant encouragement in my old-age physics efforts.

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