EARLY EXPERIMENTAL STUDIES OF THE ROPER RESONANCE AT THE LOS ALAMOS MESON PHYSICS FACILITY — LAMPF

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The Roper resonance ($P_{11}(1440)$ or $N^{+}_{\frac{1}{2}}(1440)$) has been and continues to be the subject of experimental studies at both hadronic and electromagnetic facilities. This year, we celebrate and honor its discoverer, L. David Roper, on the occasion of his 90th birthday. Recent studies and publications have emphasized the role of electromagnetic beams in studying the properties of the Roper resonance. In this article, we review the role of early experiments using hadronic beams that were sparked by the discovery of the "Roper", and also motivated and encouraged the design and construction of the early meson factories such as LAMPF (Los Alamos Meson Physics Facility), TRIUMF (TRI University Meson Facility), PSI (Paul Scherrer Institute, formerly SIN), and INR (Institute for Nuclear Research).

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1. Introduction

The Roper resonance, or $P_{11}(1440)$, has led to a number of theoretical and experimental studies since its epiphany by L. David Roper [1]. Its properties have been very difficult to explain, and this lightest excited state of the proton has been the impetus of many experimental studies. Most recently, precise measurements were and are being continued at electromagnetic facilities; these studies have recently been very well documented [2] and need not be discussed here. In this contribution, I will focus on the pion–nucleon program at LAMPF, the Los Alamos Meson Physics Facility (formally the Clinton P. Anderson Meson Physics Facility), which was inspired by the discovery of the Roper resonance.

1.1. Why are pion–nucleon experiments interesting

In general, hadronic processes at energies up to several GeV are rich in QCD-related problems that are approachable via experimentation. Theoretical efforts are hampered by a large QCD coupling constant that precludes perturbative approaches. Among the basic questions are the following:

— How does confinement work?

— How does one identify exotic hadronic matter, *e.g.* glueballs and hybrids?

— Why do simple quark models work well in describing baryonic resonances?

— How does one quantify the gluon contributions in resonances?

— What is the strange quark content of the nucleon?

— Why do many of the baryonic resonances appear in clusters?

— How good are isospin invariance and charge symmetry?

— Is it better to observe these interactions at lower energies, or far above threshold, where Coulomb effects are not important?

In particular, the pion–nucleon system is well suited for shedding light on some of these problems: it is easily accessible experimentally, there is no beam polarization to worry about, and the simple spin–isospin structure greatly simplifies theoretical analysis. If one considers the spin–isospin nature of pion–nucleon interactions, there are only two spin amplitudes to consider, the non-spin-flip and the spin-flip amplitudes. Additionally, the pion–nucleon system is limited to two isospin amplitudes, $I = 1/2$ and $3/2$. Measured quantities are represented by quadratic relations among the four complex amplitudes; a complete description of the pion–nucleon system requires only 4 complex amplitudes determined in 8 (some would argue 7) experiments, except for the overall phase factor. Our measurements included some redundancy in data as needed as a check of our systematics.

1.2. Some archaeology of experimental meson–nucleon physics

The goal of this contribution is to restore the forgotten history of the experimental work done at what we used to call "Meson Factories" [3, 4], and mainly work done at LAMPF in which I was strongly involved. Although this may seem a bit self-promoting, it is also the body of work most available in the refereed literature; many other experiments performed in the mid-20$^{\rm th}$ century, prior to the 1980s, were only available in abstracts of presentations and conference proceedings; even when available in written form, full descriptions of experimental techniques, systematic uncertainties, and error analysis were not available in many cases. The latter problem led to the development of the "Star System", the history of which seems to have been lost by those not involved in its inception. As described by Arndt *et al.* in endnote 13 of Ref. [5]: *Historically, B.M.K. Nefkens, W.J. Briscoe, M.E. Sadler,* *R.A. Arndt, and G. Höhler analyzed and classified all πN measurements completed before 1983. Zero, one, two, and three star ratings were assigned to the πN database entries. This star rating system was described in 1983 by B.M.K. Nefkens at the First Workshop on pN scattering and the Tenth International Conference on Few Body Problems in Physics that followed in Karlsruhe, Germany* [6, 7]. I believe that these references, and those contained therein, are an excellent review to the pre-meson factory work on baryon resonances and will go on from there.

It might be noted that not only did I have a first-hand connection with the experimental program at LAMPF, but I was also responsible for the transfer of SAID from Virginia Tech to The George Washington University, where it currently resides. In the end, most of the basis of SAID and the other historical partial-wave analyzes incorporate the results of measurements made using hadron beams, whether primary or secondary. A primary justification of the "Meson Factories" was, in part, to provide these data. Thus, without the work of L. David Roper, these facilities may not have ever come to fruition.

1.3. Preparations for the experimental program

For the Nefkens/Haddock group at UCLA, the chief encouragement to perform measurements of pion–nucleon scattering parameters was related to our discussions with those theorists and phenomenologists performing partial-wave analyzes at several global centers such as Karlsruhe–Helsinki [8], Carnegie–Mellon–Berkeley [9], and VPI/SAID [10] now at GWU [5]. The latter group, which was then located at Virginia Polytechnic Institute and State University in Blacksburg, Virginia, was led by L. David Roper and Richard Arndt [10, 11]. Nefkens and I made several pilgrimages to Blacksburg to discuss our experiments and shared preliminary results so that we could get immediate feedback from Arndt and Roper on how our results were affecting the SAID partial-wave analysis. They also provided us with clues as to where we needed more data, better statistics, and refinement of our systematics. Our discussions also gave us insight into the new measurements we should propose in the future. Of course, we did not neglect our colleagues in Pittsburgh and Karlsruhe, and often consulted with them.

1.4. Meson Factories

Meson Factories were medium-energy proton accelerators that produced 100–1000 MeV nucleons and mesons in beams much more intense than the existing machines of the day. Thus, they would allow for experiments never before possible with increased precision and statistics [3, 4]. There were three historic Meson Factories: LAMPF in Los Alamos, New Mexico; the

Swiss Institute for Nuclear Research (SIN) (now the Paul Scherrer Institute (PSI)) in Villigen, Aargau; and TRI University Meson Facility (TRIUMF) in Vancouver, British Columbia [12]. A more detailed and inclusive discussion of the Meson Factories is given in Chapter 2 of Ref. [13]. As mentioned in the introduction, my contribution here will mainly discuss the work done at LAMPF in which I was involved as a member of and a collaborator with the UCLA group of Nefkens [14]. Since the results of these measurements have been well published, I will not reproduce tables and figures here. I have all the materials in my possession and will gladly provide them to interested parties upon request; with one exception, all published material is available in digital form.

1.5. Rational behind our pion–nucleon program at LAMPF

With the rise of the Los Alamos Meson Physics Facility and its Pion-Particle-Physics (P3) beamline, it was possible to perform a full series of measurements under close to the same experimental conditions with respect to the pion beam. Of course, the properties of the beam had to be well determined. For that reason, our group took it upon itself to systematically determine these properties for the P3 channel [15].

Although it was true that many groups had performed individual measurements in several laboratories, these were performed in different laboratories under differing experimental conditions with little coordination to the best of my knowledge. It might also be noted that in our review of existing results existing before 1983, many of these were only available in conference abstracts and proceedings or even only in internal laboratory reports and not in peer-reviewed journals. So with the Nefkens/Haddock UCLA program, in close consultation with our theoretical collaborators, this was remedied, driven in part by the discovery of the Roper resonance.

2. The "complete" UCLA pion–nucleon experimental program at LAMPF

The full UCLA program consisted of several individual experiments, each designed to be as close as possible to the same beam parameters and measurement angles. Naturally, different targets and detectors were used as needed to provide proton polarization and optimum detection of outgoing particles. Here, I summarize the spectrum of the experiments performed over more than a decade in the P3 channel at LAMPF. This contribution is meant to give the reader only a taste of the scope of the work accomplished and is not a detailed report; the reader is encouraged to read the dissertations and published papers for more details. Since this program spanned more than a decade, members of the collaboration moved on to their permanent institutions, including The George Washington University, Los Alamos National Laboratory, and Abilene Christian University.

2.1. Differential cross sections for π^+p and π^-p elastic scattering from 378 to 687 MeV/c

In LAMPF Experiment 363 [16], the differential cross sections for elastic π^+p and π^-p scattering were measured at pion beam momenta of 378, 408, 427, 471, 509, 547, 586, 625, 657, and 687 MeV/c in the angular range $-0.8 < \cos\theta < +0.8$ in the center-of-mass. The scattered pion and recoil proton were detected in coincidence using scintillation counter hodoscopes that were constructed by members of the group at UCLA. A liquid hydrogen target was used except for measurements at forward angles, in which a solid CH_2 target was used.

Statistical uncertainties in the data are typically less than 1%. The systematic uncertainties in acceptance and detection efficiency are estimated to be 1%. Absolute normalization uncertainties are 2% to 3% for most data. The details and results of Experiment 363 are found in Ref. [16]. At the level of precision of this experiment, *i.e.* 2%, every uncertainty in the cross-section parameter had to be reduced to below the level of 1%, which involved a lot of painstaking and time-consuming labor down to fluoroscopic measurements of the two 4- and 5-inch liquid H_2 targets, *in situ*, while cooled. These images also allowed us to measure the bubble density of the liquid hydrogen in the target cell. This was the first full angular measurement of the differential cross section of these reactions in this momentum range.

These data were also analyzed using Legendre expansions to extract total elastic cross sections. Our measurements were in good agreement with existing data, particularly at lower momenta. Some discrepancies with older data did exist, particularly in the forward angle region, highlighting the importance of our precise measurements.

2.2. Analyzing powers in π^+p elastic scattering at intermediate energies

LAMPF Experiment 120a [17] measured the analyzing power, A_N, for π^+p elastic scattering at p_π = 471, 547, 625, and 687 MeV/c over a wide range of center-of-mass scattering angles $-0.9 < \cos\theta < +0.7$, using a transversely-polarized hydrogen target. The target consisted of propanediol beads contained in a cylindrical cell 2 cm in diameter and 4 cm long, with the pion beam incident along the cylinder axis. The target was dynamically polarized in a 2.5 T magnetic field; reversal of the polarization was accomplished by the appropriate shift in the frequency of the microwaves used for dynamic polarization. The target polarization, which was typically 80%, was measured using an integrating NMR system that was read every 3–5 minutes during data collection. Absolute calibration of the NMR system was achieved by periodic measurements of the thermal equilibrium polarization signal at 1°K. The systematic uncertainty associated with polarization is ±3%. This type of target, while standard today, was quite new at the time. The transverse size and location of the beam at the target position were established by exposing a film placed just downstream of the target; a pair of wire chambers in the beam upstream of the target was used to monitor beam drift during the experiment. The beam flux was typically $10^6\,\pi^+$/sec in a 2 cm diameter spot on the target. The central momenta and momentum bites of the incident beam (FW) were known to ±0.3%.

Scattered pions and protons were detected in the LAMPF Large Acceptance Spectrometer (LAS) and in the recoil detector consisted of a wire chamber with an active area 100 cm (x-plane) by 65 cm (y-plane) placed between two scintillator hodoscopes. The position data from the wire chamber, the pulse heights in the scintillators, and the TOF relative to LAS scintillators were measured for each particle. The highly over-constrained signal derived from this detection system resulted in excellent background suppression; the signal-to-background ratio was typically 7:1, even though the target contained only 7% free hydrogen, and the beam interaction rate in the walls of the target cell and cryostat was substantial. The background yields were measured in separate runs in which the propanediol sample was replaced by graphite beads with the same density as the carbon component of the propanediol.

The results were compared with the then existing PWAs for the isospin-1/2 channel. The agreement of our data with these analyzes was good at 471 MeV/c and reasonable at 547 and 625 MeV/c. At 687 MeV/c, two of the analyzes show a sharp maximum near $\cos\theta = -0.4$ which is not seen in our data. In our data, there was no indication of the existence of new narrow resonances Δ claimed by others at the time.

2.3. Analyzing power for $\pi^- p$ elastic scattering in the energy region of the Roper resonance

LAMPF Experiment 120b [18] measured A_N in $\pi^- p$ elastic scattering at $p_\pi = 471$ to 687 MeV/c and compared with the results of the then existing πN PWAs by the Karlsruhe–Helsinki, CMU-LBL, and VPI groups. The experimental details were similar to 120a. Whereas positive pion scattering off the proton only involves $I = 3/2$ amplitudes, in negative pion scattering off the proton both $I = 1/2$ and $I = 3/2$ amplitudes contribute. Using the VPI Scattering Analysis Interactive Dial-in (SAID) program, we added our $\pi^+ p$ elastic scattering data to the SAID database to obtain a new, single-energy solution. Our data did not change any phase significantly, indicating that the $I = 3/2$ amplitudes were well determined. Thus, the addition of our $\pi^- p$ data to the VPI database for single-energy solutions could be expected to affect only the $I = 1/2$ partial waves; this is indeed what we observed. At 471 and 547 MeV/c, the changes were insignificant. However, at 625 MeV/c, the P_{11} phase decreased from 56° to 54° and D_{13} decreased from 36° to 32°. The effects are even greater at 687 MeV/c, where P_{11} increased from 86° to 99° (a change of 13°) and at the same time S_{11} decreased from 26° to 23°, D_{13} from 58° to 55°, and D_{15} from 13° to 9°. Thus, we concluded that the current PWAs did not correctly represent the Roper resonance. A complete and up-to-date analysis that included our new data on elastic $\pi^- p$ scattering and charge exchange was needed and performed.

2.4. Analyzing power and transversity cross sections for $\pi^+ p$ and $\pi^- p$ elastic scattering from 471 to 687 MeV/c

In LAMPF experiment 120c [19], we combined data from our measurements discussed above. In addition to the analyzing power, we used our differential cross sections previously measured at the same beam momenta, to determine the transversity cross sections defined as

$$\Sigma_{+-0} = \mathrm{d}\sigma/\mathrm{d}\Omega_{+-0}\,(1 \pm A_{N+-0})$$

and the bounds of the isospin triangle inequalities. Comparisons of our final values for A_N with the predictions of the existing PWAs were made. As expected, our measured values of $\pi^+ p$ were in better agreement with the PWA predictions than our values of $\pi^- p$. It should be noted that the PWAs did not include our measurements and thus, were not biased by our results. I discuss here the results of our transversity cross sections and triangle inequality determinations.

Transversity cross sections provide an alternative perspective on the results, emphasizing their role in testing isospin invariance. They were derived from analyzing power measurements and unpolarized differential cross sections. The parallel transversity cross sections at 547 and 625 MeV/c exhibit a pronounced maximum, while antiparallel cross sections show different angular distributions. The analysis of transversity cross sections allows for a more sensitive test of isospin invariance compared to unpolarized cross sections. We determined the triangle inequality bounds using the measured transversity cross sections; the bounds were calculated based on Legendre polynomial fits to the transversity cross sections. The results provided a model-independent test of isospin invariance with implications for measurements in charge exchange reactions. Previous data show reasonable agreement with the current measurements, mainly owing to the large uncertainties in older datasets. Our experimental precision improved the signal-to-background ratios. The use of a highly-polarized target, achieving around 80% polarization, contributed to improved systematics over previous measurements. Our findings suggested no evidence for new resonances below 1450 MeV, indicating that existing amplitudes were well understood.

The addition of our data to the VPI scattering analysis database affected the understanding of phase shifts in pion–nucleon scattering. Our measurements led to adjustments in phase shifts, particularly affecting the phase shifts $I = 1/2$ in the scattering of $\pi^- p$. The phase shift of the P_{11} increased from 86° to 98° at 687 MeV/c, indicating a significant impact on the analysis. The results suggest that the $I = +1/2$ isospin amplitudes were reasonably well understood, while the $I = -1/2$ amplitudes required further investigation.

2.5. Analyzing power for $\pi^- p$ charge exchange and a test of isospin invariance up to η threshold

In experiment 120d [20, 21], the analyzing power for $\pi^- p \to \pi^0 n$ was measured at five incident momenta from 547 to 687 MeV/c using a transversely-polarized target. Data were obtained at 10 angles simultaneously covering the range $-0.9 \leq \cos\theta_{\rm cm} \leq +0.9$. Scintillation counters were used to detect recoil neutrons in coincidence with a photon from π^0 decay detected in one of two photon detectors.

2.5.1. Tests of the splitting of the Roper and isospin symmetry

There were two very intriguing questions concerning the phase shifts in this energy regime. The first of these dealt with the splitting of the Roper resonance [22]. At two separate times in the late 1970s, such a splitting was reported, but due to the limited database at the time, it did not receive much credence. The second interesting question arose from concerns of a violation of isospin symmetry in the π–N system. To resolve these issues, we carried out this complete set of measurements so that PWAs could use the data from our program exclusively to test isospin symmetry in a model-independent analysis using the transversity cross sections. The triangle inequalities could be formed using only our transversity cross sections. Our results from this experiment and those from the radiative capture of Kim *et al.* [23], were used for a model-independent test of isospin invariance based on the triangle inequalities applied to the transversity-up and transversity-down cross sections. No evidence of isospin violation was found. Our results did, however, favor the VPI analyses that show two poles in the Roper resonance.

2.6. Measurement of the spin-rotation parameters A and R for $\pi^+p \to \pi^+p$ and $\pi^-p \to \pi^-p$ scattering from 471 to 625 MeV/c

In LAMPF experiment 806 [24], the spin-rotation parameters A and R for elastic scattering of both π^+p and π^-p were measured at pion beam momenta from 471 to 625 MeV/c using a frozen-spin target polarized in the scattering plane and a recoil-proton polarimeter. At the center of this very complicated and most difficult experiment was a horizontal L- and S-type frozen-spin target using a vertical dilution refrigerator mounted in the HERA superconducting magnet. The other two major components of the experiment were the pion detector, which consisted of a simple scintillator array, and the proton detector, which consisted of the LAS spectrometer and the Janus polarimeter. The proton detector measured the spin-rotation parameters A and R simultaneously using the LAS spectrometer to bend the recoil protons vertically out of the scattering plane. This precessed the proton spin so that the P component, initially oriented normal to the scattering plane, aligned with the momentum vector, and the R component, initially oriented along the momentum vector, is aligned normal to the momentum vector. The A component, initially aligned normal to the momentum vector in the scattering plane, was not affected. Thus, the up–down scattering asymmetry measured by the Janus polarimeter measured A, and the left–right asymmetry measured R. Our results show that the major features of the recent π^-p PWAs are correct. This was the first time such confirmation was possible. Some deviations outside the uncertainties indicated the need for a new round of PWAs.

2.7. Recoil proton polarization in πp elastic scattering at 547 MeV/c and 625 MeV/c

In LAMPF experiment 807 [25], the induced polarization of the recoil proton in elastic scattering of π^+p and π^-p using an LH_2 target was measured for backward angles at 547 and 625 MeV/c. The scattered pion and recoil proton were detected in coincidence using the large-acceptance spectrometer, LAS, to detect and analyze the momentum of the pions and the Janus polarimeter to identify and measure the polarization of the protons. A series of stringent criteria was applied to filter events for analysis, ensuring that only relevant data was considered. The analysis involved calculating the distance of closest approach for proton tracks and applying cuts to enhance data quality. The analyzing power of the carbon rescattering plane was determined from measurements made in a special calibration of Janus, which was crucial for calculating the recoil-proton polarization. Results from this experiment agree with other measurements of the recoil polarization, with analyzing-power data previously taken by this group, and with predictions of PWAs.

2.8. Measurement of the left–right asymmetry in $\pi^- p \to \gamma n$ from 301 GeV/c to 625 MeV/c at backward angles

In this LAMPF experiment [23], the left–right asymmetry of $\pi^- p \to \gamma n$ was measured using a transversely-polarized target at seven pion momenta from 301 to 625 MeV/c, mostly at photon angles of 90° and 110° in the center of mass. The final-state γ and neutron were detected in coincidence. Neutrons were recorded in two arrays of plastic scintillators, and γs were recorded in two matching sets of lead-glass counters. The results were compared with the predictions from the two most recent existing single-pion photoproduction PWAs. The lack of agreement with the analysis of Arai and Fujii cast doubt on the correctness of their values for the radiative decay amplitude of the neutral Roper resonance, which were widely used at the time. The agreement was much better with the results of the VPI analysis. Also, a comparison was made with the recoil-proton polarization data from the inverse reaction measured at 90° with a deuterium target. It revealed substantial discrepancies, indicating the shortcomings of using deuterium for neutron target experiments.

The inverse photoproduction process $\pi^- p \to \gamma n$ was particularly interesting in that it provided a means for investigating the radiative decay of neutral baryon resonances with natural flavor. These, in turn, are used to test the validity of quark models, Skyrmion calculations, and to probe the existence of the postulated hybrid baryons. The radiative decay of the Roper resonance is especially useful as a testing ground for quark model calculations. Most models were conveniently divergent in their predictions of the sign and magnitude of the Roper radiative decay amplitude. There was at the time also a discussion as to whether the Roper was a hybrid baryon state.

An important experimental consideration was that a precision measurement of $\pi^- p \to \gamma n$ arises from the comparison with the inverse reaction measured using deuterium to provide the target neutrons, which is the predominant source of data on photon-induced reactions on the neutron. These experiments require the application of so-called deuterium corrections for the effects such as Pauli blocking, Fermi motion, nuclear binding, off-mass shell amplitudes, *etc.* The validity of these corrections in the photoproduction data $\gamma d \to \pi X$ could only be evaluated if good data are available on the inverse process, $\pi^- p \to \gamma n$.

3. Summary

This contribution is far from a complete history of this program, but I hope it at least shows that our program at LAMPF, propelled by the discovery of the Roper resonance and guided every step of the way by our friends and collegues at VPI, L. David Roper and Richard Arndt, did some service to the community and made excellent use of the meson factory built for just these types of experiment. Thank you Dave for providing me and my experimental collaborators a purpose in our professional lives.

Happy 90$^{\text{th}}$!

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