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PIONS AND NEUTRINOS AS PROBES OF THE NUCLEON AND NUCLEAR FEW-BODY SYSTEM

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A number of studies of few-body nucleon and nuclear systems are being pursued at LAMPF using pions and neutrinos as probes. These include: a high-statistics measurement of the cross section for the reaction $\pi^+p \rightarrow \pi^+\pi^0p$ to determine the $l=2$ $\pi\pi$ scattering length; precision measurements of the π^-p charge exchange cross section in the region of the Δ ; measurements of the cross section for the (π^+, π^+p) from D, ^3He , and ^4He as tests of charge symmetry and reaction mechanisms; measurements of the π^+p cross section below the Δ ; and studies of νp elastic scattering at low Q^2 to determine the quark content of the proton spin. Some of these experiments acquired data last year, while others are presently running. LAMPF, the highest power proton accelerator in the world, is presently in the midst of its 1993 production run.

The Reaction $\pi^+p \rightarrow \pi^+\pi^0p$ Near Threshold and Chiral Symmetry Breaking

Quantum chromodynamics (QCD) is widely accepted as the theory of strong interactions mainly because of its success in describing processes at large momentum transfer (i.e., short interaction distances). At low energies, the coupling constant becomes large and QCD becomes nonperturbative so calculations become intractable. Chiral symmetry is an important feature of low-energy hadron dynamics and can form the framework for effective Lagrangian models that allow many low-energy properties of strongly-interacting systems to be calculated. The nature of chiral-symmetry breaking can be studied with measurements of the $\pi\pi$ scattering amplitudes at zero momentum, which vanish in the chiral limit. The $\pi\pi$ scattering amplitudes can be probed by studies of the reactions $\pi N \rightarrow \pi\pi N$ at threshold. Recently Olsson and Turner [1] showed that, with rather general assumptions, the nature of the chiral-symmetry breaking can be characterized by a single parameter, ξ . Several recent measurements of $\pi N \rightarrow \pi\pi N$ near threshold led Burkhardt and Lowe [2] to perform a comprehensive soft-pion analysis to extract a value for ξ . However, the available data for the $\pi^+p \rightarrow \pi^+\pi^0p$ channel below 300 MeV/c were too poor in quality to constrain the global fit. Consequently, a group from Virginia, Stanford,

and Los Alamos [3] performed an experiment at the low-energy pion channel at LAMPF to study $\pi^+p \rightarrow \pi^+\pi^0p$ for pion kinetic energies from 190 MeV to 260 MeV (the threshold is 164.8 MeV).

All of the final-state particles were detected. Photons from the neutral pion decays were detected in the LAMPF π^0 spectrometer [4], while the protons and charged pions were detected in a telescope array of plastic scintillator detectors. Each telescope consisted of thin (3 mm) and thick (25 mm) ΔE counters, and an absorption counter capable of stopping the pions from the desired reaction. In all, 56 distinct angular bins were covered simultaneously.

Events from $\pi^+\pi^0$ and π^0p double coincidences and from $\pi^+\pi^0p$ triple coincidences were recorded. Detector acceptances, kinematics, and backgrounds are very different for these three types of events. The three data sets were analyzed separately, providing three nearly independent measurements and internal consistency checks. Comparisons with a Monte Carlo simulation show event distributions that are consistent with phase space at all energies, simplifying the evaluation of angle-integrated cross sections.

The total cross sections deduced from $\pi^+\pi^0$, π^0p , and $\pi^+\pi^0p$ coincidences are in good agreement with each other; a weighted average of these measurements is adopted as the final value. Figure 1(a) shows the measured total cross section as a function of beam energy. These data have been used in a new global fit to all five charge channels to obtain a new value of the chiral symmetry breaking parameter $\xi = -0.25 \pm 0.10$ [5]; the χ^2 of the fit is 96 for 93 degrees of freedom. Figure 1(b) shows the constrained fit of the $\pi^+\pi^0p$ amplitudes: the four other channels show similar agreement with the data. Within the soft pion model, this fixes the $l = 0$

Fig. 1. (a) The total cross section for $\pi^+p \rightarrow \pi^+\pi^0p$ measured in this work, and previously published results. The curve is the results of the new global fit of $\pi N \rightarrow \pi\pi N$ amplitudes. (b) The absolute value of the $\pi^+\pi^0p$ matrix element corresponding to the cross sections shown in (a), as a function of T^* , the total c.m. kinetic energy. The solid line is the global linear fit; the dashed lines show the uncertainties in the fit.

and 2 $\pi\pi$ s-wave scattering lengths to be $a_0^0(\pi\pi) = 0.177 \pm 0.006 \text{ m}_\pi^{-1}$, and $a_0^2(\pi\pi) = -0.041 \pm 0.003 \text{ m}_\pi^{-1}$, respectively.

Data analysis to obtain exclusive cross sections is proceeding. This should allow a model-independent $\pi\pi$ phase shift analysis.

Precision Measurements of π^-p Charge Exchange in the Region of the Δ

The simple spin and isospin structure of the pion-nucleon system makes it an ideal source of information on fundamental hadron interactions. Assuming isospin invariance, the scattering amplitudes for the three observable reactions, (π^+p and π^-p elastic scattering, and π^-p charge exchange) are functions of only two independent isospin amplitudes, $F_{3/2}$ and $F_{1/2}$. The amplitudes can be expanded into partial waves. Each complex partial wave amplitude for isospin I , orbital angular momentum l , and total angular momentum $j = l \pm 1/2$, can be written in terms of two real variables, the phase shift and absorption parameter. S - and P -waves strongly dominate pion-nucleon scattering up to the $\Delta(1232)$. The phase shifts are strongly overdetermined in this regime, allowing a reliable treatment of electromagnetic corrections and a search for isospin-breaking effects.

The most extensive set of differential cross sections for πN charge exchange in the region of the Δ were obtained by Jenefsky *et al.* [6], who made measurements from 128 to 246 MeV in the angular range $-0.98 \leq \cos \theta_{\pi^0} \leq 0.65$. This experiment detected neutrons only, and quoted total errors of 6–10%. Other data were obtained by several other experiments [7] over more restricted energy or angle regions. In addition, Bugg *et al.* [8] measured the total charge-exchange cross section from 90 to 290 MeV with quoted errors of 1%. The differential cross section data agree reasonably well with phase shift fits, but this is not true of the total cross section data. In addition, there are significant discrepancies in the elastic scattering data in this energy region. It would be particularly helpful to improve the accuracy of the charge exchange data to resolve the discrepancies [9].

Measurements of π^-p charge exchange from 140 to 260 MeV are under way at LAMPF [10] using the new Neutral Meson Spectrometer (NMS) to detect neutral pions. The NMS is able to measure final-state π^0 's at all angles including 0° . The NMS is a large acceptance (2 msr), high resolution ($\ll 1$ MeV) device that consists of two arms used to detect the two photons from π^0 decay. The NMS allows a region of 40° in scattering angle to be covered at the same time. The measurement of π^-p charge exchange does not require good π^0 energy resolution, so the photon converters are not used. The large acceptance and relatively large cross section (> 1 mb/sr) imply that the statistical uncertainties will be small. Systematic uncertainties (such as the absolute beam normalization, detection efficiencies, etc.) should be no larger than a few percent.

Data were taken last year at 0° with pions of 138.8, 166, 190, 214.6, 237, and 263 MeV incident on CH_2 and C targets. Figure 2 shows very preliminary data from that run. Final corrections for the beam normalization and contamination, and the detection efficiency are still to be completed. Data taking is presently under way at 90° and 180° .

Measurements of Exclusive ($\pi, \pi'x$) Reactions on Light Nuclei

Studies of exclusive particle knockout reactions have been pursued to obtain information on particle clusters in nuclei and on reaction mechanisms. The strong isospin dependence of the

Fig. 2. Very preliminary data for the π^-p charge exchange cross section in the forward direction as a function of pion energy from last year's run at LAMPF. The data points have been assigned systematic errors of 5%. Also shown are earlier data and predictions from two phase shift analyses.

elementary $\pi-N$ force in the region of the Δ allows measurements of the ratio of exclusive cross sections, $R_x = \sigma(\pi^+, \pi^{+'}x)/\sigma(\pi^-, \pi^{-'}x)$, to be used to uncover the reaction mechanism. If the $(\pi, \pi'p)$ reaction were to proceed exclusively by quasi-elastic πp scattering, one would expect $R_p = 9$, reflecting the ratio of the elementary π^+p to π^-p elastic scattering amplitudes. On the other hand, if the reaction were to proceed exclusively by quasi-elastic π -triton scattering, a ratio of nearly 0.5 would be expected; evidence for this latter mechanism in π - ^4He scattering at 180 MeV was uncovered in an earlier experiment [11].

New measurements were made with incident π^+ and π^- from 180 to 300 MeV on ^2H and ^3He , the simplest few-body nuclei. Some data on ^4He were also taken to supplement earlier data. These targets minimize the effects due to nuclear structure while giving several different nuclei to compare reaction mechanisms. The experiment was performed by a group from Minnesota, Texas, LANL, Rutgers, New Mexico State, Colorado, and Tohuko, in the P^3 channel at LAMPF [12]. The experiment employed the Large Acceptance Spectrometer to detect the pions and a CsI-phoswich detector [13] for the recoil particles. The phoswich detector can identify recoil protons, deuterons, and tritons. Here I give some preliminary results for recoil protons.

Table 1 gives the ratio R_p at the quasi-free knockout angle taken with a cooled-gas targets. R_p is consistent with the quasi-elastic value of 9 for hydrogen but is significantly greater

Table 1. Preliminary results for $R_p = \sigma(\pi^+, \pi^{+'}p)/\sigma(\pi^-, \pi^{-'}p)$ with light targets.

Target	T_π (MeV)	θ_π^{lab} (deg)	q (fm $^{-1}$)	R_p
H	240	32°	0.95	10.2 $\pm$ 0.5
H	300	27°	0.95	9.7 $\pm$ 0.7
^2H	180	40°	0.95	13.4 $\pm$ 1.3
^2H	210	35°	0.95	25.9 $\pm$ 3.1
^2H	240	32°	0.95	23.7 $\pm$ 1.7
^2H	300	27°	0.95	18.8 $\pm$ 1.8
^2H	300	44°	1.50	8.4 $\pm$ 0.5
^4He	180	40°	0.95	41.5 $\pm$ 16
^4He	240	32°	0.95	31.5 $\pm$ 4.6

for both deuterium and helium between 180 MeV and 300 MeV for $q = 0.95 \text{ fm}^{-1}$. Apparently, the residual core is not simply a spectator, even for the weakly-bound deuteron. $R_p \approx 9$ for the point with $q = 1.5 \text{ fm}^{-1}$, indicating that R_p is a function of momentum transfer, but it is apparently not a strong function of beam energy.

Measurements of the Pion-Proton Integral Cross Section from 60 to 260 MeV

The first comprehensive measurements of π^+p scattering below 100 MeV [14] disagreed with predictions based upon extrapolations of established phase shifts. A number of subsequent measurements have failed to resolve this problem, as some measurements reported agreement with the predictions of the phase shift programs, and others reported differential cross sections substantially below these predictions. Recently, the group of Friedman *et al.* working at TRIUMF introduced a new technique of measuring "partial total" or integral cross sections to compare with the phase shift predictions [15]. These measurements involve the integrated scattering cross section for laboratory angles greater than some minimum angle. The measured integral cross section for low-energy π^+p scattering is quite insensitive to the accuracy with which the minimum scattering angle is known because the cross section is strongly peaked in the backward hemisphere. The integral cross section is an observable that can be directly compared with predictions of phase shift fits; there is no need to make an extrapolation through the Coulomb region to zero detector solid angle.

In an effort to resolve the experimental discrepancies, a group from Colorado, LANL, Minnesota, British Columbia, and Cal State Sacramento measured integral cross sections above 30° from 60 to 200 MeV at the P^3 channel at LAMPF [16]. Pions in the incident beam were cleanly identified by time-of-flight between beam counters and the accelerator RF signal. The experiment of Ref. [15] used a polyethylene target, necessitating a subtraction for events from carbon. The new experiment used a liquid hydrogen target, thus avoiding this subtraction. Scintillation counters identified events with pions scattered outside a 30° forward cone. Pions inside this cone were identified and separated from recoil protons by means of the pulse height and time-of-flight measured in a forward counter. Figure 3 compares the preliminary results for the integral cross section as a function of energy compared with the expectation from the KH80 [17] phase shift. Figure 4 shows the ratio of the preliminary data to the cross section calculated from the phase shifts KH80 [16]: the data of Friedman *et al.* are also shown. The preliminary results are consistently below the phase-shift expectations. This is in agreement with the early measurements and disagrees with the results of Ref. [15].

Measuring the Quark Content of the Proton Spin with Neutrinos

It is not yet possible to calculate hadron structure functions in QCD. However, sum rules for the first moments of the g_1 structure functions have been derived from rather fundamental theoretical arguments. In particular, the derivation of the Ellis-Jaffe sum rule [18], $\int g_1^p(x) dx = 0.175 \pm 0.018$, relies on the assumptions that the strange quarks in the nucleon sea are unpolarized and that SU(3) symmetry holds in hyperon decays. The European Muon Collaboration (EMC) [19] and earlier SLAC experiments [20] measured g_1^p for $0.01 < x < 0.7$. By extrapolating to the entire range of x , they find $\int g_1^p(x) dx = 0.126 \pm 0.01 \pm 0.015$, which differs significantly from the Ellis-Jaffe prediction. If this deviation is ascribed to the strange quarks, then the total quark spin projection along the direction of the nucleon spin is consistent

π^+p Preliminary Results ($\theta_\pi > 30^\circ$)

Fig. 3. The integral π^+p cross section above 30° compared with the expectation from the KH80 phase shifts.

π^+p Preliminary Results ($\theta_\pi > 30^\circ$)

Fig. 4. The ratio between the preliminary results of the integral π^+p cross section as a function of energy measured in this experiment above 30° to the results expected from the KH80 phase shift solution. The data are significantly below the expectations. The data of Friedman *et al.* are also shown.

with zero. This would be surprising but not inconsistent with any fundamental aspect of QCD. It may also be that the assumptions used to derive this conclusion (SU(3), the extrapolation to $x = 0$) are incorrect. In any event, it is clear that this deserves further study. νp elastic scattering can be used to directly determine Δs , the strange quark contribution to the proton spin, without requiring SU(3) symmetry or an extrapolation in x .

The cross section for νp elastic scattering at low Q^2 ($Q^2 \ll m_p^2$) is given by:

$$\frac{d\sigma}{dQ^2} \approx \frac{G_F^2}{2\pi} \left[G_1^2 \left(1 + \frac{Q^2}{4E_\nu^2} \right) + F_1^2 \left(1 - \frac{Q^2}{4E_\nu^2} \right) \right],$$

where $2G_1(0) = -g_A + G_1^s$, and $F_1(0) = -0.034 + F_1^s/2$. We know that $g_A = 1.26$ from neutron decay, and $F_1^s(0) = 0$ because F_1^s is the strange charge radius. Thus, at low Q^2 , the cross section determines $G_1^s = \Delta s$, the strange quark contribution to the proton spin.

An experiment has been built at LAMPF to extend the sensitivity of searches for neutrino oscillations. The experiment, the liquid scintillator neutrino detector [21] (LSND), will also provide an accurate measurement of the cross section for νp elastic scattering at low Q^2 . The detector consists of a cylindrical tank, approximately 6 m in diameter and 9 m long, containing 200 tons of dilute mineral-oil-based scintillator. The scintillator is viewed by 1224 8" photomultiplier tubes, which cover 22% of the surface of the tank and yields an energy resolution of 5% for 50-MeV protons. The different characteristics of Čerenkov light and scintillator light allow electrons, protons, and neutrons to be identified.

The detector is located inside a veto shield approximately 28 m downstream of the main proton beam stop at LAMPF. In the present beam stop, ~97.5% of the π^+ produced decay at rest and emit 30-MeV muon neutrinos; 2.5% of the pions decay in flight producing a muon-neutrino beam with an average energy of 150 MeV. A major upgrade to the LAMPF beam stop will greatly increase the decay-in-flight yield.

In νp elastic scattering, the only observables are the energy and angle of the low-energy recoil proton. Only the proton energy can be measured in LSND. One can try to make an absolute measurement of the elastic scattering cross section, but this requires good knowledge of the neutrino flux. Another approach is to compare the relative yield of (νp) and (νn) events from carbon. This strategy gives a factor of 2 enhancement in the sensitivity to Δs and is insensitive to the neutrino flux. However, one must understand possible nuclear effects and the detector response for neutrons. There has been an initial study of the nuclear effects [22]; Fig. 5 shows the sensitivity of the ratio of (νp) to (νn) events as a function of Δs for a wide range of values of $F_2^s(0)$, the strange magnetism form factor; F_2^s will be measured in the SAMPLE experiment at Bates [23]. In order to eliminate quasi-elastic events from free protons, only events with recoil nucleons above 60 MeV can be used. With the LAMPF beam stop in its present configuration, 15 νp elastic scattering events per day with $T > 10$ MeV from free protons, 3.5 events with $T > 60$ MeV from bound protons, and 0.75 νn with $T > 60$ MeV are expected. The principal background is cosmic-ray induced neutron events. After a minor upgrade to the beam stop, next year's run should result in approximately 750 (150) νp (νn) events yielding an uncertainty in Δs of ± 0.1 . The major beam stop-upgrade, presently under consideration for 1995, would lower the expected uncertainty in Δs to ± 0.04 in 1995; if the major upgrade is not undertaken, Δs will be determined to ± 0.06 .

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Fig. 5. The ratio of (vp) to (vn) elastic scattering events as a function of $G_1^f(0)$ for several values of F_2^s .

References

1. Olsson, M.G., Turner, L.: *Phys. Rev. Lett.* **20**, 1127 (1968); *Phys. Rev.* **181**, 2141 (1969); and Turner, L.: Ph.D. Thesis, Univ. of Wisconsin, 1969 (unpublished).
2. Burkhardt, H., Lowe, J.: *Phys. Rev. Lett.* **67**, 2622 (1991).
3. LAMPF Experiment #1179, D. Počanić, spokesman.
4. Baer H., et al.: *Nucl. Instrum. Methods* **180**, 445 (1981).
5. Frlez, E.: Ph.D. Thesis, Univ. of Virginia, 1993 (unpublished).
6. Jenefsky, R.F., et al.: *Nucl. Phys.* **A290**, 407 (1977).
7. Comiso, J.C., et al.: *Phys. Rev.* **D12**, 738 (1975); Bayer, W., et al.: *Nucl. Instrum. Methods* **134**, 449 (1976).
8. Bugg, D.V., et al.: *Nucl. Phys.* **B26**, 588 (1971).
9. Hohler, G., Stahov, J.: πN Newsletter No. 2, Hohler, G., Kluge, W., Nefkens, B.M.K. (eds.), **42**, May 1990.
10. LAMPF Experiment #1268, M. Sadler, spokesman.
11. Langenbrunner, J., et al.: *Phys. Rev. Lett.* **69**, 1508 (1992).
12. LAMPF Experiment #1216, J. Langenbrunner, spokesman.
13. An earlier CsI phoswich detector is described in Langenbrunner, J. L., et al.: *Nucl. Instrum. Methods* **A316**, 450 (1992). A faster detector was used in this experiment.
14. Frank, J.S., et al.: *Phys. Rev.* **D28**, 1569 (1983).
15. Friedman, F., et al.: *Phys. Lett.* **B231**, 39 (1989); **B254**, 40 (1991), *Nucl. Phys.* **A514**, 601 (1990).
16. LAMPF Experiment #1190, C. L. Morris and R. A. Ristinen, spokesmen.
17. Koch, R., Pietarinen, E.: *Nucl. Phys.* **A336**, 331 (1980).
18. Ellis, J., Jaffe, R.: *Phys. Rev.* **D9**, 1444 (1974); **D10**, 1669 (1974).
19. Aschman, J., et al.: *Phys. Lett.* **B206**, 364 (1988); *Nucl. Phys.* **B328**, 1 (1989).
20. Alguard, M.J., et al.: *Phys. Rev. Lett.* **37**, 1261 (1976); *ibid.* **41**, 70 (1978); Baum, G., et al.: *Phys. Rev. Lett.* **51**, 1135 (1983).
21. LSND Proposal, Los Alamos National Laboratory Report LA-UR-3764 (1989) [unpublished].
22. Garvey, G.T., et al.: *Phys. Lett.* **B289**, 249 (1992).
23. McKeown, R.D., Beck, D.H., Spokesmen: Bates Proposal #89-06.

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