π-N charge exchange and π⁺-π⁰ scattering at low energies

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π-N and π-π interactions near threshold are uniquely sensitive to the chiral symmetry breaking part of the strong interaction. The π-N σ-term value with its implications for nucleon quark structure and the recent controversy concerning the size of the scalar quark condensate have renewed the experimental interest in these two fundamental systems. We report new differential cross sections for the reaction π⁻p→π⁰n at 27.5 MeV pion incident kinetic energy, measured between θ_CM = 0° and 55°. Our results are in excellent agreement with the existing comprehensive πN phase shift analysis. We also report on a Chew-Low analysis of exclusive π⁺p→π⁺π⁰p data at 260 MeV pion incident energy.

1. π-N CHARGE EXCHANGE AT 27.5 MeV

While the basic mechanism of spontaneous breaking of chiral symmetry is reasonably well in hand, certain aspects of the explicit breaking of chiral symmetry (χSB), due to nonzero quark masses, remain not fully resolved to date. In the π-N system at low energies the quantities of interest are the chiral symmetry breaking “sigma term” and the scattering lengths. In particular, the σ-term has been found to have an unexpectedly large value (for the most recent comprehensive analysis see Ref. [1]). The discrepancy between the σ-term values obtained from the baryon mass splitting and from extrapolation of the isospin-even π-N scattering amplitude has been attributed to a nonzero ¯sσ content of the nucleon [2]. π-N scattering lengths are related quantities that provide an independent check of the chiral lagrangians. Thus, low energy π-N interactions have retained a fundamental significance and interest over the years.

Unfortunately, inconsistencies in the existing π-N data set have given rise to significant uncertainties of the low energy π-N amplitudes. These, in turn, are reflected in the error limits of the extracted “experimental” value of the σ-term. This situation has led to an effort to remeasure all low energy π-N observables at the remaining meson facilities. In this work we focus on the charge exchange reaction below 30 MeV pion incident energy.

Absolute measurements of the pion-nucleon charge exchange reaction π⁻p→π⁰n below 50 or even 100 MeV are sparse. The difficulties stem from the requirement that the beam composition, beam flux, and the π⁰ detection efficiency all have to be measured or determined accurately in an absolute way.

Early published data below 50 MeV were measured by detecting the neutron at a single angle, 0°, corresponding to the π⁰ angle of 180° [3]. Another set of measurements [4] used a large NaI(Tl) crystal counter to detect single photons from the final state π⁰ decay.

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at 27.4 and 39.3 MeV incident pion energy, covering a wide angular range. Due to the nature of this method, yields from a broad range of $\pi^0$ angles were mixed in at any given laboratory angle of a detected single photon. Hence, the authors could only report a Legendre polynomial decomposition of the $\pi^- p \rightarrow \pi^0 n$ angular distribution, up to order 2.

First published direct measurements of angular distribution data of the $\pi^- p \rightarrow \pi^0 n$ reaction below 50 MeV were made using the LAMPF $\pi^0$ spectrometer [5] at seven energies between 32.5 and 63.5 MeV for $\theta_{\text{lab}}(\pi^0) = 0 - 30^\circ$ [6]. A device such as the $\pi^0$ spectrometer detects the two photons following the $\pi^0$ decay in coincidence. This, in turn, enables a full reconstruction of the neutral pion’s momentum four-vector. In our work we used the same technique.

1.1. Experimental method and normalization

The present measurements of the differential cross sections for the reaction $\pi^- p \rightarrow \pi^0 n$ at 27.5 $\pm$ 0.2 MeV were carried out in the LEP secondary beam channel at the Clinton P. Anderson Meson Physics Facility (LAMPF) in Los Alamos. We used a weakly focusing 30 MeV $\pi^-$ beam tune with 12 mr divergence (both horizontal and vertical), a beam spot size of 9 mm FWHM, momentum spread $\Delta p/p = 3\%$ and pion flux averaging $5 \times 10^5 \pi^-$/sec.

Relative on-target beam intensity was monitored with a sealed ion gas chamber in combination with a high precision charge integrator. Absolute cross-calibration of chamber ionization counts was obtained through activation measurements of the $^{12}\text{C}(\pi^- , \pi^- n)^{11}\text{C}$ reaction using cylindrical plastic scintillator targets [7]. The $^{11}\text{C}$ activation measurements were reproducible to better than $\pm 2\%$, while the $^{11}\text{C}$ activation cross section used for normalization has an uncertainty of 4.7% [8]. The electron and muon contaminations in the beam were determined by a combination of direct measurement and constraints using the integrated energy deposited in the sealed ion chamber that was calibrated in absolute terms independently. The associated uncertainty of the pion flux amounted to $\pm 2.4\%$.

Our measurements were carried out using a 711 $\pm$ 2 mg/cm$^2$ polyethylene (CH$_2$) target, with a suitable $^{12}\text{C}$ target for background subtraction. In addition, we recorded charge exchange data using a 267 $\pm$ 7 mg/cm$^2$ liquid hydrogen target as a check.

We used the LAMPF $\pi^0$ spectrometer to detect coincident photons following $\pi^0$ decay in $\pi^- \rightarrow \pi^0 n$. The spectrometer multiwire proportional chamber and veto counter efficiencies were calibrated independently using cosmic muons. All tracking efficiencies were also evaluated from data and compared with a detailed simulation using GEANT [9]. The resulting uncertainty of the integral $\pi^0$ detection efficiency was 4.6%.

The measured detector response to $\pi^0$'s from the charge exchange reaction under study was compared to simulations using GEANT and PIANG [10], with excellent agreement. The rms angular resolution of the spectrometer was 2$^\circ$.

1.2. Results and discussion

Results of our measurements of the $\pi^- p \rightarrow \pi^0 n$ angular distribution between 0$^\circ$ and 55$^\circ$ (c.m.), binned into 9$^\circ$ wide bins, are plotted in Fig. [1] as full circles. Error bars shown in the figure reflect only statistical uncertainties; in addition, an overall normalization uncertainty of 7.5% applies to the data, as discussed above.

For the sake of comparison we have also included in Fig. [1] the angular distribution
predicted by the comprehensive $\pi$-N phase shift analysis SM95 by the VPI group \[11\] (solid curve). The agreement between our data and the VPI phase shift prediction is excellent. Older data at this energy from Ref. \[4\] are available only in the form of a Legendre polynomial decomposition (fit) of the angular distribution. That fit is represented in Fig. 1 by a dashed line, while dotted lines denote the associated error limits.

In summary, our results provide a new stringent constraint on the low energy $\pi$-N phase shifts, and are in excellent agreement with the existing body of $\pi$-N data.

2. Reaction $\pi^+p \rightarrow \pi^+\pi^0p$ at 260 MeV

Low energy $\pi$-$\pi$ scattering has enjoyed longstanding attention as a window into the mechanism of chiral symmetry breaking. Pion-pion scattering lengths have recently come sharply into focus due to the controversy regarding $\langle 0|\bar{q}q|0 \rangle$, the scalar quark condensate, and the two radically different and far-reaching scenarios of $\chi$SB \[12\]. The current most reliable value of $a_0 = 0.26 \pm 0.05 \mu^{-1}$ (where $\mu \equiv m_\pi$), extracted mainly from $K_{e4}$ decay data \[13\], is not accurate enough to make the required distinction.

We report here on preliminary results of a Chew-Low analysis \[14\] of exclusive $\pi^+p \rightarrow \pi^+\pi^0p$ data measured at 260 MeV $\pi^+$ incident energy. The experimental apparatus and the total cross section analysis are described in Ref. \[15\]. The Chew-Low method evaluates $\pi\pi$ cross sections by extrapolating to the pion pole the function $F(s,t,m_{\pi\pi})$:

$$\sigma_{\pi\pi}(m_{\pi\pi}) = \lim_{t\to\mu^2} F(s,t,m_{\pi\pi}) = \lim_{t\to\mu^2} \frac{\partial^2 \sigma_{\pi\pi N}(s)}{\partial t \partial m_{\pi\pi}} \cdot \frac{\pi}{f_\pi} \cdot \frac{p^2(t - \mu^2)^2}{t m_{\pi\pi}(m_{\pi\pi}^2 - 4\mu^2)^{1/2}},$$

(1)

where $m_{\pi\pi}$ is the dipion invariant mass, $t$ is the squared 4-momentum transfer to the proton, $\sqrt{s}$ is the total c.m. energy, $p$ is the incident pion momentum, and $f_\pi$ the pion decay constant. In this work, we had to perform a deconvolution of the instrumental resolution function from the data before we could construct an interpretable $F(s,t,m_{\pi\pi})$. 

Figure 1. Measured c.m. $\pi^-p \rightarrow \pi^0n$ differential cross sections (full circles). Vertical bars reflect the statistical uncertainties only; an overall normalization uncertainty of 7.5% also applies. Horizontal bars denote the angular bin size; rms angular resolution was 2°. Solid curve: VPI SM95 partial wave analysis \[11\]. Dashed and dotted curves: Legendre polynomial fit to data from Ref. \[4\].
Preliminary values of $F$, the Chew-Low extrapolation function, calculated from our $\pi^+\pi^0p$ data at 260 MeV are plotted against $t$ in Fig. 2, alongside a linear fit. Points with $|t| > 7\mu$ were excluded from the fit due to the diminishing contribution of the one pion exchange process; the lowest $t$ point was excluded due to deconvolution uncertainties.

Using the new $\pi^+\pi^0$ cross section datum we can deduce $\sigma_0^2 \simeq 0.55 \pm 0.24 \mu^{-1}$. However, further work is required in order to extract a more reliable extrapolated value of $\sigma(\pi\pi)$. That result, in turn, will be added to the existing $\pi\pi$ data set for a comprehensive dispersion-relation analysis.

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