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TWO-SPIN MEASUREMENTS OF PION PRODUCTION NEAR THRESHOLD*

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We have recently measured single pion production cross sections in proton-proton scattering with both beam and target polarized. These measurements were made at four beam energies between 325 and 400 MeV using the "Cooler" storage ring at IUCF in Bloomington, Indiana. This covers a region relatively close to threshold ($\eta < 1$) where only a few partial waves can contribute to the scattering. The spin dependence can be used to separate the contributions due to specific partial waves, even if angular distributions are statistically limited. Data have been taken for both the neutral and charged pion production, but only neutral pion data will be presented here, along with plans and prospects for the future.

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1. Introduction

It is not difficult to appreciate the importance of meson production in understanding the strong force between nucleons. Meson production near threshold can serve as a window on the fundamental vertex associated with the nucleon-nucleon (NN) interaction. Recent work has shown that even if only the lightest mesons (pions) are produced, more than just the long range part of the NN interaction is involved [1]. Accurate theoretical models should be able to predict excitation functions for all pion production channels near threshold. As excess energy increases, spin observables can provide additional information for evaluating theories. One can either use this information to experimentally separate contributions from various partial waves, or require the theoretical model to fit the measured values of

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various spin observables directly. Either way, such detailed comparisons are the best test of our theoretical understanding of such a fundamental process.

This paper follows up on a presentation made at MESON '96 [2] in which the extensive preparations for these measurements were described.

Below about 500 MeV beam energy, pion production from the nucleon-nucleon system can only involve a few partial waves, because the available relative kinetic energy limits the angular momentum in the final state. Using spectroscopic notation to specify first the relative angular momentum of the NN final state (uppercase) followed by the angular momentum of the pion relative to the NN center of mass (lower case), we need only consider final states Ss, Sp, Ps and Pp. In a previous experiment on neutral pion production in proton-proton collisions without spin polarization, measurements were made so close to threshold that only one Ss partial wave could contribute, fed by only one initial state configuration. [3] This non-resonant wave could only involve a direct (Born) term, s-wave pion rescattering, or perhaps heavy meson exchange. Traditional calculations involving only direct production and on-shell rescattering underpredicted the measured cross section by about a factor of five. Current models invoke either off-shell rescattering or heavy meson exchange (or both) to make up the difference. [4]

Instead of excess energy, we will use the parameter η to specify how far above threshold the measurements are made. η is defined as the largest possible pion momentum in the center of mass frame of reference, in units of the pion rest mass times c. (η is therefore dimensionless, and equal to zero at threshold.) For $pp \to pp\pi^\circ$, Ss is the only contributor up to about $\eta = 0.5$ (310 MeV). The energy dependence of the total cross section is adequately explained by the phase space and a final state interaction between the two protons, and goes roughly as η^2 [3]. Above $\eta = 0.6$ it is clear that higher partial waves (going as higher powers of η) become important. However, it is very difficult to separate the handful of possible contributors using the excitation function alone. This is the reason we set out to use spin observables in this energy range (up to about $\eta = 1$ or 400 MeV).

The PINTEX group (**P**olarized **IN**ternal **T**arget **EX**periments) and others have studied other pion production channels near threshold, in total cross section and a few single spin measurements [5]. The $pp \to pp\pi^\circ$ channel has the smallest cross section of all the single pion channels, in part because the delta resonance cannot contribute, but similar physics is at work in all cases. Successful models should be able to reproduce spin observables in all channels.

2. Apparatus and Techniques

The "Cooler" storage ring and synchrotron at the Indiana University Cyclotron Facility is particularly well-suited to studies of pion production near threshold. The required beam energies are well within its operating range, and the beam energy can be controlled quite precisely. Electron cooling produces a beam with very small emittance and narrow energy spread. Luminosities with a pure polarized hydrogen target are now sufficient for good statistical studies even for the relatively low cross section of $pp \to pp\pi^\circ$. The small beam emittance and the low room background allow measurements down to scattering angles less than 5°. Near threshold, the final state nucleons are restricted to a narrow forward cone, so that a resonably sized detector can cover almost all of the available phase space. Vertical beam polarization of about 70% is routinely available. With a little work, the direction of that beam polarization vector can be made almost completely longitudinal in the selected target region.

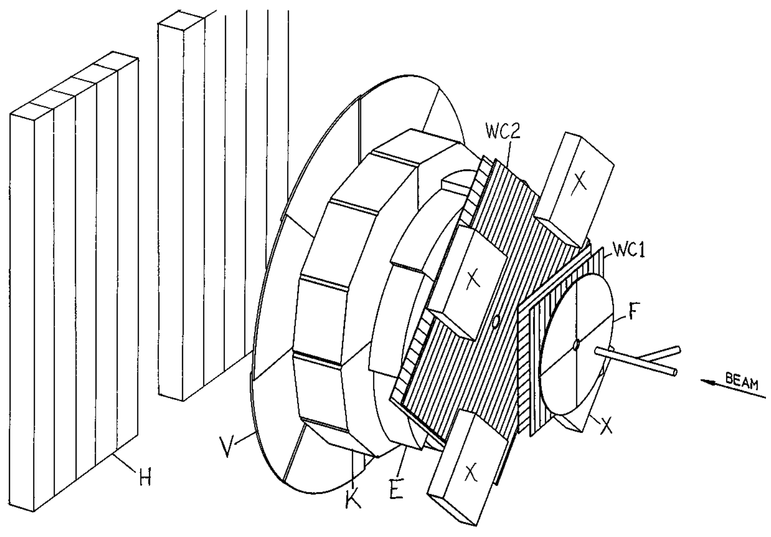

Fig. 1. Detector setup shown without vacuum chamber. The target cell is at right, fed from behind by an atomic beam source, also not shown. F is a thin starting scintillator. E and K combine to function as a stopping detector, with V as a veto detector. H is a hodoscope for detecting neutrons. WC1 and WC2 each have two perpendicular planes of MWPC wires for position measurements. The four blocks X can detect both elastically scattered protons pairwise.

The Cooler works efficiently only with internal targets. The polarized target used in this experiment consists of a high intensity atomic beam source with the appropriate RF transitions and state separators [6]. The effective thickness of the atomic beam as seen by the proton beam is increased roughly a hundredfold by directing it into an open ended tube (target cell) which is concentric to the proton beam. The tube is just large enough (11 mm diameter) that background scattering of beam halo particles is small. The target cell position can be monitored and adjusted online to minimize this background. Low-field Helmholtz coils are used to orient the target polarization in any desired direction. Their effect on the proton beam is small and compensated, and they also serve to cancel unwanted external fields.

The main detector stack (Fig. 1) consists of a thin starting scintillator, four planes of position-sensitive wire chambers, two thick plastic scintillator layers for stopping the reaction protons (or charged pions), and a veto detector to quickly reject elastic scattering events. All of these detectors completely surround the beam pipe, which passes through a small central hole in each. The size and position of these detectors is adequate for detecting both protons from $pp \to pp\pi^\circ$ for the full phase space up to 400 MeV, except for the small fraction of events where one proton goes through the central hole. A large hodoscope for detecting neutrons is located downstream of the main stack so that most of the $pp \to pn\pi^+$ phase space can also be measured by detecting the proton and neutron in coincidence. (Coincidences between a proton and a π^+ are also recorded to supplement this sample, although the detected fraction of the phase space is much smaller in this case.) Finally, four scintillator blocks are located at larger scattering angles to monitor pp elastic scattering events in coincidence, for calibration of the luminosity and beam and target polarizations. Most of the detector system is described in more detail elsewhere in the literature. [7]

With this detector, the four-momenta of two charged particles (or a proton and a neutron) can be determined with good resolution. Combining this with our knowledge of the beam energy allows the reaction kinematics to be completely determined. Good π° events, for instance, are identified by the "missing mass" calculation after identifying two final state protons. (See Fig. 2.) Background scattering from the walls of the target cell shows a consistent shape in the missing mass spectra. This same shape is produced by Monte Carlo simulations, and is also seen when the target cell is filled with nitrogen gas instead of hydrogen. The background shown in the figure is subtracted run-by-run before calculating any polarization observables.

Confidence in the operation of the detector with polarized beam and target was acquired in a series of high-precision measurements of spin correlation parameters in pp elastic scattering [7]. The analysis of these data provided ample opportunities to investigate various background sources and systematic errors, and to optimize cycle times and spin reversal patterns. The analyzing power and spin correlation parameters for elastic scattering are known very accurately, and the cross section is large enough, that a pre-

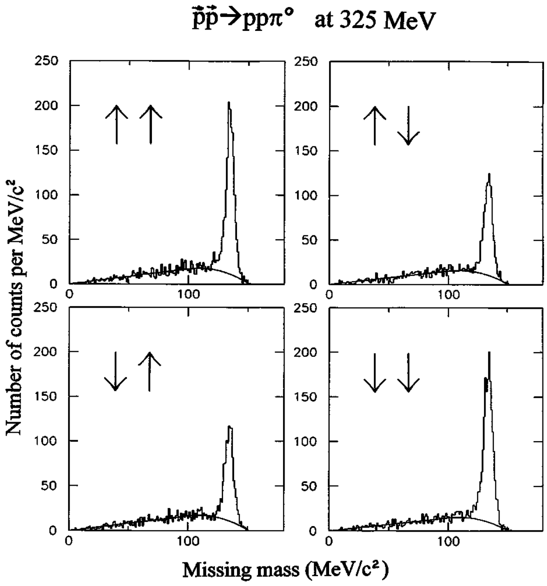

Fig. 2. Missing mass spectra for four different configurations of transverse beam and target spin (indicated by the arrows, respectively). Integrated luminosity is the same in all configurations, so the value of $\Delta\sigma_T$ (defined as anti-parallel minus parallel cross section) is obviously negative in this case. Smooth curve shows the normalized background function subtracted from each spectrum.

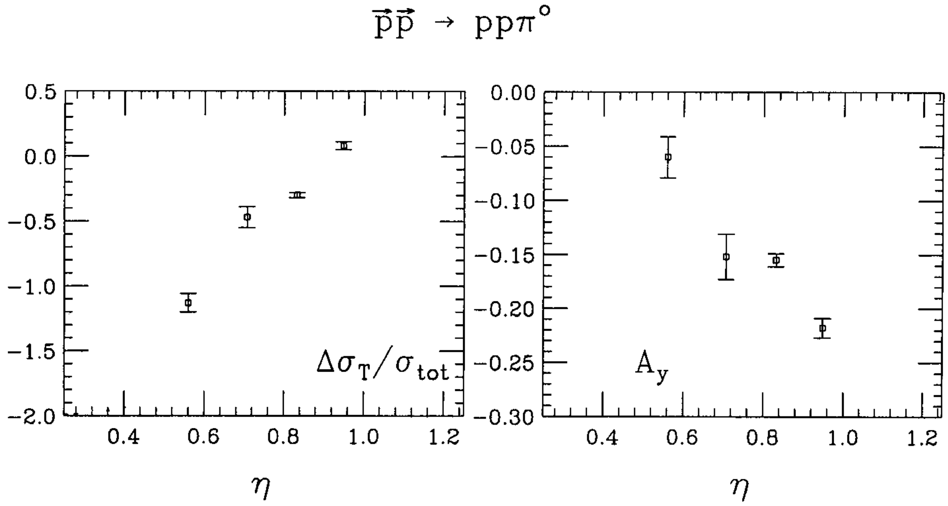

Fig. 3. Preliminary data for the transverse part of our measurement. $\Delta\sigma_T$ as a fraction of the total cross section, and the analyzing power as functions of η.

cise calibration of the product of beam and target polarizations is possible by monitoring only a small fraction of the elastic scattering events in our detector. These events are recorded simultaneously with the pion production events.

3. Preliminary results

Since the kinematics of each event are completely specified, spin dependent observables can be plotted as a function of any desired parameter. We have taken data for both the $pp\pi^\circ$ and $pn\pi^+$ final states at 325, 350, 375, and 400 MeV, in several combinations of beam and target polarization orientations. We have placed particular emphasis on measuring cross section differences between parallel and anti-parallel spins between beam and target protons, both transverse (vertical) to the beam momentum, and longitudinal. These combinations can be shown to distinguish among the possible partial waves in a model-independent way. Fig. 2 shows that $\Delta\sigma_T$, for example, is large and easy to measure at 325 MeV ($\eta = 0.55$).

Figure 3 shows some preliminary results for the ratio of $\Delta\sigma_T$ to the total cross section, and the analyzing power of the reaction as functions of η for most of our data. Preliminary calculations by Hanhart (based on [8]) show that these observables are indeed sensitive to the effects of heavy meson exchange, however, final calculations are still in progress. We would stress again that these are only two of many possible expressions of our experimental results. Various analyzing powers and spin correlation parameters may be defined and plotted against kinematic variables related to the pion, a final state nucleon, or any pair of particles that may be relevant. Data for the longitudinal spins is also in hand for the same ηs.

4. Future plans

From runs to date we already have lots of data for $pp \to pn\pi^+$ at the same energies and polarization combinations. The acceptance and efficiency of the neutron hodoscope makes the analysis a bit more complicated than for the $pp\pi^\circ$ reults shown here, and is currently underway. The transverse part of the $pp\pi^\circ$ data will be published soon, in the hope that this will spur the development of more detailed theoretical calculations.

Within the next month, we will take some more data at 375 MeV in all spin combinations. At this energy, the phase space cone of the final state nucleons fits comfortably within our detector acceptance, but occupies most of it, and the cross section is relatively large. Therefore, it is the best energy for getting enough statistics and resolution to measure good angular distributions, another handle on the partial wave decomposition.

In about a year, we plan to proceed with an approved experiment to measure $pp \to d\pi^+$ with beam and target polarized. Some modifications of the apparatus are required to detect the deuterons near threshold, at small angles. We also plan to develop polarized deuteron beam and target capabilities. A planned two-spin study of pd breakup should give some insight into the three-body nuclear force.

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