KINEMATICALLY COMPLETE MEASUREMENTS OF pp $\rightarrow$ pnπ^+ NEAR THRESHOLD

W.W. Daehnick, S.A. Dytman, W.K. Brooks, J.G. Hardie, and R.W. Flammang
University of Pittsburgh, Pittsburgh, Pennsylvania 15260

L.C. Bland, W.W. Jacobs, and T.C. Rinckel
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

P.V. Pancella
Western Michigan University, Kalamazoo, Michigan 49008

J.D. Brown and E. Jacobsen
Princeton University, Princeton, New Jersey 08544

The past year has seen completion of the production running for experiment CE03, the kinematically complete measurement of the pnπ^+ branch of pp pion production near threshold. After the 6° magnet was installed in the T-site of the Cooler in November 1990 and first tested with beam in December 1990, about four experimental test runs over six months were used to develop beam tunes and understand the apparatus. The final production run was accomplished in July 1991 during a ten-day period, using all unpolarized beam instead of some polarized beam running as initially proposed. This run successfully completed all of the planned data acquisition for the unpolarized beam experiment. Differential cross sections were measured at 294, 300, 307, 314, and 320 MeV to determine the energy dependence of the cross section near threshold (292.3 MeV). Good statistics were obtained at 294, 300, and 320 MeV in order to better determine pion angular distributions, an important objective of this experiment. All data included six kinematic variables, thereby overdetermining the measurement (five variables are sufficient). A description of the experimental apparatus has been given in previous reports.[1] Data with good statistics, resolution and background suppression were obtained at all energies, as illustrated by the 294 MeV missing mass spectrum (see Fig. 1).

The purpose of this experiment is to examine amplitudes which are of fundamental importance in the NN interaction and which may relate to nucleon substructure. The nature of the pion-nucleon vertex has been studied extensively through many reaction channels, typically using two-body reactions such as Nπ $\rightarrow$ Nπ or NN $\rightarrow$ πD. The three-body final state, although experimentally more challenging, yields a wider range of kinematic conditions and isospin states. A major interest is in the properties of the non-resonant s-wave NNπ interaction. This portion of the reaction is masked in higher energy NN pion production by production through the delta (a p-wave mechanism) and consequently has never been measured in a sensitive way. The p-wave contribution near threshold (of either resonant or non-resonant origin) is expected to cause an anisotropy in the pion angular distribution, an effect which grows with increasing bombarding energy and should be seen in CE-03 data.

The large negative Q-values for pion creation provide high momentum transfer, which means that the reaction samples the NN wave function at short distances in a process

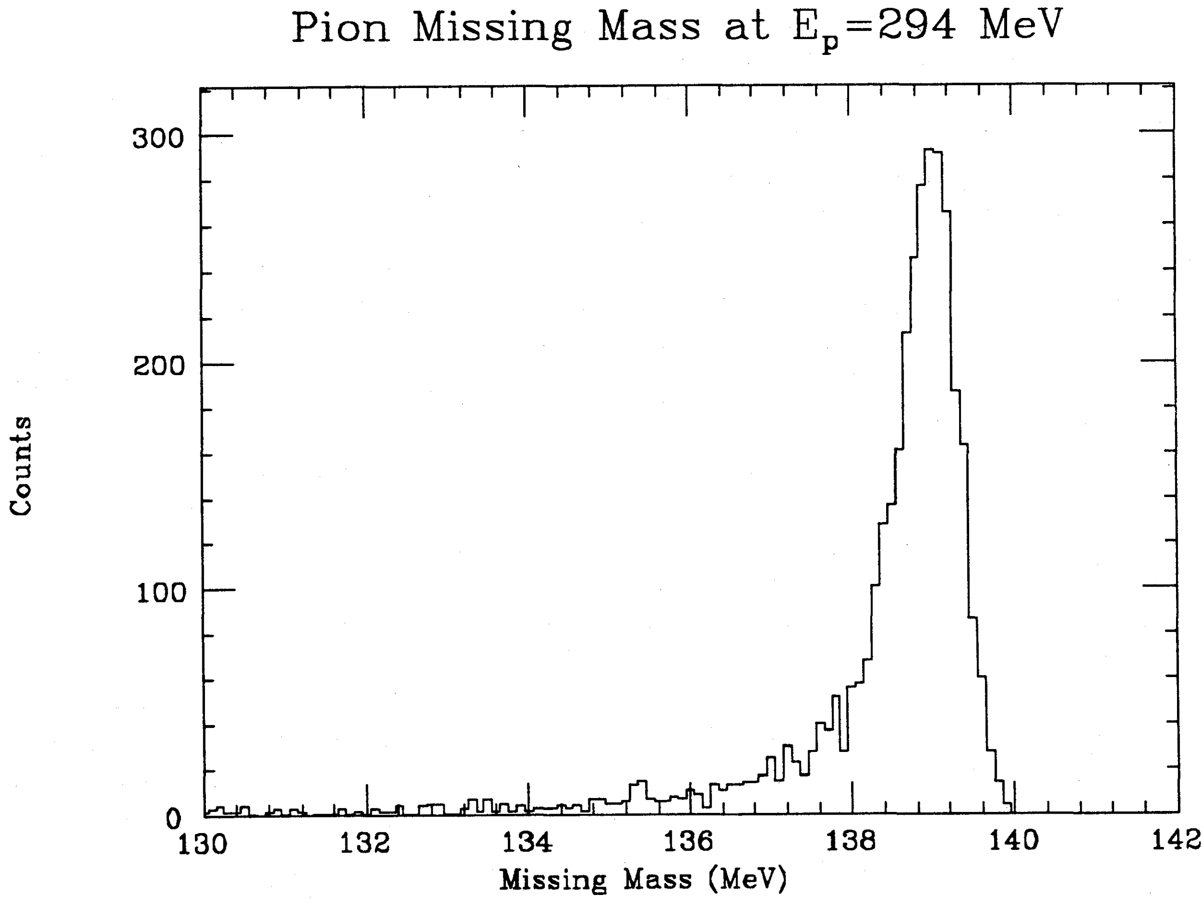

Figure 1. Pion missing mass in the reaction pp $\rightarrow$ pnπ^+ at 294 MeV bombarding energy.

involving a relatively small number of degrees of freedom. A sensitivity to off-shell characteristics of the NNπ vertex will provide a critical and hitherto unavailable constraint on theoretical models which are used to describe these reactions. The anticipated uncertainties in the experimental data will be more than adequate to better constrain these properties within the context of unitary NNπ models, for example. At this time, the only published near-threshold calculations[2] for pp $\rightarrow$ pnπ^+ are over 20 years old although more recently, Lee and Matsuyama[3] have used a coupled channel approach to calculate total cross sections for pp $\rightarrow$ ppπ^0 and pp $\rightarrow$ pnπ^+ for energies down to threshold. In a 1969 paper by Schillaci *et al.*,[2] predictions are made for the total cross section of various NN inelastic channels using two of the possible treatments of the off-shell dynamics. This calculation is accomplished by applying current algebra to the process $\gamma + 2\text{N} \rightarrow 2\text{N} + \pi$, invoking PCAC, and taking the soft pion/soft photon limit; this directly relates pion production to off-shell nucleon-nucleon scattering, and as such automatically makes s-wave pion production near threshold dependent on which off-shell treatment is used. One treatment agrees fairly well with the pp $\rightarrow$ ppπ^0 data[4] of Meyer *et al.* close to threshold, then diverges at higher energy where the approximations appropriate to threshold break down. For the pp $\rightarrow$ ppπ^+ calculation the two different off-shell treatments give a difference of a factor of three in the cross section in the energy region of the CE-03 data. The two predictions are both smaller than any of our preliminary near-threshold total cross sections. However, the model calculation that gave agreement with the Meyer *et al.* π^0 data is a factor of about three less than our measured π^+ cross sections. (As of this time, these cross sections are not well understood theoretically and it is unlikely that fundamental physics quantities are being elucidated.)

Currently the CE-03 data analysis is at an advanced stage. Principal issues in the analysis have been: efficiency of background rejection, measurement of luminosity, calculation of detector acceptance, calculation of the neutron detection efficiency, and consistency checks. Preliminary total cross sections are available now.

The efficiency of the background rejection at all energies including 294 MeV is good. In Fig. 1 the pion missing mass is plotted for 294 MeV after cuts on the reconstructed event vertex and a particle identification (E-ΔE) cut. In a run at 290 MeV (below production threshold) with 10% of the integrated luminosity of the data in the figure, after the same cuts only 5 counts were observed in the range plotted, all under the tail of the distribution. Figure 2 shows a plot of the reconstructed interaction vertex in the two coordinates perpendicular to the beam. It can be seen that there is a clean separation between the lower energy particles coming from the target and the (typically) higher energy particles from the background pn coincidences. While it was observed that the missing mass width became larger at higher energies (consistent with a Monte Carlo simulation using realistic detector resolutions), the cleanliness of the vertex separation was fairly consistent at all beam energies.

The luminosity monitor consisted of pp elastically scattered particles detected in coincidence in the forward charged particle arm and in a position sensitive detector located 12 cm from the target nearly perpendicular to the incident beam. Background in the luminosity monitor event was limited to accidental coincidences. Singles rates in the position sensitive detector were quite low and consistent from one run to the next, so that the accidentals rate was typically two orders of magnitude lower than the rate of elastically scattered particles, and a correction was easily made. As a cross-check on the accuracy of the luminosity calculation it is possible to calculate the angular distribution of elastically scattered particles up to an uncertain scale factor. Figure 3 shows the results of such a calculation, demonstrating the geometric cutoffs at either end of the detector acceptance and a well-understood region between 75° and 80° for the recoil particle.

Two Monte Carlo acceptance programs have been written for the cross section measurement; one for the monitor events and the other for the pion events. The monitor event stream is relatively straightforward, being a two-body elastic scattering into a simple rectangular geometry. The acceptance calculation for the pion events is somewhat more involved. This calculation includes the two-arm geometry and geometric cutoffs by the magnet pole faces; multiple scattering through pumping foils, the vacuum foil, air, and wire chamber materials; realistic detector resolutions as measured for each of the scintillators and wire chambers; and ray tracing through the mapped magnetic field and its out-of-plane extrapolation. The three-body Monte Carlo event is generated via the CERN program GENBOD with a modification to include pn final state interactions.

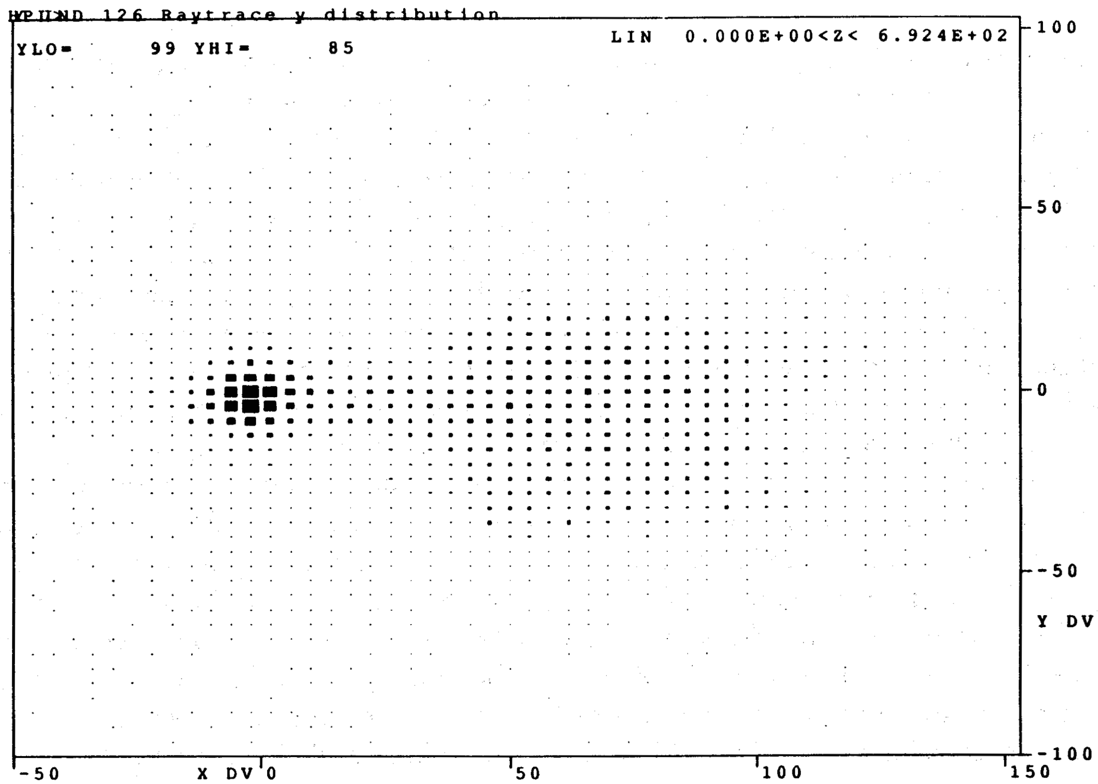

Figure 2. Reconstructed event vertex at the target location. Axes represent coordinates perpendicular to the beam. The reconstructed target "spot" as deduced from ray-tracing is approximately 1 cm in diameter.

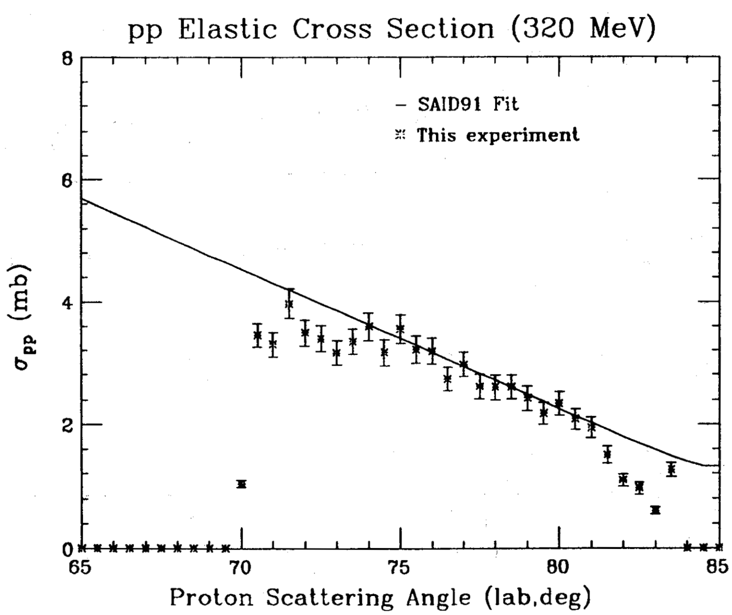

Figure 3. Elastic pp scattering cross section as measured in the luminosity event stream.

The neutron efficiency was calculated via a Monte Carlo code developed by Cecil *et al.*[5] The code uses measured neutron-induced cross sections and an input detector geometry to generate a light output profile for an incident neutron of a given energy. The efficiency is therefore determined by the effective detector threshold. One other input to the code is the light response of the particular scintillator to protons and alpha particles. This was most recently measured for an equivalent scintillator by Madey *et al.*[6] The accuracy of the efficiency predicted by this code therefore depends on the accuracy of the measured cross sections, the accuracy of the light response parameterization, and of the amplitude calibration of the scintillator. Previous comparisons of the predictions of this code with measurements have produced very good results for neutron energies in the range of interest in this experiment.[7] A plot of efficiency vs. neutron energy for the CE-03 detector's geometry is given in Fig. 4. The amplitude calibrations were performed using a pulsed ultraviolet laser and calibrated attenuators to determine the light response of each scintillator in the neutron hodoscope, then converting that light response into energy units using cosmic ray data measured at the time of the production run. This procedure results in a calibration in terms of "electron equivalent energy" which may be directly compared with the prediction of the neutron efficiency code without a need to convert from proton light units. A severe test of the success of the overall procedure is shown in Fig. 5. This is a comparison of the data at 294 MeV and the prediction of the neutron efficiency code.

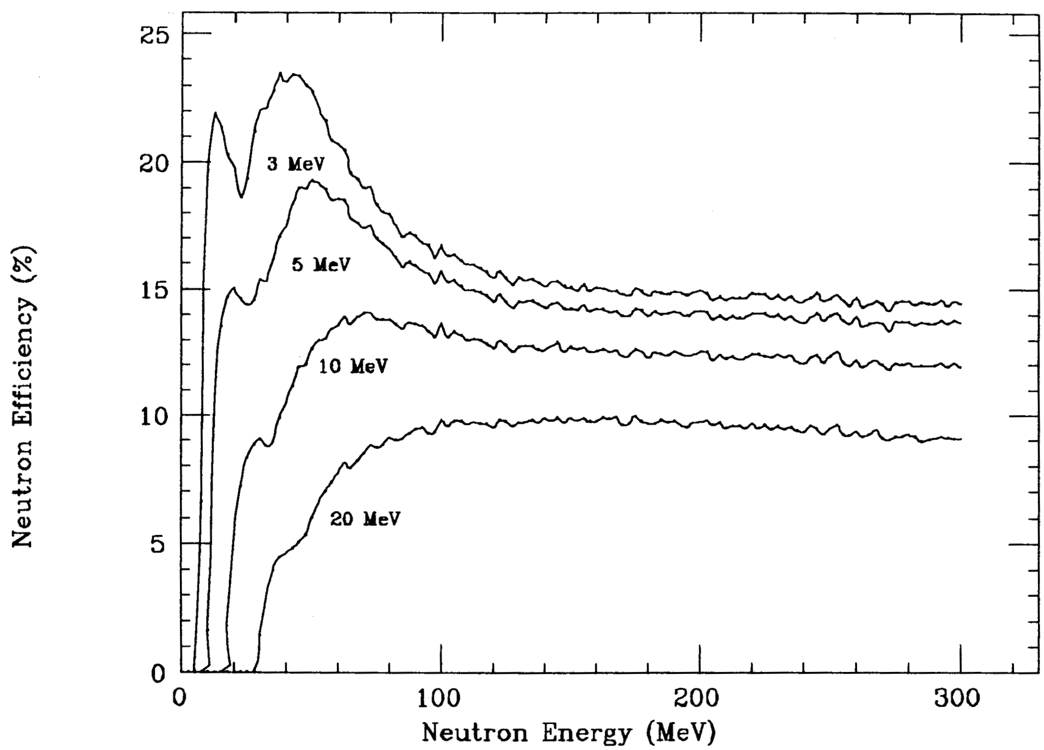

Figure 4. Neutron detection efficiency as a function of neutron energy, for four threshold values, calculated for the CE-03 detector geometry using a Monte Carlo code.

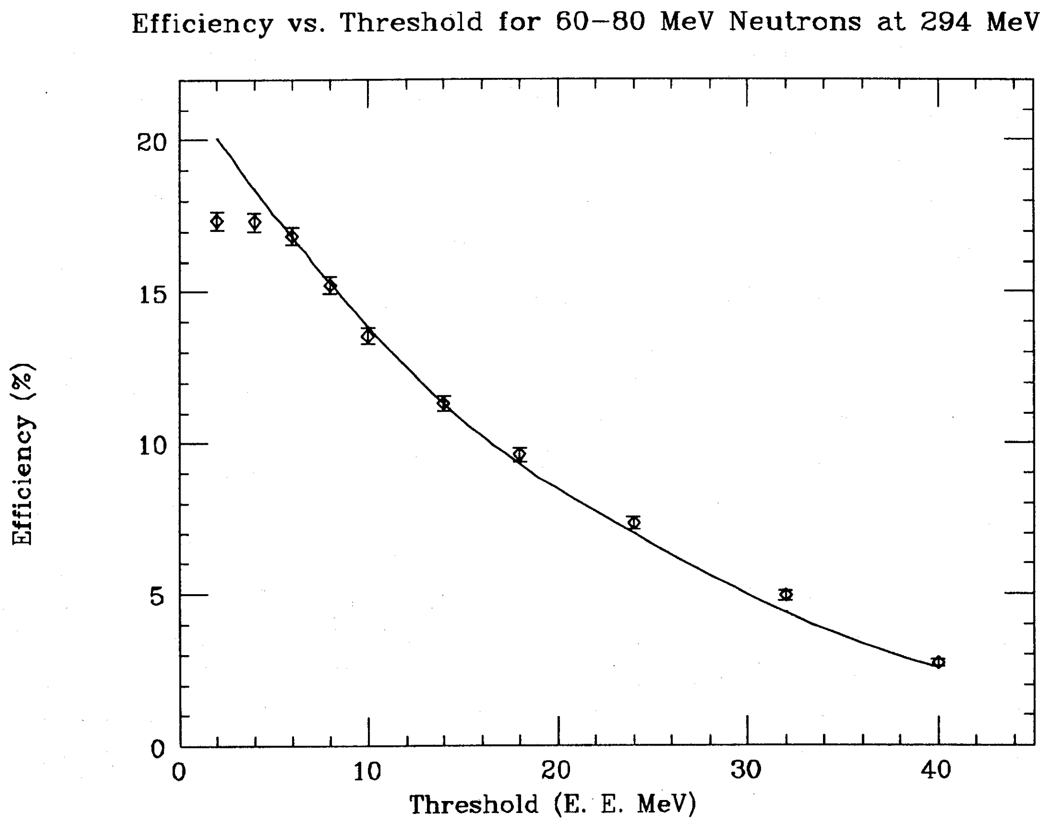

Figure 5. Efficiency as a function of threshold averaged over neutrons of 60 to 80 MeV at 294 MeV bombardment energy. The line is a Monte Carlo calculation and the points are data from the CE-03 experiment using the measured amplitude calibration.

The data are summed over the range 60-80 MeV for a range of software thresholds; the average hardware threshold is seen to be approximately 5 MeV.

A number of cross checks have been performed in the data analysis. An accurate knowledge of the wire chamber geometry is critical in this experiment, since the reaction particles are confined to a small outgoing kinematic cone. Since the target location is known very well, using raytracing to track particles back to the target location provided a sensitive test for the relative wire chamber position. The angle and energy dependence of the outgoing kinematic cone provided a good check on beam energy and position. Such tests determined the initial beam angle of incidence of a few tenths of a degree, a value which was expected due to the large fringe field of the 6° magnet.

During the production run the use of a programmable Memory Lookup Unit provided the facility to change triggers via software, so a number of quick diagnostic runs were made such as triggering on expected background events. These data have been analyzed to determine the efficiency of standard cuts on known background events, and the efficiency of charged particle vetoes for the neutron hodoscope.

1. W.W. Daehnick, S.A. Dytman, W.K. Brooks, J.G. Hardie, R.W. Flammang, L. Bland, W.W. Jacobs, T. Rinckel, P. Pancella, J.D. Brown, and E. Jacobsen, IUCF Sci. and Tech. Rep., May 1990 - April 1991, p. 52; and W.W. Daehnick, *Proc. Int. Workshop on Meson Production, Interaction and Decay* (Cracow, 1991), eds. A. Magiera, W. Oelert, E. Grosse, (World Scientific, 1991), p. 279.
2. M.E. Schillaci, R.R. Silbar, and J.E. Yound, Phys. Rev. **179**, 1539 (1969).
3. T.S.H. Lee and A. Matsuyama, Phys. Rev. C **36**, 1459 (1987) and private communication.
4. H.O. Meyer, *et al.*, Phys. Rev. Lett. **65**, 2846 (1990). H.O. Meyer, *et al.*, Nucl. Phys. A, (1992) to be published.
5. R. Cecil, B. Anderson, R. Madey, Nucl. Instr. and Meth. **161**, 439 (1979).
6. R. Madey, F. Walterman, A. Baldwin, J. Knudson, J. Carlson, J. Rapaport, Nucl. Inst. and Meth. **151**, 445 (1978).
7. J. Watson, B. Anderson, A. Baldwin, C. Lebo, B. Flanders, W. Pairsuwan, R. Madey, C. Foster, Nucl. Instr. and Meth. **215**, 413 (1983); B. Anderson, J. Knudson, R. Madey, C. Foster, Nucl. Instr. and Meth. **169**, 153 (1980); R. Cecil, B. Anderson, R. Madey, Nucl. Instr. and Meth. **161**, 439 (1979); M. McNaughton, N. King, F. Brady, J. Ullmann, Nucl. Instr. and Meth. **129**, 241 (1975); M. McNaughton, F. Brady, W. Broste, A. Sagle, S. Johnsen, Nucl. Instr. and Meth. **116**, 25 (1974).