PION PRODUCTION

TOTAL CROSS SECTION FOR p+p → p+p+π° CLOSE TO THRESHOLD

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During the year covered by this report, the first nuclear physics experiment with the Indiana Cooler (CE01) has been brought to a conclusion and an account of it has been published.[1] The measurement has resulted in pp→ppπ° total cross section data of unprecedented precision at energies much closer to threshold than those covered by previous experiments.[2,3] Its results are shown in Fig. 1.

Pion production in the NN system is of fundamental importance. The threshold region is particularly interesting, since at sufficiently low energy the cross section is dominated by the single partial wave $^3P_0 \to (^1S_0 s)_0$. In addition, theoretical arguments limit the possible mechanisms for pion production. Thus, near-threshold production provides a crucial testing ground for models of non-resonant pion production.

The energy dependence of the total NN→NNπ cross section, close to threshold, is expected to be determined by the density of final states. In addition, if the outgoing nucleons are in a $^3S_1$ (T=0) or a $^1S_0$ (T=1) state, the NN final-state interaction is important. The CE01 data[1] are consistent with an energy dependence predicted from the phase-space factor and a final-state interaction expressed in terms of an effective range expansion which includes the Coulomb interaction, as shown by the curve in Fig. 1. This calculation has been normalized to fit the data.
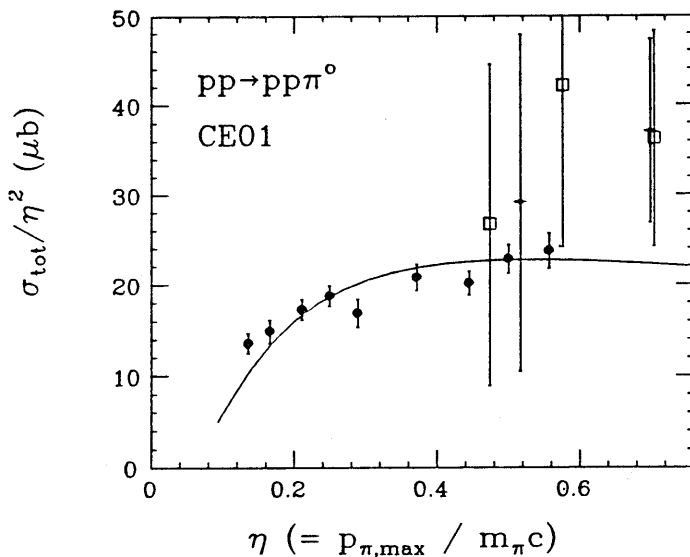

Figure 1. Total cross section for pp→ppπ° divided by η^2 as a function of η (η is the dimensionless maximum pion momentum; it is simply related to the bombarding energy). Data from two previous experiments[2,3] are indicated by squares and horizontal bars. The solid dots are the results[1] of the first Cooler experiment (CE01). The curve is described in the text.

The energy region covered in CE01 (282.5 MeV − 325.0 MeV) contains the thresholds for the channels pp→dπ^+ (T_p=287.5 MeV) and pp→pnπ^+ (T_p=292.3 MeV). The fact that the cross section measured by CE01 at η=0.289 (T_p=292.4 MeV) is somewhat low, raised the suspicion that this could be caused by the coupling between channels. It was thus decided to follow up on CE01 and to repeat the pp→pp$\pi°$ experiment in smaller energy steps and with improved statistics. The new experiment (labelled CE23) was carried out during 6 days in December 1990.

The target consisted of a gas jet of $5{\cdot}10^{19}$ hydrogen molecules/second, emerging from a 0.11 mm diameter nozzle, cooled to 40 °K. It was the same as for CE01, except for larger openings in the differential pumping apertures, needed to accommodate the increased beta functions β_x=1.84 m, β_y=2.04 m (CE01: β_x=0.51 m, β_y=1.03 m) at the G section waist. The change in beta functions was caused by the use of a new tune designed to yield a larger machine acceptance. The target thickness was about $7{\cdot}10^{15}$ atoms/cm^2. About 40% of the total target thickness was uniformly distributed along ±8.2 cm of the beam path on either side of the jet. The target was mounted in the downstream position of the CE01 target box.

Except for some minor improvements, the detector system was the same as for CE01. The detector positions are variable relative to the target. Three settings with angular acceptances of 11.6°, 15.6° and 20.4°, respectively, were used, corresponding to three ranges of bombarding energies. As explained elsewhere,[1] the detector setup was capable of measuring the direction and the energy of outgoing charged particles falling within its acceptance. In addition, recoil protons from pp scattering were detected by position-sensitive silicon detectors mounted in the midplane on either side of the target. The concurrent observation of pp scattering provided the normalization needed to determine an absolute pp→pp$\pi°$ cross section (see below).

The trigger for a pp$\pi°$ event was based on the observed scintillator pattern. This was also true for pp scattering events for which, in addition, a coincidence with one of the position-sensitive detectors was required.

Data were acquired in so-called cycles. Each cycle lasted about 30 s and consisted of injection of 45 MeV protons from dissociating a 90 MeV H$_2^+$ beam on a thin carbon stripper foil, acceleration to the final energy, data acquisition while cooling (8-17 s), and restoration of initial conditions. The high voltage to the wire chambers and the flow of gas through the target nozzle were turned on only during the data acquisition phase. During data taking, the RF cavity was run at a constant frequency, whose value, together with the known ring circumference, determined the beam energy.

During the course of the CE23 experiment, about 100 individual runs at 31 different bombarding energies between 278 and 325 MeV were carried out. Stored beam currents ranged from 50 to 250 μA, resulting in luminosities, averaged over the whole duration of a run, between $5 \cdot 10^{29}$ and $3 \cdot 10^{30}$ cm^{-2}s^{-1}. During a total time of 52 h (CE01: 110 h) for production runs, a total integrated luminosity of about 170 nb^{-1} (CE01: 16 nb^{-1}) was achieved. This represents about a factor of 20 improvement over the CE01 performance.

Some of the machine parameters are not yet sufficiently well controlled to guarantee consistent optimum performance. This explains the large difference between the smallest

and largest luminosity seen. In Fig. 2 some relevant parameters are shown as a function of the run number, i.e., the time through the experiment. They include the luminosity (from the pp coincidence rate), the beam current (measured with a beam position monitor), the beam energy spread (obtained from the time between the RF and the arrival scattered protons in the first scintillator element of the detector stack), and the beam lifetime (from the time dependence of the event rate).

Considerable effort went into the offline analysis of the data. The main improvements included refined matching criteria of the reconstructed track with the firing scintillator elements, recovery of abnormal firing patterns of the wire chambers, and a tracking algorithm that enhanced the angular resolution of the detector system and improved the missing-mass resolution by about a factor of two.

For an internal target in a stored beam it is difficult to measure the beam current and the target thickness with sufficient accuracy to derive a luminosity. Instead, the integrated luminosity was obtained from the number of pp scattering events, observed concurrently
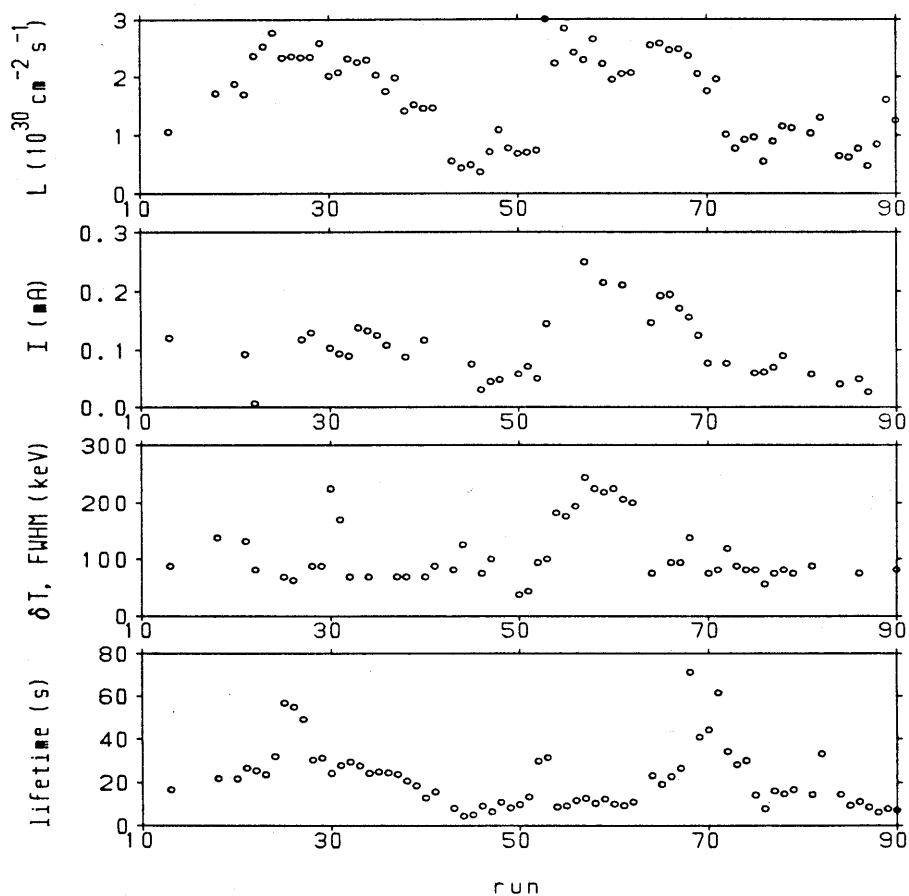

Figure 2. The luminosity, the stored beam current, the beam energy spread, and the beam lifetime recorded during the duration of the CE23 experiment.

with pion production, using pp scattering cross sections reported in the literature. For this purpose, the luminosity was derived from the factor needed to scale a model calculation of the distribution of scattering centers along the beam axis to the corresponding measured distribution. As a check, a second method was devised to derive the luminosity. It made use of a run with a diffuse target (gas flowing into the target chamber, no jet) to assess the contribution from the target gas outside the jet. Comparison of the two methods led to the discovery of an error in the analysis of the CE01 data. The published data[1] must be corrected downwards by about a standard deviation. This correction has been applied to the CE01 data shown in Fig. 1. With this error eliminated, the two methods to determine the luminosity agreed within a few percent.

The detectors must accommodate the beam pipe, resulting in a dead region around the beam axis. A Monte-Carlo simulation of the detector was used to calculate the fraction $pp\pi^\circ$ events that were not seen because of this. For the lowest energy with a given detector setting the required correction could be as much as a factor of two, but it was known to within a few percent. Other adjustments due to systematic effects are small (less than 10% total). Measurements at the same energy and with the same detector geometry were found to be internally consistent and were thus combined.

The resulting total cross sections are shown in Fig. 3. Different symbols (crosses, circles, and diamonds) are used to identify the three different geometries. The errors
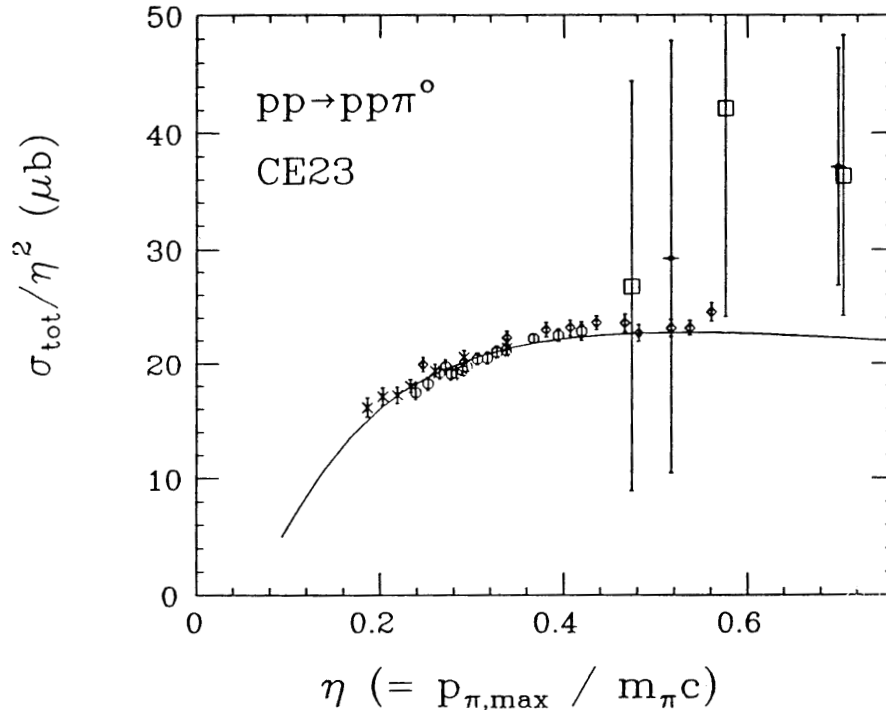

Figure 3. Total cross section for $pp \rightarrow pp\pi^\circ$ divided by η^2 as a function of η (same as Fig. 1). Instead of the CE01 data, the results from the follow-up experiment CE23 are shown (crosses, circles, and diamonds). The curves in Figs. 1 and 3 are identical.

shown include counting statistics, the uncertainty of the luminosity, and errors associated with the adjustments mentioned above. An overall normalization error of about 5% due to the uncertainty of the pp scattering cross section is not included. The data with large errors (squares and horizontal bars) are from two previous experiments.[2,3] The curve shown represents the energy dependence of the total cross section deduced from the phase space factor and the final-state interaction between the outgoing protons. In this calculation, the matrix element is assumed to be energy-independent and its magnitude is adjusted to fit the data. The curves in Figs. 1 and 3 are identical.

The stated goal of this experiment was to investigate the possibility of coupling between pion production channels in the NN system. On the level of about 5% <u>no</u> deviation from a smooth energy dependence (or 'cusp') of the pp→ppπ° total cross section was observed. A full report of this experiment for publication is currently in preparation.

1. H.O. Meyer, M.A. Ross, R.E. Pollock, A. Berdoz, F. Dohrmann, J.E. Goodwin, M.G. Minty, H. Nann, P.V. Pancella, S.F. Pate, B. v. Przewoski, T. Rinckel, and F. Sperisen, Phys. Rev. Lett. **65**, 2846 (1990).
2. A.F. Dunaitsev and Yu.D. Prokoshkin, Zh. Eksp. Teor. Fiz. **36**, 1656 (1959) [Sov. Phys. JETP 9, 1179 (1959)].
3. S. Stanislaus, D. Horvath, D.F. Measday, and A.J. Noble, Phys. Rev. **C41**, R1913 (1990).