

Figure 3. Raw data for elastic scattering of $^{208}\text{Pb}(p,p)^{208}\text{Pb}$ with the proton arm. The measurement was performed at the injection energy of 200 MeV to provide independent angular calibration for the forward detectors.

MEASUREMENT OF HIGH MOMENTUM TRANSFER REACTIONS ON THE INDIANA COOLER BY RECOIL DETECTION

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The system shown in Fig. 1, which has been described previously,^{1,2} has been used to measure differential cross sections for the reaction $^{12}\text{C}(p,\pi^+)^{13}\text{C}$ by detection of the ^{13}C recoil ions. Measurements were made at extreme forward and backward angles at bombarding energies of 166, 294, and 330 MeV. The system consists of a parallel grid

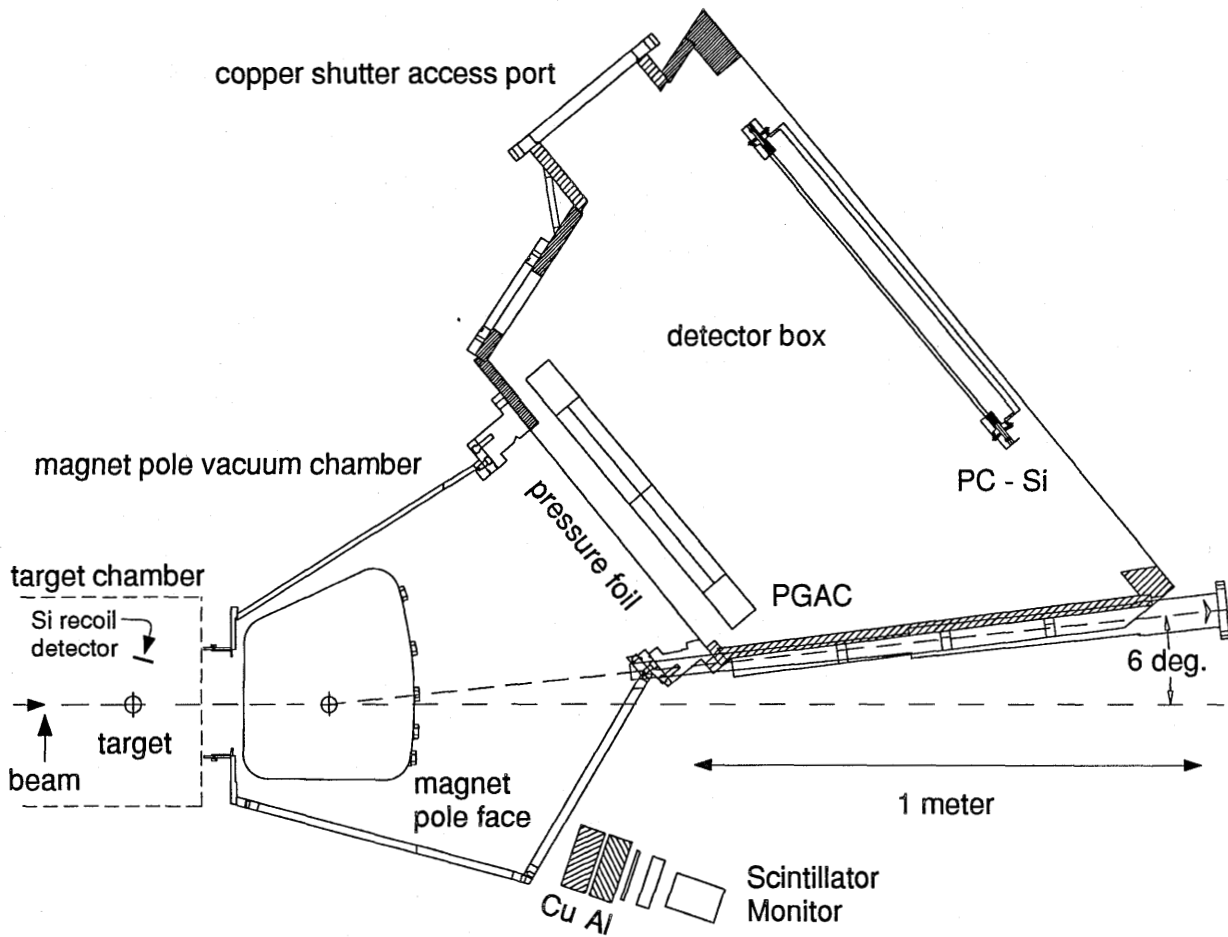


Figure 1. Schematic of the target and dipole magnet vacuum chambers in the Cooler ring and the recoil-ion detector box showing the locations of the PGAC and PC-Si detectors.

avalanche counter (PGAC), proportional counter (PC), and large-area, microstrip silicon detector array, all attached to a large-gap, dipole magnet on the Cooler ring that bends the primary beam through 6° and sweeps the recoil ions into the detection system. The detector stack measures the energy, time-of-flight, nuclear charge, mass, and angle of recoil-ion emission products. Backward ray tracing gives the emission angle of the recoil-ions at the target. The experiments were carried out in December 1992 and February 1993 using carbon fiber and foil skimmer targets. Luminosities from 5×10^{28} to a few $\times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ were achieved.

Figures 2 and 3 show the angle-rigidity correlations for ^{13}C ions produced by the reaction $^{12}\text{C}(p, \pi^+)^{13}\text{C}$ at $T_p = 166$ and 294 MeV, respectively. At 166 MeV, the recoils are sufficiently confined in angle that the acceptance for $^{13}\text{C}^{6+}$ ions is 4π steradians. In general, the projected kinematic ellipses may overlap for different charge states; however, these are separable since the atomic charge is measured. The kinematic recoil loci for the $^{12}\text{C}(p, \pi^+)^{13}\text{C}_{\text{g.s.}}$ reaction and the detector acceptance are shown by the dashed and solid lines, respectively. Many of the events occur on the inside edge of the calculated ground

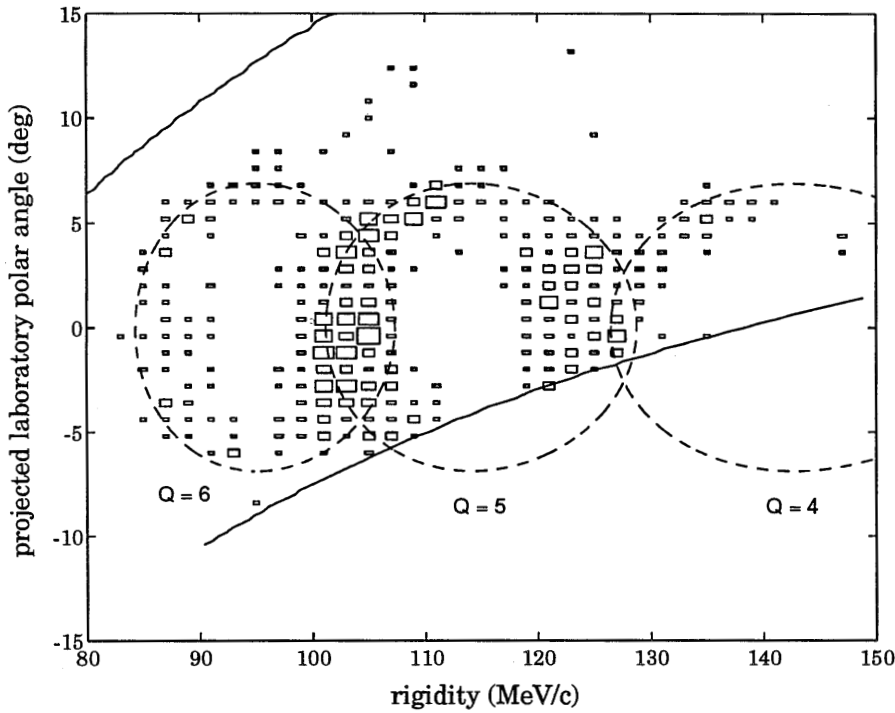


Figure 2. Angle vs. rigidity of ^{13}C recoils from $p + ^{12}\text{C}$ at $T_p = 166$ MeV. Also shown are the kinematics for the reaction $^{12}\text{C}(p, \pi^+)^{13}\text{C}_{g.s.}$ (dashed lines) and the calculated detector acceptance (solid lines), both for $\phi_p = 0^\circ$. The charge state of the recoil ion is given by Q .

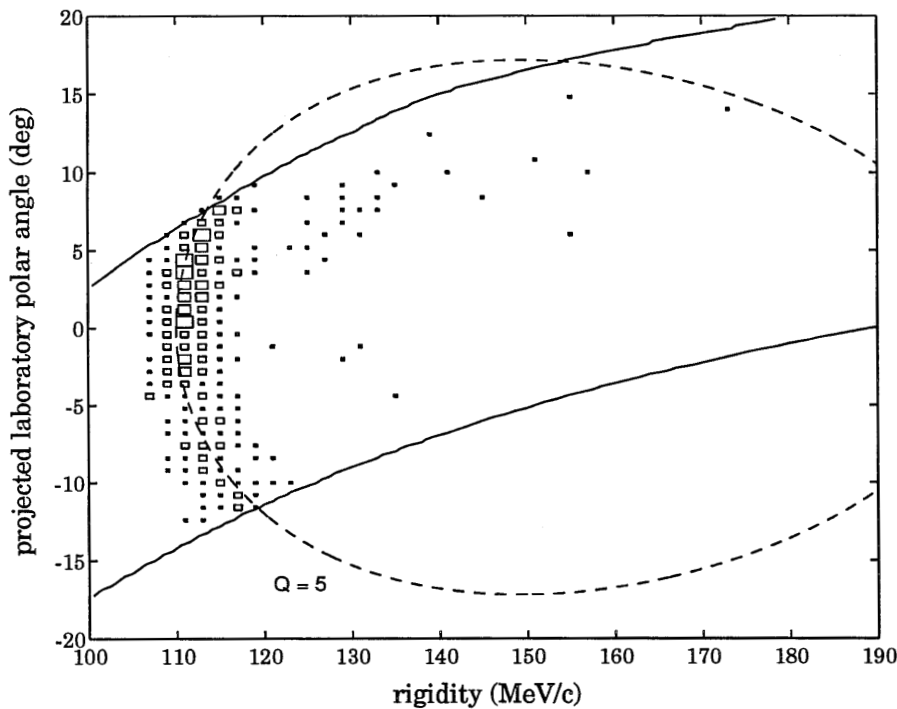


Figure 3. Angle vs. rigidity of $^{13}\text{C}^{5+}$ recoils from $p + ^{12}\text{C}$ at $T_p = 294$ MeV, with kinematics and acceptances shown for $\phi_p = 0^\circ$, as in Fig. 2.

state ellipse, suggesting that there is a strong population of the bound ^{13}C excited states at 3.09, 3.68, and 3.85 MeV.

In Fig. 2, the distribution of events on the ellipse for a given charge state corresponds to the pion angular distribution, with the highest rigidity events corresponding to 180°

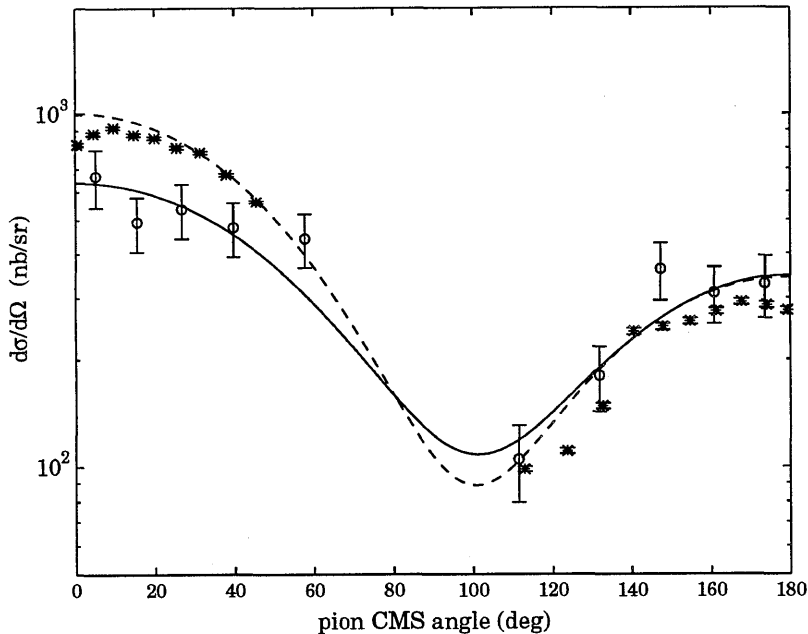


Figure 4. Center-of-mass differential cross sections vs. angle for the reaction $^{12}\text{C}(p, \pi^+)^{13}\text{C}$ at $T_p = 166$ MeV. Data from the present work are shown by the open circles; stars refer to previous recoil data.³ The dashed line is a sum of (p, π^+) spectrograph data⁴ to separate states in ^{13}C . The solid line is a Legendre polynomial fit to the open circles.

pion emission and the lowest rigidity events to 0° pion emission. Differential cross sections for the $^{12}\text{C}(p, \pi^+)^{13}\text{C}$ reaction at $T_p = 166$ MeV extracted from these data are shown in Fig. 4 by the open circles. The finite width of the low- and high-momentum branches of the recoil locus precluded calculation of the cross section for $60^\circ \leq \theta_\pi \leq 110^\circ$ (cms).

Differential cross sections for the $^{12}\text{C}(p, \pi^+)^{13}\text{C}$ reaction at $T_p = 294$ MeV and 330 MeV are shown in Fig. 5. At these energies, only recoils corresponding to forward and backward pion emission are accepted by the detector stack. No recoils corresponding to backward pion emission were observed above background at either energy. In contrast to the $T_p = 166$ MeV data, at these higher bombarding energies the pion angular distribution is strongly forward peaked.

Some improvements in experimental technique are suggested by the present work. These include better energy resolution in the PC detector and better timing resolution between the PGAC and silicon detectors, both of which are necessary to achieve cleaner mass separation. Greater beam luminosity ($\sim 10^{31} \text{ cm}^{-2}\text{s}^{-1}$) is needed for systematic studies of the very low yield $(p, 2\pi)$ and (p, γ) reactions. The method may have useful applications to studies of pion production in heavy ion reactions.

A limitation of the recoil method is that, so far, carbon is the only solid target that has been made thin enough for use as an internal target in the Indiana Cooler. Gas targets would be less suitable for the recoil experiments because the ray tracing and luminosity monitoring would be more difficult with an extended target.

1. P. Heimberg, *et al.*, IUCF Sci. and Tech. Rep. May 1991 - April 1992, p. 149; R.E. Segel, *et al.*, IUCF Sci. and Tech. Rep. May 1992 - April 1993, p. 64.
2. Erik Jacobsen, Ph.D. Thesis, Princeton University, June 1994.
3. J. Homolka, W. Schott, W. Wagner, W. Wilhelm, M. Saber, R.E. Segel, R.D. Bent, M. Fatyga, R.E. Pollock, P. Kienle, and K.E. Rehm, Phys. Rev. C **45**, 1276 (1992).

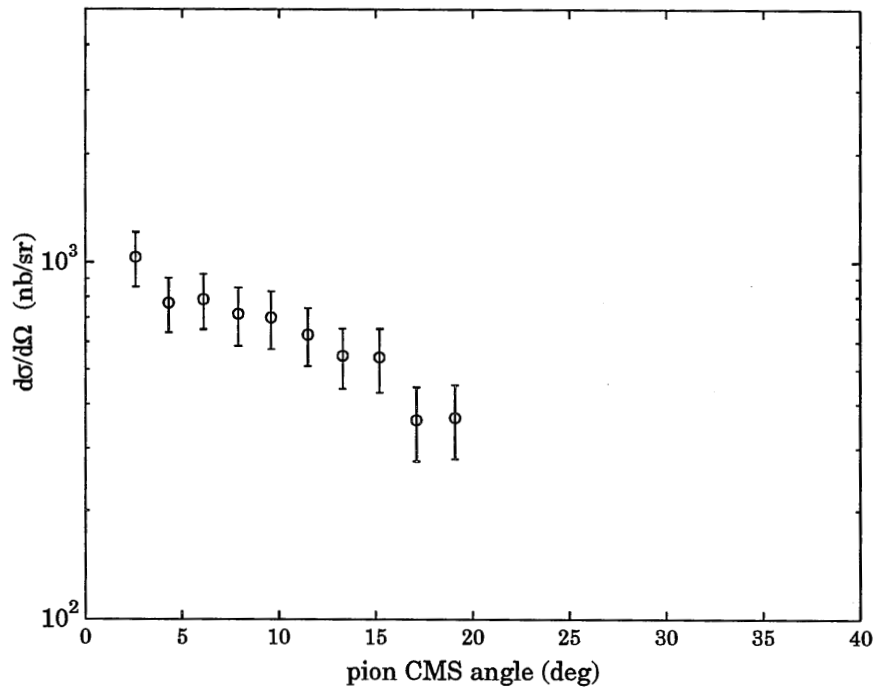
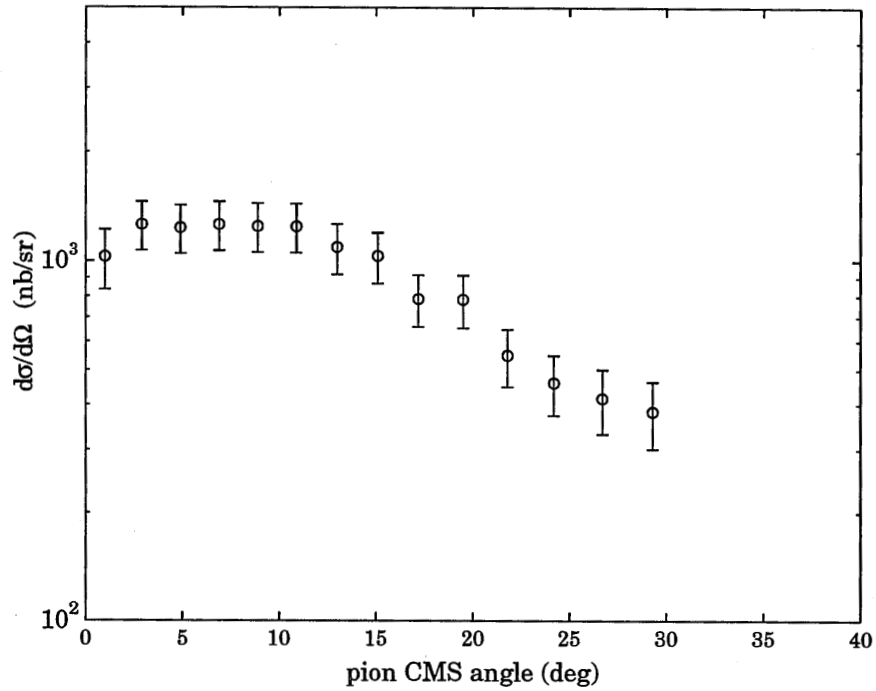


Figure 5. Center-of-mass differential cross sections vs. angle for the reaction $^{12}\text{C}(p, \pi^+)^{13}\text{C}^*$ at $T_p = 293.7$ MeV (top) and 328.5 MeV (bottom).

4. F. Soga, P.H. Pile, R.D. Bent, M.C. Green, W.W. Jacobs, T.P. Sjoreen, T.E. Ward, and A.G. Drentje, Phys. Rev. C **24**, 570 (1981).