STUDIES OF HIGH MOMENTUM TRANSFER REACTIONS
BY RECOIL DETECTION: \((p,\pi), (p,2\pi), \text{AND} (p,\gamma)\)

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A technique for studying high-momentum transfer nuclear reactions on the Cooler
using recoil-ion detection has been developed at IUCF. This program is a continuation
of pion production\(^1,2\) and high-momentum transfer \((p,N)\) reaction\(^3\) studies made at the
cyclotron. The magnet in the Cooler ring that bends the primary beam 6° sweeps the
recoils into a detection system, where they first pass through a parallel grid avalanche
counter (PGAC) that measures the time and position of the particles emerging from the
magnet. The PGAC has 0.9-micron thick entrance and exit foils and a time resolution
of 650 ps. After traversing a 64-cm flight path, the recoils pass through a proportional
counter (PC) which measures \(dE/dx\). The recoils stop in an array of silicon microstrip
detectors, which has 1 mm position, 800 ps time and 160-keV energy resolution, and is
mounted in the same housing as the PC. The detector array is shown in Fig. 1.

The first experiments were carried out in November–December 1992 and February
1993 at bombarding energies of 166, 200, 250, 290, 330, and 350 MeV using carbon fiber
and foil skimmer targets. Luminosities of several \(\times 10^{29} \text{ cm}^{-2} \text{s}^{-1}\) were achieved. Fig. 2
shows the results of off-line analysis of the 166 MeV \(p + ^{12}\text{C}\) data taken in the February
1993 run:

(a) \(\Delta E\) vs. \(E\) showing primarily light recoils (He, Li, Be and B) from spallation reactions.
A diagonal software cut has been applied to eliminate the intense He and Li recoils.

(b) Magnetic rigidity vs. energy in the silicon detectors \(E(\text{Si})\) with the \(Z=6\) window
shown in (a) and a mass-13 window in the \(E/\gamma^2\) vs. \(E(\text{Si})\) plane (not shown). The
forward and backward peaking of the \(^{12}\text{C}(p,\pi^+)^{13}\text{C}\) angular distribution is clearly
visible in the spectrum of \(^{13}\text{C}\) recoils in the \(q = 5\) charge state.
**CE-06 Detector Stack**

PGAC: \( X, Y \)

PC: \( DE, Y \)

SI: \( E, X \)

PGAC-SI: TOF

PC-SI: *Recoil identification*

Raytracing: \( P/Q, \theta \)

*Figure 1.* Recoil-ion detector array.
(c) angle of emission ($\theta_{lab}$) vs. magnetic rigidity ($p/q$) at the target for $^{13}$C recoils in the $q = 5$ charge state from the $^{12}$C($p,\pi^+$)$^{13}$C reaction. At 166 MeV bombarding energy (18 MeV above threshold) the $^{13}$C recoils are confined to a $7^\circ$ cone about the beam axis. The diagonal cut in the lower right-hand part of the figure is due to the detector acceptance; high-rigidity recoils emitted to the right (looking downstream) aren't bent enough by the $6^\circ$ magnet to hit the detectors. The well-defined width of the ellipse is probably mainly due to multiple scattering, but wandering of the beam position may also be an important factor.

(d) Same as (c) except for $^{13}$C recoils in the $q = 6$ charge state. Here the detector acceptance includes the entire ellipse.

The angles and rigidities plotted in Figs. 2(c) and 2(d) were calculated from the recoil-ion positions in the PGAC and Si detectors using a backward raytracing program.

Analysis is in progress to determine $^{12}$C($p,\pi^0$)$^{13}$N differential cross sections in the 200–350 MeV region, check the $^{12}$C($p,\pi^0/\pi^+$) cross section anomaly at 166 MeV reported by Homolka, et al., and search for ($p,2\pi$) events at 330 and 350 MeV bombarding energy. At bombarding energies above the ($p,2\pi$) threshold ($\sim 294$ MeV), the ($p,\pi$) ellipses will be much larger, and ($p,2\pi$) events will fill (because of three-body kinematics) small ellipses in the central hole. Reliable relative ($p,2\pi$) cross sections for different isospin channels (including those involving neutral pion emission) should be obtainable using the recoil technique, because the various recoils are all detected simultaneously using the same beam, the same target, and the same detection system.

Experiments planned for the future include: measurements of the cross section and isospin selectivity of the ($p,2\pi$) reaction near threshold to obtain information about nonlinear terms (to third and fourth order in the pion field) in the $\pi N$ interaction; a search for evidence of a possible quasi-bound two-pion state in nuclei; a search for corroborative evidence of possible resonant two-pion production near 350-MeV bombarding energy, and studies of the ($p,\gamma$) reaction with polarized beam. In addition, the possibility of using the detector stack to measure recoils accompanying pion production by heavy ions is being investigated.

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3. Z. Yu, et al., to be published.
Figure 2. Results of off-line analysis of $p + ^{12}C$ data taken at 166 MeV bombarding energy in February 1993 showing $^{13}C$ recoils from the $^{12}C(p,\pi^+)^{13}C$ reaction.