Tracking rare-isotope beams with microchannel plates

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Abstract

A system of two microchannel-plate detectors has been successfully implemented for tracking projectile-fragmentation beams. The detectors provide interaction positions, angles, and arrival times of ions at the reaction target. The current design is an adaptation of an assembly used for low-energy beams (~ 1.4 MeV/nucleon). In order to improve resolution in tracking high-energy heavy-ion beams, the magnetic field strength between the secondary-electron accelerating foil and the microchannel plate had to be increased substantially. Results from an experiment using a 37-MeV/nucleon ^{56}Ni beam show that the tracking system can achieve sub-nanosecond timing resolution and a position resolution of ~ 1 mm for beam intensities up to 5×10^5 pps.

Keywords: microchannel plates, rare-isotope beams, tracking detector,
transfer reactions

1. Introduction

Many modern nuclear-physics facilities utilize secondary rare-isotope beams to investigate the properties of neutron-rich and neutron-deficient nuclei [1–10].

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21 Studies that employ radioactive-ion beams are crucial for understanding top-
 22 ics ranging from astrophysics to addressing the quantum many-body problem
 23 of the atomic nucleus [5]. Facilities that use projectile fragmentation or fis-
 24 sion, produce secondary beams composed of a broad range of isotopes. Specific
 25 isotopes in these beams are selected using fragment separators that utilize com-
 26 binations of electric fields, magnetic fields, and degraders [11–13]. The resulting
 27 beams, however, typically have a large emittance arising from the broad momen-
 28 tum distributions of the secondary-beam particles produced in fragmentation or
 29 through the fission process as well as scattering and straggling introduced by the
 30 degraders. In experiments requiring high-resolution position and energy data,
 31 event-by-event measurements of the momenta of secondary-beam particles are
 32 needed to compensate for this intrinsically large beam emittance [14–21].

33 Several related tracking-detector systems have been developed previously [22–
 34 26]. Most of them are rate limited on the order of $\sim 10^3$ – 10^4 particles per
 35 second (pps). In this paper we report on the performance of position-sensitive
 36 microchannel-plate (MCP) detectors that can handle rates as high as 5×10^5 pps.
 37 Since our MCP system detects and amplifies secondary electrons emitted by fast
 38 beam ions passing through a thin foil, problems associated with beam-induced
 39 background reactions, energy losses, and the effects of multiple scattering are
 40 minimized [27]. While the efficiencies involved in detecting light particles using
 41 thin foils are low, the efficiencies of the system for isotopes with $Z > 20$ are
 42 found to approach unity [23].

43 This paper is organized as follows. In Section 2 we describe the MCP system
 44 used in our measurements. In Sections 3 and 4 we demonstrate its performance
 45 both with α particles from a radioactive source and heavy-ion beams, respec-
 46 tively. In Section 5 we describe the implementation of the microchannel-plate
 47 tracking detectors in fast-beam experiments and show how they improve the
 48 angular and energy resolution of transfer-reaction data. Finally, we summarize
 49 our findings in Section 6.

50 **2. Position sensitive microchannel-plate detectors**

51 *2.1. Microchannel plates*

52 Microchannel plates are compact arrays of single-channel electron multipli-
53 ers [27, 28]. As described in Ref. [27], these electron multipliers are glass tubes,
54 with individual diameters of about 30 microns or less, that have been fused to-
55 gether in a closed packed array and subsequently cut into wafers of the order of
56 a millimeter in length. The front and back surfaces of these wafers are coated
57 with a conductive surface that allows a uniform bias to be applied across the
58 MCP and consequently between the two ends of each tube or “channel” in the
59 MCP. Electrons that enter a channel and strike its interior surface can produce
60 secondary electrons that are accelerated down the channel and multiplied. The
61 efficiency for detection depends on the angle and energy of incidence, reaching a
62 maximum at energies of about a few hundred eV [27]. The gain of such a chan-
63 nel depends on the average number of collisions inside the channel and is largely
64 governed by the ratio of its length to its diameter [28]. Progress in fabrication
65 techniques has made it possible to scale this technology to produce channels with
66 diameters as small as 2 μm and length/width ratios of up to 80 [29]. Gain within
67 a single channel can be limited by space charge, but gain factors of $> 10^7$ can be
68 reached by stacking three or more MCP wafers in a Z-stack configuration [30].
69 The large gains of MCPs make them an excellent option for applications requir-
70 ing single electron counting. The short length of the individual channels gives
71 them the property of being excellent timing detectors [31]. As a result of their
72 narrow channels, MCPs are relatively immune to magnetic field effects at low
73 magnetic fields, however, gain reductions of three to five have been observed in
74 axial magnetic fields of 2 T [32].

75 In our configuration, both large gain and stability are enhanced by stacking
76 two MCPs in a Chevron design as shown in Fig. 1. In addition to increasing the
77 gain of the system due to the larger number of multiplication steps, stacking
78 can prevent positive ions that are generated at the output end of the channel
79 from flowing back toward the input end and producing delayed pulses. Such

Figure 1: (color online). Signal amplification from secondary-electron emission with two chevron-design microchannel plates.

Figure 2: (Color online). (Left) Schematic and (right) photographic top view of a MCP tracking detector. The magnetic-flux return yoke used in the current detector setup is visible in the photo.

80 delayed pulses are minimized by forcing the ions to undergo a significant change
 81 in direction at the juncture between the two MCPs [27].

82 2.2. Detector setup

83 The design of the position-sensitive MCPs used in this work is based on
 84 detectors previously described by Shapira et al. [23, 33], which were optimized
 85 to detect low-energy ions (~ 1.4 MeV/nucleon). A schematic layout as well as a
 86 photograph of a single MCP tracking detector is shown in Fig. 2.

87 When an ion, traveling from left to right in Fig. 2, traverses the MCP
 88 foil, electrons are scattered from its surface and are multiplied in the MCP.

89 A thin 290- $\mu\text{g}/\text{cm}^2$ aluminized Mylar foil is mounted to an insulating fiberglass-
 90 composite frame and directly connected by an electrode to a bias-voltage supply.
 91 The entire tracking-detector structure is rotated by 60° to allow the beam to
 92 pass through the tracking assembly. A bias voltage of -1000 V provides an elec-
 93 tric field of $\sim 2 \times 10^4\text{ V/m}$ that accelerates secondary electrons ejected from the
 94 foil towards the MCP whose front surface is at ground potential. A set of high-
 95 voltage divider resistors supply the correct biases to the individual plates where
 96 the overall MCP operating voltage is adjusted between $+2000\text{ V}$ to $+2200\text{ V}$.
 97 Secondary electrons entering the microchannels are multiplied through an elec-
 98 tron avalanche and deposited on the anode behind the MCPs. Two permanent
 99 rare-earth magnets provide a magnetic field that is roughly parallel to the elec-
 100 tric field, confining the electrons to tight helical orbits spiraling around the
 101 magnetic field lines. The result is an “image” of the beam-interaction point at
 102 the foil projected onto the front surface of the MCP via the emitted secondary
 103 electrons [23, 33–35].

104 We purchased the microchannel plates in a Chevron configuration and as-
 105 sembled with a circular-arc terminated resistive anode, which is position sen-
 106 sitive, from Quantar [36, 37]. Each plate is 0.46-mm thick, 40 mm in active
 107 diameter, and composed of 10- μm diameter channels with a spacing of 12 μm
 108 between centers of adjacent channels. The channels are biased at an angle of
 109 8° relative to the surface normal. The anode layer is located 4 mm behind
 110 the second MCP. Operation of this device requires a vacuum pressure better
 111 than $5 \times 10^{-6}\text{ torr}$ to prevent discharge of electrons in the microchannel tubes.
 112 Similar setups have been implemented successfully in several nuclear physics
 113 experiments [18, 19, 21, 38].

114 We should note that the MCP tracking-detector setup used here for fast
 115 heavy-ion beams differs from the previous work of Shapira et al. [23] in that we
 116 do not employ any accelerating grids. In the work of Shapira et al. accelerating
 117 grids were placed at the target foil to create a fast acceleration region for the
 118 purpose of rapidly imparting large longitudinal velocities to the electrons to
 119 minimize the effect of lateral electron drift on position resolution. Both the grids

120 at the MCP foil and MCP detector were used to explore the effects on electron
121 transport. It was found, however, that the addition of a magnetic field would
122 have a more significant effect. We therefore chose to forgo the complication of
123 accelerating grids in light of this work as well as to remove any excess material
124 from the beam and electron-transport paths.

125 *2.3. Position determination from resistive charge division*

126 The MCP position signals are encoded by a resistive anode. Capacitively-
127 decoupled position signals are taken from the Upper Left (UL), Lower Left
128 (LL), Upper Right (UR) and Lower Right (LR) corners of the anode. The
129 amplitude of each anode corner signal is proportional to the number of secondary
130 electrons produced in the microchannel plates and inversely proportional to the
131 resistance between the charge-deposition location on the resistive layer and the
132 corner electrode. Thus, the amplitude of a corner signal will be greater if the
133 deposition is closer to that corner. Conversely, it will have a lower amplitude if
134 the signal originates from a point farther away.

135 A diagram of the electronics setup used to process the corner signals and the
136 timing signal, T, is shown in Fig. 3. The capacitively-decoupled timing signal is
137 picked off directly from the biasing electrode of the second microchannel plate
138 and amplified by an Ortec VT120 fast-timing preamplifier which is placed close
139 to the MCP detector inside the scattering chamber. After the preamplifier, the
140 signal is sent to a Phillips 715 constant-fraction discriminator (CFD) located
141 outside the chamber. The discriminator output is digitized by a CAEN V1920N
142 Time-to-Digital Converter (TDC) and also used to generate gates for the CAEN
143 N792 Charge-to-Digital Converters (QDC). A “master” event trigger establishes
144 a coincidence between the MCP and events occurring in additional detectors in
145 the setup.

146 The circuits for the corner signals UL, UR, LL, and LR are identical. Each
147 corner signal is amplified by a factor of 100 in an ORTEC 820 fast amplifier. In
148 the most recent measurements, two gain stages are employed to accommodate
149 the wide dynamic range of the position signals. Each position signal from the

Figure 3: MCP signal-processing diagram for the timing signal and a single corner channel. During the $p(^{56}\text{Ni},d)^{55}\text{Ni}$ experiment two gain stages (low and high) were implemented.

150 fast amplifier is split, with a low-gain branch sent directly to a QDC, where
 151 it is digitized. A second high-gain branch is further amplified by a factor of
 152 eight using an NSCL fast amplifier before being digitized by another QDC.
 153 Signals from both gain stages are matched with a precision pulser and verified
 154 using experimental data. We have found that using two gain stages alleviates
 155 problems with position reconstruction near the anode center, where the corner
 156 signal amplitudes are the smallest.

The relative amplitudes of the digitized corner signals provide horizontal- and vertical-position information. We employ charge division techniques to obtain the raw (uncalibrated) horizontal X_{raw} and vertical Y_{raw} coordinates from the four resistive-anode outputs of the MCP,

$$X_{\text{raw}} = \frac{(\text{UL} + \text{LL}) - (\text{UR} + \text{LR})}{(\text{UL} + \text{UR} + \text{LL} + \text{LR})} \quad (1)$$

$$Y_{\text{raw}} = \frac{(\text{UL} + \text{UR}) - (\text{LL} + \text{LR})}{(\text{UL} + \text{UR} + \text{LL} + \text{LR})} \quad (2)$$

157 As described in the next section, data taken with a Cartesian mask placed at

Figure 4: Brass mask used for position calibration of the MCPs. The larger holes in the center of the mask are used to determine orientation.

the MCP foil location are used to convert these raw position-signal coordinates into the final calibrated horizontal, X , and vertical, Y , coordinates.

3. MCP mask calibrations with α particles

A mask made of a 0.16-mm thick brass plate with a matrix of holes as illustrated in Fig. 4, was placed at the MCP foil position. The smaller holes in the mask have a diameter of 0.75 mm. The L-shaped pattern on the mask, composed of 1.5-mm holes, serves to confirm the orientation of the mask. A 290- $\mu\text{g}/\text{cm}^2$ aluminized Mylar foil is attached to the mask. The foil-covered mask is mounted on an insulating fiberglass-composite frame and biased to -1000 V , which again provides the electric field that accelerates the secondary electrons ejected from the foil toward the MCP.

In our first test, a ^{228}Th source was used to develop the position calibration procedure and to determine the position resolution. This source emits α particles with energies ranging from approximately 5.4 MeV to 8.78 MeV. At these energies α particles are stopped in the mask but pass through the aluminized Mylar foil covering the holes with an energy loss of $\sim 200\text{-}300\text{ keV}$. Coincidence measurements with a plastic scintillator paddle placed on the opposite side of the mask from the ^{228}Th source allowed us to identify the α particles passing through the holes in the mask. The uncalibrated and calibrated α -source mask data, shown in Fig. 5, was taken with an MCP detector setup consisting of two

Figure 5: (Color online). (Left) Raw and (right) calibrated MCP α -source position spectra with magnetic fields of $B_{\text{MCP}} = 0.05$ T and $B_{\text{foil}} = 0.03$ T.

178 permanent magnets without a magnetic-flux return yoke. These magnets create
 179 a field of $B_{\text{MCP}} = 0.05$ T at the surface of the MCP and $B_{\text{foil}} = 0.03$ T at the
 180 MCP foil, as measured with a Gauss meter. The magnetic field is smaller at
 181 the foil location than it is at the anode position of the MCP. As the electrons
 182 follow tight spirals along the magnetic field lines, the image of the mask is com-
 183 pressed when it is projected onto the MCP. As a result the mask, which contains
 184 holes covering an area of $60 \text{ mm} \times 60 \text{ mm}$, can be imaged on an anode with an
 185 active-area diameter of 40 mm.

186 The procedure we followed to transform the uncalibrated position spectra,
 187 X_{raw} and Y_{raw} , into calibrated physical Cartesian positions consists of the fol-
 188 lowing steps:

- 189 1. Pedestals, or channels corresponding to signals when no input is present,
 190 are initially determined by a special pedestal run and subtracted from the
 191 raw data so that the average QDC channel values for UL, UR, LL and LR
 192 are zero when no signals are present.
- 193 2. The initial pedestal values are fine-tuned to minimize the dependence of
 194 the calculated position of selected holes in the calibration mask on the
 195 sum of the corner signals. Typically, smaller signals are generated at the
 196 center partly due to radiation damage of the central part of the MCP and
 197 possibly from loading of the MCP, both of which can be caused by the

more intense beam rate experienced by the MCP at its center. Thus, the pedestal settings affect the position spectra in the center of the MCP more severely. The left spectrum in Fig. 5 shows the raw position spectrum for an MCP after determining and tuning the best pedestal settings. In this spectrum, the L-shaped pattern corresponding to the larger holes in the calibration mask is rotated and the spacing between neighboring holes is not uniform.

3. A two-dimensional third-order polynomial is used to fit the raw position information to the mask pattern. The fit is optimized to correct the uncalibrated positions to match the known physical positions of the holes in the mask as given by,

$$\begin{aligned}
X_{\text{cal}} = & a_1 + a_2 X_{\text{raw}} + a_3 Y_{\text{raw}} + a_4 X_{\text{raw}}^2 + a_5 Y_{\text{raw}}^2 + a_6 X_{\text{raw}}^3 \\
& + a_7 Y_{\text{raw}}^3 + a_8 X_{\text{raw}} Y_{\text{raw}} + a_9 X_{\text{raw}}^2 Y_{\text{raw}} + a_{10} Y_{\text{raw}}^2 X_{\text{raw}} \\
Y_{\text{cal}} = & b_1 + b_2 Y_{\text{raw}} + b_3 X_{\text{raw}} + b_4 Y_{\text{raw}}^2 + b_5 X_{\text{raw}}^2 + b_6 Y_{\text{raw}}^3 \\
& + b_7 X_{\text{raw}}^3 + b_8 Y_{\text{raw}} X_{\text{raw}} + b_9 Y_{\text{raw}}^2 X_{\text{raw}} + b_{10} X_{\text{raw}}^2 Y_{\text{raw}}
\end{aligned}$$

where X_{raw} , Y_{raw} , X_{cal} and Y_{cal} are the raw and calibrated coordinates respectively and a_i , b_i are the fit parameters.

The position spectrum after fitting and calibration is shown in the right panel of Fig. 5. For holes at the center of the mask, the centroids of the peaks are located to within 0.5 mm of their correct physical positions. Individual hole positions cannot be resolved near the edge of the channel plate active area, where the centroids of the peaks can differ by as much as 2.0 mm. Normally, this region and the corner regions lies outside of the area illuminated by most secondary beams.

4. Performance of microchannel-plates with fast heavy-ion beams

In this section we discuss the performance of the MCPs with rare-isotope beams used in two experiments conducted at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University [19–21]. Both of these

Figure 6: (Color online). Schematic drawing illustrating the complete MCP beam-tracking system used in rare-isotope beam experiments with HiRA. By correcting for the actual interaction point at the target, the scattering angle of the charged particles detected in HiRA can be properly reconstructed.

experiments used two MCP detectors to track the beam to correct for the interaction location and properly reconstruct the trajectory of reaction products detected in a set of silicon-strip detectors known as the High Resolution Array (HiRA) [39], as shown in Fig. 6. These experiments involve radioactive beams which contain $\sim 70\%$ of the beam of interest, while the remaining $\sim 30\%$ is composed of other isotopes with the same Q/A ratio. This mixture of beam is termed a “cocktail beam”. In the next section, details regarding beam-particle identification will be discussed. To evaluate the performance of the MCP, however, beam selection is not required since the properties of each beam component are similar, resulting in the emission of nearly identical secondary electrons from the foil. The position calibrations discussed and spectra shown in this section use data generated by all components of the beams. Including all beam particles increases our statistics, thereby improving the overall calibration.

The first experiment involved a ^{70}Se cocktail beam containing approximately 67% ^{70}Se , 9% ^{71}Br , and 24% ^{69}As at an energy of 72 MeV/nucleon and used the same MCP tracking detectors as those for the α -source test described in section 3. The MCPs were equipped with identical magnets generating field strengths of $B_{\text{MCP}} = 0.05\text{ T}$ and $B_{\text{foil}} = 0.03\text{ T}$.

236 The second experiment used a 37-MeV/nucleon ^{56}Ni cocktail beam contain-
 237 ing about 71 % ^{56}Ni , 24 % ^{55}Co , 2 % ^{54}Fe , and 2 % ^{53}Mn . Stronger neodymium
 238 iron boron (NdFeB) magnets 3'' in diameter and 2'' in length (Magnet Sales
 239 and Manufacturing Inc., Part No. 35NERR192) were mounted on magnetic-flux
 240 return yokes resulting in fields of $B_{\text{MCP}} = 0.21$ T at the MCP and $B_{\text{foil}} = 0.13$ T
 241 at the target foil [40].

242 In both experiments, the relative position of the masks for each MCP track-
 243 ing detector system were aligned using an optical telescope installed in the up-
 244 stream beamline. In general, the telescope is calibrated to the beamline central
 245 axis and used to align various components in the experimental setup. A central
 246 hole for each MCP mask was aligned using this method to better than 0.25 mm.
 247 A laser alignment system was also employed to confirm the relative positions of
 248 the MCP masks as well as the positions of the HiRA detector pixels [41].

249 4.1. Position calibration with ^{70}Se cocktail beam at 72 MeV/nucleon

250 Since the 0.16-mm thick brass mask in Fig. 4 does not stop the beam, a
 251 scintillator is inadequate to distinguish particles passing through the holes in
 252 the mask from those passing through the brass. Instead, the NSCL S800 spec-
 253 trograph — a high-resolution, large-acceptance mass spectrometer composed of
 254 superconducting magnets — located downstream of the target directly after the
 255 scattering chamber was used [42]. The magnetic rigidity of the S800 was set to
 256 select only beam particles that pass through the mask holes, allowing them to
 257 be detected at the S800 focal plane. Beam particles that pass through the brass
 258 portion of the mask lose sufficient energy so that their trajectories are deflected
 259 off the focal-plane detector of the S800 spectrometer.

260 Fig. 7 shows the uncalibrated and calibrated mask spectra from the ^{70}Se
 261 secondary beam. During the beam calibration test, the incoming secondary
 262 beam is defocused so that beam particles arrive at the target with nearly parallel
 263 trajectories and incoming angles close to 0° . The L-shaped pattern of the 1.5-
 264 mm holes, as shown in Fig. 5 for the α -particle calibrations, can be clearly seen
 265 in Fig. 7. Similar to the calibrated spectrum shown in Fig. 5, the calibration

Figure 7: (Color online). (Left) Raw and (right) calibrated position spectra using 72-MeV/nucleon ^{70}Se cocktail beam. The data was taken with magnetic field of $B_{\text{MCP}} = 0.05$ T and $B_{\text{foil}} = 0.03$ T.

266 procedure correctly rotates the L-shaped pattern so that the center of the mask
 267 is located at $(0, 0)$ mm and the spacing between holes is calibrated to the nominal
 268 5 mm. The calibration procedure also corrects most of the non-linear distortions
 269 of the hole pattern at the edges of the uncalibrated spectrum.

270 There is a clear difference between the resolution of the position spectra for
 271 the α particles in Fig. 5 and the ^{70}Se secondary beam particles in Fig. 7. The
 272 position resolution for the α -source spectrum corresponding to the larger holes
 273 is approximately 1.5-mm FWHM in both the vertical and horizontal directions.
 274 In contrast, the position resolution for the data taken with the ^{70}Se beam is
 275 approximately 2.5-mm FWHM in both the vertical and horizontal directions.
 276 After unfolding the influence of the hole size in the calibrated mask spectrum,
 277 the corresponding observed intrinsic resolution for the ^{70}Se beam is about 2-mm
 278 FWHM, approximately 2 times larger than the α -source.

279 It is not obvious why the ^{70}Se beam exhibits a resolution that is worse than
 280 that obtained with the α particles from the ^{228}Th source. The conditions for
 281 both measurements are similar. The MCP foil voltages are set to -1000 V.
 282 The beam counting rate is higher than the α -particle rate, but there is no
 283 indication of a strong dependence of the resolution on the beam rate in the
 284 work of Shapira et al. [23, 33].

285 One possible difference is the particle energy. The α particles range in en-
 286 ergies from 1 to 2 MeV/nucleon while the ^{70}Se beam energy is 72 MeV/nucleon
 287 before striking the MCP foils. Kinetic energies of electrons scattered at angles
 288 greater than 60° from the MCP foil by α particles are estimated to be less than
 289 0.6 keV, while the corresponding kinetic energies of electrons scattered from the
 290 MCP foil by the ^{70}Se beam can be up to 37 keV as estimated using elastic scat-
 291 tering kinematics [43]. Thus, a magnetic field that is adequate to provide good
 292 resolution with low-energy electrons may not be strong enough to confine the
 293 trajectories of the high-energy electrons to give similar position resolution.

294 In the following, we estimate this effect; the accuracy of our estimates, how-
 295 ever, is limited by the fact that we do not have a measurement of the electron
 296 spectrum. We therefore take the electron spectrum to be consistent with a pri-
 297 mary distribution given by Mott scattering of electrons by the incident-beam
 298 particles [44]. Assuming the magnetic field varies slowly on the scale of the
 299 radius of the electron helical orbit, the motion can be assumed to be adiabatic
 300 and the final radius will be given by $r_{\text{MCP}} = r_{\text{foil}} \times \sqrt{B_{\text{foil}}/B_{\text{MCP}}}$, where r_{MCP}
 301 and B_{MCP} are the orbital radius and magnetic field at the MCP and r_{foil} and
 302 B_{foil} are the orbital radius and magnetic field at the foil [20, 23]. The initial
 303 orbital radius r_{foil} is determined by the component of the electron momentum
 304 perpendicular to the magnetic field $P_{\perp} = \sqrt{\frac{2}{3}(2m_e\langle E \rangle)}$, where $\langle E \rangle$ is the mean
 305 kinetic energy of emitted electron [20, 23].

306 From the Mott scattering cross section, one can estimate the mean energy
 307 of primary electrons to be approximately $\langle E \rangle \approx E_{\text{min}} \ln(E_{\text{max}}/E_{\text{min}})$ where the
 308 relevant electron energies effectively range from an upper limit, E_{max} , given
 309 approximately by elastic scattering kinematics to the lower limit, E_{min} . Our
 310 choice of 0.040 keV for E_{min} is approximate because the spectrum is dominated
 311 by secondary electrons. It reflects a compromise between the strong produc-
 312 tion of secondary electrons in the target and the energy-range relationship for
 313 electrons [45, 46], which prevents the emission of most of them from the MCP
 314 foil (290- $\mu\text{g}/\text{cm}^2$ aluminized Mylar). The energy for electrons back-scattered
 315 at $\theta > 60^\circ$ from the ^{70}Se beam at 72-MeV/nucleon incident energy can reach

316 $E_{\text{max}} = 37 \text{ keV}$. Due to dominance of the low-energy electrons, however, the
 317 mean scattered-electron energy is estimated to be approximately 0.273 keV from
 318 the Mott scattering equation. For the data in Fig. 5 and Fig. 7, the magnetic
 319 field in the MCP assembly has values of $B_{\text{MCP}} = 0.05 \text{ T}$ and $B_{\text{foil}} = 0.03 \text{ T}$
 320 yielding $\sqrt{0.04/0.03} = 1.3$. Thus, for collisions involving the ^{70}Se beam, we
 321 find $r_{\text{foil}} = 1.5 \text{ mm}$ resulting in a FWHM contribution to the position resolution
 322 of about 2.0 mm .

323 In the case when α particles of 1 to 2 MeV/nucleon strike the MCP foil, we
 324 estimate that the primary electrons rarely exceed 0.6 keV in energy and that
 325 most electrons are emitted from the surface of the foil. Our estimate of the
 326 mean scattered-electron energy is 0.1 keV and the FWHM contribution to the
 327 resolution is 1.2 mm . Based on the above calculations, the increase of scattered-
 328 electron energy with particle energy can degrade the position resolution of the
 329 microchannel-plate tracking detector.

330 4.2. Position calibration with ^{56}Ni cocktail beam at 37 MeV/nucleon

331 To further explore the influence of the primary electrons on the resolution,
 332 we examine the performance of these MCPs in another experiment involving a
 333 ^{56}Ni beam at 37-MeV/nucleon incident energy. In the second experiment, both
 334 tracking detectors were equipped with stronger permanent magnets [40]; The
 335 magnetic field measured at the MCP and the MCP foil positions are $B_{\text{MCP}} =$
 336 0.21 T and $B_{\text{foil}} = 0.13 \text{ T}$ respectively, nearly quadruple the magnetic field of the
 337 preceding MCP setup. Using a similar estimate as discussed in section 4.1, the
 338 mean scattered-electron energy from the ^{56}Ni beam is approximately 10 keV .
 339 With the increased magnetic field, we estimate the FWHM contribution on the
 340 position resolution to be 0.4 mm , better than the resolution obtained in the
 341 α -source test.

342 Fig. 8 displays the calibrated mask spectra for both MCPs with the ^{56}Ni
 343 beam. The resolution is significantly better than the observed resolution for the
 344 ^{70}Se beam in Fig. 7. Unfolding the influence of the hole size in the mask for
 345 the ^{56}Ni beam, a corresponding intrinsic resolution of 1.1 mm is obtained. The

Figure 8: (Color online). Calibrated position spectra for MCP0 (left) and MCP1 (right) obtained from the ^{56}Ni cocktail beam. The data was taken with $B_{\text{MCP}} = 0.21\text{ T}$ and $B_{\text{foil}} = 0.13\text{ T}$.

position resolution is similar to the resolution obtained with α particles from the ^{228}Th source. Thus, we see an improvement due to the use of a stronger magnetic field that is within our estimates given above. The correlation, however, between predicted and measured trends is more suggestive than conclusive. To be quantitative, one would need accurate measurements of the electron spectra emitted from the target for these three cases.

5. Application to rare-isotope beam experiments

In this section, we discuss the position resolution we obtained in an experiment in which we measured the differential cross sections for the $p(^{56}\text{Ni}, d)^{55}\text{Ni}$ transfer reactions [20, 21]. A mixed secondary beam consisting of 70 % ^{56}Ni at 37 MeV/nucleon was produced through projectile fragmentation of a ^{58}Ni primary beam at NSCL. Other major isotopes in the cocktail beam are nuclei containing the same number of neutrons such as ^{55}Co and ^{54}Fe , as shown in Fig. 9. These beams had similar magnetic rigidities to ^{56}Ni , thus they also pass through the A1900 fragment separator to the reaction chamber. The isotopes composing the secondary beam are identified event-by-event by comparing their measured time-of-flight (ToF) signals given by the cyclotron RF and a scintillator at the A1900 extended focal plane (XFP) relative to the timing signal

Figure 9: (Color online). Secondary-beam particle identification based on time-of-flight signals from the cyclotron RF and a A1900 scintillator.

generated by the S800. A gate on the ^{56}Ni beam has been imposed on all the data discussed in this section.

The transfer reaction $p(^{56}\text{Ni}, d)^{55}\text{Ni}$ is produced by bombarding a polyethylene $(\text{CH}_2)_n$ target with 37-MeV/nucleon ^{56}Ni beam. Deuterons produced in the reactions are detected by the High Resolution Array, HiRA [39], and the associated heavy ^{55}Ni residue is detected in coincidence using the S800 spectrograph [42]. In order to resolve the energy states of the ^{55}Ni residuals at high resolution, accurate determinations of the deuteron energy and emission angle are required. The 16 HiRA telescopes were located 35 cm downstream of the target. They are arranged to subtend polar laboratory angles of 5° – 40° . Each telescope consists of a single-sided ΔE ($65\ \mu\text{m}$) and a double-sided E ($1500\ \mu\text{m}$) silicon strip detector, with active areas of $6.25\ \text{cm} \times 6.25\ \text{cm}$, backed by four separate CsI(Tl) crystals mounted in quadrants. The $32 \times 32 = 1024$ pixels defined by the vertical front and horizontal back strips in the double-sided silicon E detector allowed the angles of emitted deuterons to be determined, relative to the center of the target, with a precision of $\pm 0.16^\circ$.

The actual laboratory emission angle for the deuterons, however, depends on the position where the reaction occurs in the target and on the momentum direction of the incident ^{56}Ni beam before the reaction. The MCP tracking system

383 is used to constrain these quantities. This system employed two microchannel-
 384 plate tracking detectors, MCP0 and MCP1, which measure the position of the
 385 beam at two points along the incoming beam trajectory. The detectors are
 386 placed 50 cm apart, with MCP0 and MCP1 denoting the upstream and down-
 387 stream MCPs, respectively. The reaction target is located 10 cm downstream
 388 of MCP1 and is perpendicular to the beam axis. Each tracking-detector as-
 389 sembly is rotated by 60° with respect to the beam so as not to obstruct the
 390 incoming beam particles. Due to the sub-nanosecond timing resolution of the
 391 MCPs, MCP1 also provides a time signal for residues detected in the focal plane
 392 detectors of the S800 mass spectrometer. The time-of-flight and energy loss of
 393 the residues in the S800 provides good identification of ^{55}Ni particles, which is
 394 critical in the analysis. Additional details on the experimental set up can be
 395 found in Ref. [18].

396 The strong magnetic fields in the MCP setup necessary for increasing posi-
 397 tion resolution, however, influence the trajectories of the ^{56}Ni beam ions. For ex-
 398 ample, the first MCP magnet deflects the beam by an angle of $\theta = Bd \sin(\gamma)/B\rho$.
 399 Here, B is the magnetic field at the MCP foil ($B_{\text{foil}} = 0.13 \text{ T}$), d is the distance
 400 the beam traveled in the magnetic field ($8.0 \pm 0.5 \text{ cm}$), γ is the angle of the foil
 401 with respect to the normal (60°), and $B\rho$ is the magnetic rigidity of the beam
 402 ($1.72 \text{ Tesla} \cdot \text{m}$). The estimated deflection angle is 0.17° . To compensate for this
 403 deflection, the magnetic fields of the two MCPs were arranged to have opposite
 404 polarity with respect to each other. In this configuration, the main overall effect
 405 of the two sets of magnets on the beam is an upward shift by 1.5 mm. Because
 406 the experiment only depends on the position and angle of the beam at the tar-
 407 get, this shift is of no consequence as long as it is small compared to the beam
 408 spot.

409 *5.1. Reaction target beam-tracking reconstruction*

410 To evaluate the uncertainties in the beam-tracking reconstruction and the
 411 MCP calibration procedure, a mask was inserted at the reaction-target position.
 412 The mask is made out of a 1.6-mm thick aluminum plate with five 2-mm holes,

as shown in the schematic diagram of Fig. 10. The four outer holes form a

Figure 10: A schematic view of the reaction-target mask.

413

414 square with 10-mm sides while a fifth hole is located at the mask center. Again,
 415 as with the MCP beam calibrations, the S800 spectrograph is used to detect
 416 coincident particles that pass through the holes in the mask.

417 From the position data of MCP0 and MCP1 the beam is tracked, and the in-
 418 dividual beam-particle trajectories extrapolated to the reaction-target location.
 419 A comparison of the data obtained with the mask inserted to the actual mask
 holes is shown in Fig. 11. The calculated positions reproduce the reaction-target

Figure 11: Calculated position at the reaction target using measured MCP tracking data. The overlaid circles represent the reaction-target mask holes from Fig. 10.

420

Figure 12: Position spectrum of the ^{56}Ni beam on the reaction target reconstructed by the MCP tracking system. The circles show the reaction-target mask holes from Fig. 10.

mask reasonably well, but the resolution of reconstructed positions at the target is worse than the position resolution for the individual MCP mask calibrations. For the outer holes, the resolutions are 1.2 mm in the horizontal direction and 1.5 mm in the vertical direction. The difference in the horizontal and vertical resolutions is mainly due to the rotation of the MCP foils. The distribution of the errors is not uniform, however, and is somewhat worse at the center of the target (~ 2 mm) than at the edges. Also, the resolution of the left side is better than the right side. We note that the average resolution is comparable to the 2-mm pitch of the HiRA silicon-strip detectors.

Fig. 12 shows a position spectrum of the ^{56}Ni beam at the reaction target, extrapolated from the tracking positions measured at the two MCPs. For this experiment the ^{56}Ni secondary beam has dimensions of 11-mm FWHM in the horizontal direction and 17-mm FWHM in the vertical direction. The target mask from Fig. 10 is also superimposed on the spectrum. Comparing Fig. 11 and Fig. 12, one can estimate that the tracking system yields an improvement in the interaction position by a factor of ~ 10 better than the width of the beam spot. If we made no correction for the interaction point on the target, particles emitted from reactions occurring at the target center and at a position $1\sigma = 7.3$ mm away from the beam spot center would have significantly different scattering angles of approximately 1.2° , even if they are detected in the same

Figure 13: Beam angle spectrum of the ^{56}Ni beam on the reaction target reconstructed by the MCP tracking system.

441 pixel of the HiRA device.

442 The scattering angle of an emitted particle after a nuclear reaction also de-
 443 pends on the incident-beam angles at the reaction target. Fig. 13 shows the
 444 spectrum of the incident-beam angles. The angular distributions have widths of
 445 $\delta\theta_x^{\text{beam}} = 1.5^\circ$ FWHM and $\delta\theta_y^{\text{beam}} = 1.35^\circ$ FWHM. Folding the beam angle dis-
 446 tribution against the target spot-size distribution, one has $\delta\theta_x^{\text{total}} = 2.3^\circ$ FWHM
 447 and $\delta\theta_y^{\text{total}} = 3.0^\circ$ FWHM, respectively. Most transfer-reaction experiments are
 448 designed to achieve an angular resolution of less than 0.3° , thus the target
 449 beam-spot size and beam angular resolution are critical issues if uncorrected.

450 5.2. Improvements in angular and energy resolution

451 In the neutron-transfer experiment energy and angles of the deuteron are
 452 measured along with the momentum of the residue, ^{55}Ni , from the $p(^{56}\text{Ni}, d)^{55}\text{Ni}$
 453 reaction. Since the ^{56}Ni beam energy is fixed and the target is at rest, conserva-
 454 tion of energy and momentum dictates that the kinematic relationship between
 455 E_d and θ_d forms a hyperbolic curve for a fixed energy state of ^{55}Ni . Fig. 14 shows
 456 two-dimensional spectra without and with MCP correction of the measured lab
 457 angle versus lab energy of the emitted deuterons.

458 Using beam position and angle information from the MCP tracking system,
 459 the deuteron energy and scattering angle is corrected as shown in the right spec-

Figure 14: (Color online). Deuteron energy as a function of θ_{lab} without MCP correction (left) and with MCP correction (right).

trum in Fig. 14. Both the ground state and the excited state at 3.185 MeV [47] are clearly observed. At angles less than 15° , the first excited-state peak at 2.089 MeV is identified in the bottom panel of Fig. 14 after the data has been corrected using the MCP tracking. The improvement in energy resolution is minimal ($\sim 20\%$ from 0.5 MeV to 0.4 MeV) at forward angles, but increases by a factor of two (from 3 MeV to 1.5 MeV) at backward angles. Improvement of the resolution obtained in the center-of-mass will be described in detail in a forth coming paper discussing the physics of the experiment.

The current energy resolution is limited by the target thickness of 9.6 mg/cm^2 . A thick target is needed to obtain sufficient counts for the first excited state. If a thinner target such as 2.5 mg/cm^2 is used, the ground-state energy resolution would be better than 0.4 MeV at the forward angles. In future studies of states at higher excitation energy, thinner targets could be used to maximize resolution.

6. Summary

We have successfully used devices based on microchannel plates with position-sensitive resistive anodes to track fast heavy-ion beam particles. Strong magnetic fields on the order of 2 kG were required, however, to obtain position resolution of $\sim 1 \text{ mm}$ for fast ($> 35 \text{ MeV/nucleon}$) heavy ions such as ^{56}Ni . Our

experience from a $p(^{56}\text{Ni},d)^{55}\text{Ni}$ transfer experiment suggests the MCPs can withstand incident-beam intensities of $\sim 5 \times 10^5$ pps for up to 10 days before degradation in resolution of the microchannel plates occurs. Such features make MCPs desirable as tracking detectors for experiments requiring high intensity rare-isotope beams.

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