A New Type of Particle Detector for Nuclear Scattering Experiments

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A NEW TYPE OF PARTICLE DETECTOR FOR
NUCLEAR SCATTERING EXPERIMENTS

by

PHILIP UGOROWSKI

A Dissertation
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
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Western Michigan University
Kalamazoo, Michigan
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A new detector was needed for counting recoil protons resulting from proton-proton (pp) elastic scattering during pion production experiments by the Polarized Internal Target Experiments (PINTEX) group at Indiana University Cyclotron Facility (IUCF). The previous silicon detectors were only usable for incoming protons up to 9 MeV, and a stopping power of at least 40 MeV was needed. In addition, the detector had to operate in nanotorr vacuum, and near strong varying magnetic fields, ruling out standard organic plastic scintillators and photomultiplier tubes. We needed to find the most suitable inorganic scintillator and another method of detecting the photons produced when a proton entered the detector. We used a photodiode for light collection, which can be made to work with the right choice of preamplifier. CsI scintillator gave the best light output, and the signal risetime (1 ms) was sufficient to handle the expected event rate. We wanted to eventually use the signal to trigger the data collection electronics, which required a risetime of ~100 ns or less. This required a switch to BiGeO as a scintillator, with much less light output. The minimum required energy detection threshold is the ability to detect 15 MeV incident protons. Using the Tandem Accelerator at WMU, a minimum sensitivity of 5 MeV was achieved. During subsequent experiments at IUCF the new detector was tested, with good results.
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Steve Ferguson, Western Michigan University

Philip Ugorowski
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I. INTRODUCTION

The short range of the strong interaction requires that it be studied when nucleons are within $\approx 10^{-15}$ meters of each other. One way to achieve this is to bring nuclei close together in the laboratory by sending a beam of nuclei toward other target nuclei which are at rest or traveling in the opposite direction. All nuclei have a positive charge, and sufficient kinetic energies are required to overcome Coulomb repulsion. Once the nuclei are within range of the strong force, the strong interaction dominates the collision. The nuclear fragments resulting from these collisions that are scattered away from the beam axis can be detected. From information about the identity of these products, as well as their trajectories, details of the strong interaction can be inferred.

The kinetic energies required for nuclear scattering studies require large accelerators, which are expensive, and not numerous. These facilities are typically funded through a consortium of universities and/or governments. These types of facilities must be shared, as there are more researchers with questions than there are accelerators that can provide answers. Researchers from around the world form research groups to conduct experiments. Some of these accelerators are known as "user facilities", and research time is granted solely on the merits of the proposed research. One such user facility is the Indiana University Cyclotron Facility (IUCF), in Bloomington, Indiana.

A major component of IUCF is the Cooler Storage Ring, or “Cooler”. This combined accelerator and storage ring is capable of producing beams of protons or
deuterons in an evacuated beam tube, following a closed path. For the scattering experiments described in this thesis, the beam and target nuclei were hydrogen. The most abundant isotope of hydrogen is a single proton, the only nucleus which is a single nucleon. Beams of protons were accelerated and directed at target protons contained in atomic hydrogen gas, which was at rest with respect to the laboratory. At IUCF, the beam can be directed at a gas target within the beamline tube (internal target). The vast majority of beam protons miss the target nuclei during scattering experiments, since the nucleus takes up so little of the volume of any atom. With the use of an internal target, those beam protons that miss the target nuclei go around the ring again, with another chance to interact with a target nucleus. With the beam circulating in the storage ring millions of times each second, the chances of a given beam proton interacting with a target nucleus are greatly enhanced.

Another feature of the IUCF Cooler is the ability to produce a proton beam which can be polarized. Polarization is an ensemble quantity related to the quantum-mechanical spin possessed by all spin-$\frac{1}{2}$ particles. Their spin vectors, according to the rules of quantum mechanics, have two possible orientations. For any choice of reference axis, measurement of the spin of a spin-$\frac{1}{2}$ particle will find it either aligned or anti-aligned with the reference axis. A collection of protons all measured to have the same spin direction are fully polarized. If one-half of the spins of a group of protons are parallel to a direction (with the other half being in the opposite direction), the ensemble is unpolarized. The polarization of the beam along the y-axis ($P_y$), for example, is:
In this thesis, we will use a standard, right-handed Cartesian system of axes, with the direction of beam travel in the lab considered the $+z$-axis, the vertical up direction in the lab is the $+y$-axis, and the $+x$-axis defined as usual. We will also use standard spherical coordinates, where $\theta$ is the angle from the $+z$-axis, and $\phi$ is the angle projected into a plane perpendicular to $z$, referenced to the horizontal (here the $x$-direction). In the above equation, $N_\uparrow$ is the number of beam protons with spins oriented along the $+y$-axis, and $N_\downarrow$ is the number of those with spins along the $-y$ direction. Thus, $P_y$ will vary from $+1$ for a beam 100% polarized in the $+y$-direction, to $-1$ for a beam polarization of 100% in the $-y$-direction. An unpolarized beam would correspond to a $P_y$ of zero. Experiments using unpolarized beam nuclei and unpolarized target nuclei can yield measurements of only those observables which are not spin-dependent, because any spin-dependent effects would cancel. An applied magnetic field can polarize a group of nuclei, revealing some spin-dependent effects, from which additional information about the strong interaction can be derived.

An example of one of these effects is an asymmetry in the numbers of protons scattered in the horizontal direction. Using a polarized beam and an unpolarized target, the beam polarization $P_y$ can be determined at any time by comparing the scattering cross-sections of protons resulting from proton-proton (p-p) elastic

$$P_y = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$
collisions which are deflected to the left of the beam direction ($\sigma_L$), with those
deflected to the right ($\sigma_R$). The asymmetry is:

$$P_y A_y = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

where $A_y$ is the analyzing power, a measured function of energy and angle$^1$. The analyzing power contains the interesting physics of the effect, and can be calculated from the asymmetry, provided the polarization is already known.

Scattering experiments where both the beam nuclei and the target nuclei can be separately polarized provide an opportunity to measure observables which depend on beam and target spin. The ability to provide polarized beams in the medium energy range and polarized internal gas targets makes the IUCF Cooler unique in the world.

When two protons interact, the differential scattering cross section ($d/d\Omega$) represents the probability that the path of a resulting outgoing proton will fall within a given solid angle. During pion production ($pp \rightarrow pp\pi^0$) experiments at IUCF, continuous measurement of the beam polarization $P$ and the target polarization $Q$ are needed, along with measurement of the scattering cross section, to find the spin-correlation coefficients, $A_{ij}$, as illustrated in the following equation where $B = Beam$, $T = Target$, and $d\sigma/d\Omega$ is abbreviated as $\sigma$.$^2$

$$\sigma(P, Q) = \sigma_{nospin} \left[ 1 + (P_y A_y) \cos \phi + (Q_y A_y) \cos \phi + P_y A_y \frac{A_{xx} - A_{yy}}{2} \sin 2\phi 
+ P_y A_y \left( \frac{A_{xx} + A_{yy}}{2} + \frac{A_{xx} - A_{yy}}{2} \right) \cos 2\phi \right]$$
Although the spin correlation coefficients are unknown during the pion production experiments, their measurement is accomplished by monitoring elastic p-p collisions, where the coefficients were previously measured by our research group. Therefore, the latter reaction could be used to keep track of both beam and target polarization and verify that the measurement of the unknown quantities was correct (by comparing with known quantities measured simultaneously by the same method).

Different models of the nucleon-nucleon interaction potential predict different spin correlation coefficients. Determination of these and other spin-dependent observables allows comparison between different contemporary theories of the strong interaction.

An extracted beam can be dumped into a Faraday cup to measure the total charge, or integrated current, but this is not possible with the continuously-circulating beam of a storage ring. During a data-taking cycle at the IUCF Cooler, beam protons are injected into the storage ring, and the kinetic energy is increased until the beam current is in the $10^{-4}$ Amp range. After the gas target is introduced into the target chamber, data is taken for 120 seconds. Due primarily to interactions with the target gas nuclei, the beam current decreases by roughly one-half during data-taking. After 120 seconds, the target gas flow is discontinued, the remaining stored beam is dumped and the next group of beam protons is injected.

Not only does beam current continuously change, the target thickness may also vary with time. The thickness of a solid target has units of area (density times length). For solid targets, these values can be precisely measured and remain constant. A gas
target’s thickness depends on the flow rate, and cannot be measured directly with sufficient precision.

The beam current and target thickness cannot be separately measured, but we can measure the product of beam current and target thickness, known as “luminosity”, which changes continuously during an experiment. The instantaneous event rate measured by a detector is an integration of the scattering cross section over the solid angle of the detector, multiplied by the instantaneous luminosity. The integral of the luminosity over the data-taking time is the integrated luminosity. Thus, the overall number of events reported by a detector during the data-taking time is an integration of the scattering cross section over the solid angle of the detector, multiplied by the integrated luminosity. The p-p elastic event rates are used to continuously monitor the luminosity, since the elastic scattering cross sections are well known.

In the next section, we will discuss the experimental setup at IUCF, and the detectors used to measure the angles, energies and count rates of outgoing protons. A change in the monitoring detector system was needed, in order to carry out experiments with increased beam energies. The remainder of the thesis will concern the design, development and testing of a new type of proton detector, to monitor the elastically-scattered protons near the target. We will specify the requirements for the new detector and detail the initial tests of energy resolution and efficiency with two possible types of detector materials, conducted at IUCF and Western Michigan University (WMU). Then, we will discuss the preliminary results and our choice of material for the new detector. We will also discuss our simulation of the data we
expected from the new detector during experiments, once it was installed at IUCF. We will use data taken during an experiment at IUCF for more precise measurements of energy calibration, energy resolution and efficiency. Finally, we will compare the requirements for the new detector with its actual performance, discuss future uses for the detector and give suggestions for further improvement.
II. EXPERIMENTAL SETUP

A. IUCF Cooler

At the IUCF, scattering experiments are carried out in the Cooler, a high-vacuum storage ring and synchrotron for protons or deuterons, with a circumference of about 87m. Protons from a pre-accelerator (not shown) are injected at 200 MeV (1 MeV = $10^6$ electron-Volts) kinetic energy at point (A), and circulate in the direction shown. Once the hexagonal “ring” is filled, the beam’s kinetic energy can be raised to any value, up to 450 MeV for protons. The internal target is then placed in the path of the beam by allowing the target gas to enter a target cell which is open to the beam at both ends, as detailed in the next section.
The name “Cooler” derives from the electron-cooling region labeled (B) in Fig. 1. In this section of the beamline tube, the proton beam is surrounded by a beam of electrons with the same average velocity as the protons. In the rest frame of the beam, some of the protons will have a component of their momentum in a direction transverse to the beam direction. In the electron cooling section, some of the proton’s transverse momentum is transferred to the electrons, cooling the beam. Likewise, protons with a longitudinal velocity greater or less than the average velocity transfer this momentum difference to the electrons. This process is necessary because interactions with the internal target cause heating of the beam on each pass through the target chamber. Accelerators which use external targets do not require beam cooling, since the beam is dumped after a single pass through the target. Our research group’s target chamber and forward detectors are located in the straight section labeled (C), as detailed in the next sections. The Cooler ring has a total of four straight sections in which different research groups can set up their experiments, although only one experiment can be performed at any one time.

The IUCF Cooler is unique, in that it is the only facility capable of providing both polarized beams and polarized internal targets. Accordingly, the research group using all these features is called PINTEX (for Polarized INternal Target EXperiments).
The target cell assembly sits in the target chamber and allows the ≈1 mm diameter beam to pass through a target cell tube 1 cm in diameter connected via a teflon tube to the Atomic Beam Source (ABS) developed at University of Wisconsin\(^4\). The ABS provides a flow of polarized hydrogen gas atoms into the target cell tube. The target cell tube (shown in green in Figs. 3a, 3b and 3c) is open at both ends and lined with teflon. The hydrogen target gas atoms enter this tube, and after multiple collisions with the tube walls, leak out the ends of the tube. Teflon reduces the time that hydrogen atoms are in contact with surfaces, upon collision of the hydrogen atoms with the tube walls. Reducing the atoms’ contact time with the walls reduces the
chances of recombination with another hydrogen atom. Recombination into $\text{H}_2$ molecules depolarizes the target gas. All around the target chamber, vacuum pumps (not shown) remove the hydrogen from the chamber before it reaches the beamline, to maintain high vacuum within the rest of the Cooler. Beam protons which do not interact with target protons continue to travel within the beamline tube for the next pass at the target cell.

Fig. 3a Target chamber cutaway view, showing target cell and proposed recoil detectors
If an elastic collision occurs between a beam proton and a target proton, conservation of energy and momentum predicts their final paths will differ by 90°, due to their equal masses, and their final paths will lie on a single plane along with the beam axis. Relativistic corrections at these energies reduce this angle difference by about 0.15°. The proton which scatters forward (an angle $\theta < 45^\circ$ relative to the beam direction), will have the higher kinetic energy, while the recoil proton scatters with a lower energy. The beam direction is the $+z$-direction, shown by the arrow in Figs. 3a and 3b. The proposed recoil detectors at positions marked A and B would be mounted within the target chamber, in order to detect these lower-energy protons. For example, a recoil proton entering the lower detector in Fig. 3c would correlate with a forward-scattered proton entering the upper part of the forward detector array. This higher-energy forward-scattered proton exits the target chamber through a thin stainless-steel window, which makes up part of the forward (downstream) wall of the target chamber. The forward proton then enters the forward detectors (Figure 4),
which are mounted surrounding the beam tube. The lower-energy recoil proton does not have enough kinetic energy to pass through such a window target chamber, necessitating the recoil detector’s placement inside the high-vacuum target chamber.
C. Forward Detector Array

The forward-scattered proton passes first through a thin plastic scintillator (F) to generate a start signal for time-of-flight measurements. Next, the proton passes through a wire chamber (WC1) with two wire planes at right angles to each other. A second two-plane wire chamber (WC2) is oriented at 45° relative to (WC1), and provides a second reference point to determine the angle of flight. The four detectors marked (X) are used for coincidence measurements, to detect both protons from proton-proton (p-p) elastic collision events. The (E) and (K) detectors are thick plastic scintillators, intended to measure deposited proton energies. The (E) detector...
is divided into eight segments, while the (K) detector is divided into four segments. Lastly, another thin scintillator (V) functions as a veto detector, to indicate if a proton has passed completely through the detector array. For such protons, the energy deposited in the scintillator is not the total kinetic energy, and their remaining kinetic energy is unknown.

Each layer of forward detectors shown in Fig. 4 has a hole in the center to accommodate the beam tube. Except for the wire chambers, each set of detectors is of the scintillator-photomultiplier type, which is an efficient approach to measuring charged particle kinetic energies above ≈10 MeV, when the resolution requirements are modest. The details of the operation of a typical scintillator-photomultiplier detector are shown in Fig. 5.

![Fig. 5 Standard scintillator-photomultiplier detector schematic](image)

The proton (A) enters a piece of scintillator material (B), which produces a number of photons in proportion to the kinetic energy lost to the scintillator by the incoming proton. A Lucite® lightguide (C) optically couples the scintillator to a photomultiplier tube (D). Photons entering the photomultiplier tube (D) cause a cascade of electrons to be released, resulting in a pulse of current to the amplifier (E).
Upon reaching the amplifier, the pulse can be shaped by differentiation or integration, to make it more suitable for recording by the computer’s analog-to-digital converter (F). The number of photons produced in the scintillator is proportional to the portion of the proton’s kinetic energy lost in the scintillator. The amplitude, (or height) of the signal is proportional to the integrated current, which is in turn proportional to the number of photons reaching the photodiode from the scintillator. Therefore, the height of the signal pulse can be calibrated to the amount of the proton’s kinetic energy lost in the scintillator, since the proportionality relationships are linear. If the proton comes to rest within the scintillator, this value will match the proton’s total initial kinetic energy. If the proton passes through the scintillator, it exits with some kinetic energy, and the proton’s total initial energy is not known from the height of the signal pulse. The maximum proton kinetic energy less than this “punch-through” is called the “stopping power” of the scintillator.

There are two main types of scintillator materials, organic plastics and inorganic crystals. Two types of inorganic scintillator were used in this project: CsI (cesium iodide), and BGO (bismuth germanium oxide). Organic plastic scintillators are generally used because they produce a greater number of photons per MeV of energy lost by the particle in the scintillator, but we used these two inorganic types for reasons detailed in the next section.
III. NEW RECOIL DETECTOR SPECIFICATIONS

Prior to this research project, the recoil detectors were the position-sensitive silicon (Si) type. These thin (~1mm) detectors had certain limitations. Recoil protons with kinetic energies above 9 MeV, pass through the silicon detectors without giving up all of their kinetic energy, making the energy deposited in the detector less than the proton's initial energy. In order to perform experiments with higher beam energies (and correspondingly higher recoil energies), a thicker type of detector was desired, capable of stopping protons with higher kinetic energies. Besides the low stopping power of 9 MeV, other drawbacks of the silicon detectors were the susceptibility to damage from stray beam protons, and the high cost of replacement. The specifications for a new recoil proton detector were:

1. Minimum stopping power of 40 MeV, more is better.
2. Minimum detected proton kinetic energy ≈ 15 MeV.
3. Location inside target chamber, which has ultra-high (~10^{-9} torr) vacuum.
4. Increased resistance to damage from stray protons.
5. Maximum detector response time of 10^{-6} seconds, if possible, 10^{-7} sec.

The scintillators with maximum light output are composed of organic plastics, and could meet all of the above criteria, except for (2.). Plastic scintillators placed directly in a high vacuum will outgas, making nanotorr pressures difficult to attain. In addition, conventional photomultiplier tubes will overheat in vacuum, due to the lack of convective air currents. Inserting conventional scintillator/photomultiplier
combinations into the target chamber in pressurized tubes was not feasible due to space limitations, even using lightguides or the smallest available photomultiplier tubes. Inorganic scintillators will not outgas as much, but generate fewer photons for the same amount of kinetic energy lost by the proton.

Replacement of the photomultiplier tube is more problematic. A photodiode (PD) is a solid-state device similar to a solar cell, and can be biased such that it will pass a pulse of current roughly proportional to the amount of light shining on it. Due to the poorer performance of inorganic scintillators and photodiodes, they are not generally used together, but in the absence of other options, the PINTEX group decided to explore an inorganic scintillator/photodiode combination\textsuperscript{5,6}.

PINTEX’s timing requirements for the new recoil detector/preamp combination were that the signal pulse should reach its maximum value (the signal risetime) within about 1µs, in order to be recorded with the signals from the other detectors and wire chambers, and to meet count rate dead-time requirements. While the signals from all detectors are being processed (deadtime), new signals from the detectors cannot be accepted. In order for the signal to be included in the “trigger stream” (key signals that indicate an event should be recorded), the preamplifier signal risetime should be no more than ~0.1µs.

While the BGO signal pulse has a faster risetime (~1µs for CsI, compared to ~0.1µs for BGO using the same preamp), the manufacturer’s literature states that BGO requires “at least a few” MeV of proton kinetic energy (for charged particles) for good results using a photomultiplier tube. While the new recoil detector does not need to
be sensitive to protons of less than 15 MeV for experiments at IUCF, the accelerator at WMU would provide only up to 12 MeV protons. Coincidence tests (detailed in the next section), would provide protons in the 6-8 MeV range. Since these energies are near the threshold of detection for BGO, CsI was also chosen for testing at IUCF and WMU. CsI’s greater light collection characteristics would allow optimization of the pulse-shaping settings at the main amplifier, in the event that the BGO-PD signal height at WMU was insufficient to set up coincidence studies between a BGO-PD detector and a standard silicon detector.
IV. DETECTOR DEVELOPMENT

A. Tests with radioactive sources at IUCF

The first step was to see if a photodiode is sufficiently sensitive to the light pulses from a scintillator. Two inorganic scintillators were tested: Cesium Iodide for its greater light output per MeV of kinetic energy lost in the scintillator by the detected proton, and Bismuth Germanium Oxide for its faster light pulse response time. The first measurements with the photodiode (Hamamatsu 2744, 1 cm × 2 cm) were geared toward finding the optimal photodiode bias voltage, finding a well-matched preamplifier, and determining the best amplification and pulse shaping settings. The testing set-up is shown in Fig. 6.

![Fig. 6 Scintillator/photodiode test setup](image)

Both the photomultiplier and photodiode are optically coupled to the scintillator material using a thin layer of optical grease (Dow-Corning Q2-3067). This
transparent grease ensures that a continuous optical medium exists between the scintillator material and the glass of the photomultiplier tube or the resin coating on the active surface of the photodiode, minimizing reflection of the light photons when passing between these media. The photodiode is reverse-biased, which means that when light shines on the active surface, some charge should leak through the diode in the direction which is usually blocked. A ≈1 MeV \( \gamma \) from Bi-207 source would enter the scintillator, and the resulting light photons would travel to both ends of the scintillator, where the photodiode signal could be compared to the photomultiplier signal at the oscilloscope. A gate-and-delay generator must be used, since the photomultiplier signals are not only stronger, but are created more quickly. A one-to-one correspondence between these two signals indicates that the photodiode signals are in coincidence with the light pulses detected by the photomultiplier, and thus not random noise. The photodiode was particularly susceptible to interference from other equipment, which required using shielded cable for the leads, and surrounding the preamplifier with grounded aluminum foil.

The choice of preamplifier proved to be critical to the production of a signal pulse above background noise signals. We tried several models of preamplifiers, from different manufacturers, and also some preamps designed and built at IUCF. Eventually, a suitable preamp (Ortec 2001) was found that was capable of reverse-biasing the photodiode up to 30 Volts (the manufacturer’s stated breakdown limit).

We were able to obtain a one-to-one correspondence between signals from the CsI-photodiode-preamp combination and signals from the CsI-photomultiplier
combination, for source-related events. This meant we were not getting false signals from the photodiode or missing signals from the photomultiplier. Coincidence tests for the BGO scintillator required the greater particle energies available at WMU.
Western Michigan University operates a HVEC Tandem Electrostatic Accelerator (High Voltage Engineering Corp., Model EN), capable of accelerating protons up to an energy of 12 MeV. The particle flux and energy are much greater than those available from radioactive sources, and both can be more precisely controlled. This beam is the same type of particles and same order-of-magnitude energy range which we expect to measure, once the detector is installed for experiments at IUCF. The beam is extracted from the accelerator and directed at an external target. A small scattering chamber, which can be evacuated relatively quickly, is ideal for detector testing, as shown in Fig. 7, above. Beam currents can be measured precisely by a
Faraday-cup beam stop. The proton beam enters the evacuated scattering chamber, striking a hydrocarbon target foil. If the proton collides elastically with a carbon nucleus, the proton scatters with nearly its initial kinetic energy. If it collides inelastically, the proton will scatter with a kinetic energy lowered by the amount corresponding to the difference in energy levels between the ground state and the first excited state of the carbon nucleus. If the proton strikes another proton, (a p-p elastic collision) the two protons will continue forward with a $90^\circ$ angle between their paths.

Two detectors were placed $90^\circ$ apart, one being the inorganic scintillator/photodiode detector and the other being a standard silicon (Si) surface barrier detector. A p-p elastic collision between a beam proton and a target proton should cause a proton to enter the scintillator in coincidence with the other proton entering the Si detector. Lead shielding protects the photodiode and scintillator from stray protons. A typical energy spectrum with the Si detector placed at a scattering angle of $45^\circ$ from the beam direction (Fig. 8), shows the number of protons detected by the silicon detector as a function of the analog-to-digital-converter (ADC) channel number, which is directly proportional to the proton’s kinetic energy.
The peak marked (A) is a “background” noise peak. The peak marked (E) represents the protons scattering elastically from the much heavier carbon nuclei. The carbon nucleus recoils, and the incoming proton of 8 MeV scatters elastically with a kinetic energy of 7.6 MeV. The (B) peak shows low-energy recoil carbon nuclei ejected from the target. The (C) peak represents beam protons which have scattered inelastically from the carbon nuclei. These interactions have raised the carbon nuclei from the ground state to the first excited state, a difference of 4.4 MeV. In addition, the excited carbon nucleus recoils. Accordingly, these protons have about 3.2 MeV left of their original beam kinetic energy of 8 MeV. The peak of interest (D) resulted from elastic collisions with target protons, with each proton carrying half of the total beam energy, or 4 MeV. Fig. 9 shows the energy spectra and corresponding peaks, as shown by the CsI-PD detector and BGO-PD detectors (Figs. 9a and 9b, respectively).
The BGO-PD detector shown in Fig. 9b used an 11 MeV beam, so its p-p elastic scattering peak corresponds to 5.5 MeV protons, and is barely resolved from the noise. Neither organic scintillator detector’s energy resolution is sufficient to distinguish between carbon-recoil and noise peaks (\(A, B\)) or between the proton-proton elastic peak and the proton-carbon inelastic peak (\(C, D\)), but the energy resolution (as judged by the peak separation) of the BGO-PD detector is clearly worse than that of the CsI-PD detector.

1. Efficiency Tests

These tests at WMU were intended to measure the efficiency of the new detectors and to ensure that the new detectors were neither failing to detect incoming protons, nor yielding false signals when no protons were detected. For this test, we placed the scintillator-PD detector and the silicon detector both at 45° from the beam, to detect elastically scattered protons of equal energies. If the scintillator-PD detector is as...
efficient as the standard silicon detector, the count rates should be the same, as long as the solid angles subtended by the two detectors are equal. We used the CsI scintillator to optimize the reverse-bias voltage of the photodiode and the pulse-shaping settings on the main amplifier. We then looked at the signals from one detector that arrived in coincidence with signals from the other, by using an electronics setup similar to that of Figure 6. Protons resulting from proton-carbon collisions were filtered out by setting upper and lower limits on the amplified detector pulse signal height. The p-p elastic peak (D) in Fig. 8 is now isolated for further tests, as shown in Fig. 10. The differences in channel number for the p-p elastic peak result from different amplifier gain settings for the Si and BGO-PD detectors.

![Graph](image)

**Fig 10 Typical coincidence tests** (a) Si gated on CsI, (b) CsI gated on Si

The data-acquisition computer was able to read only one input at a time, so the count rates for both Si and inorganic scintillator detectors could not be compared simultaneously. The count rates were determined by summing under the peaks in Fig. 10, using the same integrated beam current for each detector (as measured by the Faraday-cup beam stop). The collimator apertures for the two detectors were not the
same, but after correcting for the differences in solid angle, the CsI-PD detector counts were still ~10% lower than the counts for the silicon detector. When the positions of the two detectors were reversed, the silicon detector now showed ~10% fewer counts than the CsI-PD detector, suggesting some asymmetry in the target chamber, beyond the different sized apertures. The BGO-PD detector was barely able to discern the 5.5 MeV proton’s signal from background noise, so a measurement of its efficiency was not possible by this method.

2. Kinetic Energy-Scattering Angle Dependence Tests

When two protons collide, they cannot change their internal energies, and therefore inelastic collisions between protons are forbidden. When elastic collisions occur between the equal-mass protons, energy and momentum conservation predicts that the scattered protons will have an inverse relationship between kinetic energy and the scattering angle $\theta$. As mentioned earlier, the paths of the scattered protons will be at right angles to each other, regardless of the kinetic energy distribution between the two protons. If both detectors are at 45° from the beam direction, then the kinetic energies of the two protons will be equal. When a detector is working properly, we expect to see a dependence of energy on scattering angle in the detected protons, if the angle between the beam and the detector is varied, as in Fig. 11.
When the silicon detector was 45° from the beam, the channel number of the elastic peak (#308) is roughly double the channel number when the silicon detector was 60° from the beam (#144). For a beam energy of 8 MeV, momentum and energy conservation predicts 4 MeV protons at $\theta = 45^\circ$, 2 MeV protons at $\theta = 60^\circ$, and 6 MeV protons at $\theta = 30^\circ$. This process was repeated with the inorganic CsI and BGO detector. Using the method of coincidence with the Si detector stated in the previous section, we observed the predicted percentage shifts when varying the forward scattering angle of the CSI detector, as shown in Fig. 12a.
Fig. 12a  Dependence of p-p elastic scattering peak on scattering angle, using a CsI-PD detector

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Fig. 12b  Dependence of p-p elastic scattering peak on scattering angle (BGO-PD detector)

Fig. 12b shows a shift of the peak in the proper direction, but the BGO energy resolution is not sufficient to determine if the shift is consistent with energy and momentum conservation predictions.
As expected, the signal strength of the CsI-PD combination was greater than that for the BGO-PD detector. The CsI detector had a lower energy threshold for detection of protons, and better energy resolution. With a signal risetime of $1\mu s$, CsI is fast enough to be used as a detector in the PINTEX target chamber at the IUCF Cooler, but too slow to be part of the trigger stream. BGO’s signal risetime of $0.1\mu s$ makes it a candidate for inclusion in the trigger stream, provided the energy threshold and resolution are acceptable. At 5.5 MeV, the BGO’s kinetic energy threshold for proton detection is well below the 15 MeV requirement, although we expect this threshold to rise when using a larger BGO crystal. This is because the ratio of the surface area of the scintillator (where light can be lost) to the area of the photodiode (where light is collected) will rise. We consider the resolution between the 5.5 MeV and 11 MeV peaks to be sufficient to use BGO for the recoil detectors. The thickness of BGO needed for sufficient stopping power was calculated, and two full-size BGO scintillators grown from single crystals were ordered from Bicron Corporation, measuring as shown in Fig. 13.
3. Simulation of Expected IUCF Data

While waiting for delivery of the BGO crystals, we simulated the expected IUCF Cooler data\(^7\). A simulated graph of Forward-Scattered Proton Scattering Angle vs. Recoil Proton Kinetic Energy, with a scintillator thickness of 0.78 cm and a beam energy of 325 MeV, is shown in Fig. 14.
During p-p elastic scattering, the forward-scattered proton leaves the target chamber and enters the forward detector array in coincidence with the arrival of the recoil proton in the BGO-PD recoil detector. In Figure 14, the arrows indicate the direction of increasing recoil proton kinetic energy. When charged particles pass through solid materials, the kinetic energy lost to the scintillator depends on the incident proton’s actual path length in the material, which in turn depends on the angle of incidence of the incoming proton. In addition, the Bethe-Bloch Equation predicts that the amount of energy left behind in the scintillator per unit length traveled is inversely proportional to the proton’s instantaneous kinetic energy. In accordance with energy and momentum conservation, as the fraction of the total beam energy available to the forward-scattered proton decreases, the forward scattering angle increases and the kinetic energy of the recoil proton increases. This relationship shows in the curve...
region marked (A), where the recoil proton comes to rest in the scintillator, losing all its kinetic energy. In the (A) region, the detector’s signal height is proportional to the recoil proton’s initial kinetic energy, and units of signal height can be calibrated to MeV. At the point marked (B), the recoil proton’s kinetic energy is just equal to the scintillator’s stopping power, and still comes to rest. The projection of point B onto the x-axis is the “punch-through” energy. For recoil energies higher than the stopping power, the proton passes completely through the scintillator and retains some of its initial kinetic energy. For these “punch-through” recoil protons, the scattering angle of the forward-scattered proton continues to increase, but the signal height decreases, as shown in the curve region marked (C). Due to this punch-through effect, there are two possible energies that create the same size signal in the BGO-PD detector.

When the two BGO scintillator crystals arrived, a photodiode was attached to each with permanent optical cement (Bicron Stycast). As expected, the full-size BGO-PD detector yielded a noise signal which was a greater percentage of maximum signal height, than when using the smaller piece of BGO (a lower signal-to-noise ratio), due to light losses from its greater surface area. Using two photodiodes in parallel, in order to increase the light collection area, only lowered the signal-to-noise ratio further.
V. TESTS OF RECOIL DETECTOR IN FINAL CONFIGURATION

A. Recoil Detector Setup

The placement of the full size BGO-PD detectors in the PINTEX target chamber at IUCF, relative to the previous silicon detectors is shown in Figure 15 below. Two detectors were placed in this configuration, one below the beam, (position A in Figures 3a-3c) and one rotated 90° about the beam axis, and located to the left, as viewed from above along the beam direction (position B in Figures 3a-3c).

Besides the increased stopping power requirement, the relatively high cost of replacing radiation-damaged silicon detectors provided another reason to find an alternate type of recoil proton detector. BGO is less susceptible than silicon to permanent defects from protons passing through it. Replacing the Si detectors with
the larger but less expensive BGO scintillator resulted in a detector of similar price, without penalty in solid angle, for being farther away from the beam. The anticipated final installation of recoil detectors at IUCF was four detectors: up, down, left and right. Moving the detector position from 5cm from the beam to 12 cm from the beam results in far fewer “halo” protons striking the detector. Halo protons are those surrounding the main beam which result from scattering at an upstream portion of the beampipe or target chamber, and which have not passed through the target. By being farther from the beam, the new BGO scintillator recoil detector receives fewer halo protons than the Si detector, and thereby less radiation damage. If necessary, a small piece of lead can be added to protect the photodiode, in a manner similar to the shielding used in the WMU coincidence tests of Figure 7. One of the two recoil detectors is shown in Figure 16.

Figure 16 BGO scintillator crystal and photodiode
The reflective Mylar foil seen on the left in Figure 16 aids in light collection, and is loosely wrapped around the BGO scintillator crystal to allow air to escape while the target chamber is evacuated. For the same reason, the white coaxial cable insulation is spiral-cut. In the right side of Figure 16 the foil is removed, exposing the BGO crystal and the back of the photodiode. The two recoil detectors were installed in the PINTEX target chamber of the IUCF Cooler with aluminum brackets, as shown in Figures 3a-3c.

B. IUCF Cooler Data

1. Data Format

A Cooler experiment in 1999 afforded an opportunity to test the performance of the new recoil detectors. Proton beam energies were 325, 350 and 400 MeV. Data taken at 350 MeV beam energy, for the detector below the beam, is shown in Figure 17, and resembles the simulation of Figure 13. A problem with the optical cement on the left recoil detector interfered with light transfer from the scintillator to the photodiode, and no data from it was analyzed. Figure 17 shows a 2-dimensional spectrum of forward angle vs. recoil pulse height. The density of dots is proportional to the counted number of collision events falling within each 2-dimensional histogram bin.
As the recoil proton comes to rest in the BGO scintillator, its kinetic energy is deposited in the scintillator, converted into light photons and finally into signal pulse height. The vertical axis corresponds to the forward-scattered proton’s scattering angle channel number, as measured by the forward detector array. Each channel number corresponds to $0.1^\circ$. The horizontal channel number represents the post-amplification signal pulse height from the recoil detector, which is in turn proportional to the amount of the proton’s kinetic energy which was lost in the
scintillator. As in the simulation of Figure 13, the punch-through point (B) in Figure 17 represents protons entering the detector at the “stopping power” of the scintillator, and therefore generating the largest possible signal pulse heights at the amplifier. The densely shaded area marked (D) represents low-level noise signals from the BGO-PD detector, and regions A and C represent the non-punch-through and punch-through regions respectively, as in the simulation of Figure 13. The x-axis in Figure 17 is divided into 512 ADC channels. The y-axis corresponds to forward scattering angle $\theta$, in increments of 0.1 deg. The calibration between vertical axis channel number and forward angle is known for the forward detector array, but the calibration of horizontal axis channel number with actual recoil energy must be determined for the new detector.

2. Energy Calibration

To calibrate the recoil detector signal height channel number to the recoil proton’s initial kinetic energy, only points with a channel number above the noise region (D) in Figure 17, and below the punch-through energy (B) were chosen for analysis. To get enough counts for good statistics, the x-axis was divided into 32 “slices”. Each of these slices was projected onto the y-axis, and subjected to a Gaussian fit, using the XPAW data analysis program at IUCF, which also calculated the mean peak values and sigmas for these fits. The peak of each Gaussian fit is a y-axis channel number. Each y-axis channel corresponds to a forward $\theta$ increment of 0.1°. Slices 12-20 for the spectrum in Figure 17 are shown in Figure 18, along with the Gaussian fits.
Figure 18  X-Slice y-projections, 4 channels/slice, showing Gaussian fits

As the slices correspond with increasing pulse height in the recoil detector, the punch-through peaks seen in successive slices approach, and eventually merge with, the non-punch-through peaks. The channel number of the peak centroid was then divided by 10 to yield the actual forward angle. Using conservation of momentum and energy, a kinematics program (see Appendix A.) was used to calculate the recoil proton’s kinetic energy from the forward proton’s scattering angle (indicated by the peak centroids), for a given beam energy. Uncertainties were calculated based on the Gaussian sigmas, and corrections were made for energy losses that occurred when the proton passed through the wall of the aluminum target cell. A plot of the calculated
recoil proton kinetic energy (corrected for losses) vs. the central bin are shown in Figure 19, for the sum of all data with beam energy of 350 MeV.

![Figure 19 Calibration of MeV/channel, 350 MeV beam energy](image)

The straight line is a least-squares fit (weighted by uncertainty), and its slope gives a calibration of the inverse of the gain for the recoil detector, while the y-intercept represents the minimum energy detection threshold, or “offset”, of the detector. The offset is zero, within error, and is subsequently ignored. These values depend solely on the characteristics of the BGO-PD-preamp-amplifier combination, and should be independent of beam energy. The same procedure was used for all four data sets (beam energies 325, 350 and 400 MeV). Therefore, it was a surprising result when the values of inverse gain were different for the data sets with different beam energies, as shown in Figure 20.
If the inverse gain calibration is graphed versus the average time of the data sets (since beginning of data-taking), a decrease in pulse height over time (as read by the ADC) becomes clear, as shown in Figure 21. This effect caused the pulse height channel to decrease for the same proton energy in MeV, raising the value of inverse gain. This decrease in pulse height is shown in Figure 21, and was apparently caused by a gradual loss of gain in the recoil detector amplification, over the course of several days of data collection.
3. Energy Resolution

To find the energy resolution, we used a procedure similar to that of the previous section, but this time, the $\theta$ vs. pulse height spectra were sliced along the $\theta$ axis, and projected onto the pulse-height axis. As before, the XPAW data analysis program at IUCF calculated the Gaussian fits, mean peak values and sigmas. The peaks of the Gaussian fits were given as channel numbers, and converted into energies using the inverse gain results of the previous section. The slices were 12.5 channels each, corresponding to an angle range of $1.25^\circ$. The XPAW sigmas were a combination of the actual energy uncertainty and the spread of energies resulting from the width of the $\theta$-slice. To separate these effects, four evenly-spaced trial means were generated in the slice, around the XPAW mean. A Poisson distribution for each mean was then generated, with a trial value of sigma. When these four functions were added and the
total was scaled, it was compared to a Poisson distribution generated from the XPAW values of the mean and sigma. By adjusting the trial sigma, the total trial distribution could be made to match the XPAW distribution. An example is shown in Figure 22. Xpaw P(x, sig) refers to the distribution generated from the XPAW mean and sigma, and P4-1 through P4-4 are those generated from the trial means and trial sigma.

![Figure 22: Comparison of Poisson distributions with trial means and trial sigmas with the Poisson distribution, using the reported mean and sigma](image)

The result of using ten evenly-spaced trial means was not noticeably different from the result using four trial means, which indicated that four trial means was sufficient. For clarity, Figure 23 shows only the distribution generated from the data and the total distribution generated from the four trial means. The match between the two distributions makes them nearly appear as one.
In the above example, a reported sigma of 6.5 channels became an actual sigma of 6.3 channels. Using the energy calibrations of the previous section, the relative uncertainties of the energy measurements are 16%, 17%, and 17%, for the beam energies of 325 MeV, 350 MeV and 400 MeV, respectively.

4. Efficiency Tests

a.) Theoretical Expectation of Recoil Counts

The final test was to determine the efficiency of the recoil detector. This involved counting the recoil protons correlated to the forward-scattered protons, as a function of forward angle. This count can then be compared with theoretical predictions, for each value of beam energy.
The number of recoil protons expected to enter the BGO detector in coincidence with forward-scattered protons per second can be expressed as a function of \( \theta \):

\[
N(\theta) = T \cdot I \cdot \frac{d\sigma}{d\Omega}(\theta) \cdot d\Omega \cdot f(\theta) \cdot e_f \cdot e_r
\]

\( T \) = “target thickness”, which is a product of the target gas density and the length of the gas target, in units of area, (1 mb = 1 millibarn = \( 10^{-28} \) m\(^2\)).

\( I \) = Beam Current (in sec\(^{-1}\)).

\( d\Omega \) = solid angle subtended by the detector = sin\( \theta \) d\( \theta \) d\( \phi \)

\( d\sigma/d\Omega \) = “differential scattering cross-section”, a function of forward scattering angle \( \theta \) and beam energy, (in mb-steradian\(^{-1}\)).

\( f \) = “viewed fraction”, that portion of the target from which scattered protons can reach the target, as a function of forward angle \( \theta \).

\( e \) = efficiency of the detector (dimensionless), unknown for the recoil detector, 0.9114 for the forward detectors.

Integration of the rate \( N(\theta) \) over the data-taking time will give a total number of counts, \( C(\theta) \) as a function of \( \theta \). The product of the target thickness and the beam current is the luminosity, and is found by the 45° detectors (marked X in Figure 4).

The time-integrated luminosity contains the time integral, and is measured for each data set. Integrating \( C(\theta) \) over \( \theta \) and multiplying by d\( \phi \) will yield a total number of counts for that data set. The \( \theta \) integration was done numerically, with 1° \( \theta \) bins and used limits of integration within the region (A) of Figure 17. Since we are looking at
coincidence protons, the $\phi$ coverage of the recoil detector ($20^\circ$) can be used as the $d\phi$ for the forward detector array solid angle. Finally, dividing the measured number of counts for each data set by the total number of expected counts yields the remaining unknown: the efficiency of the recoil detector.

Figure 24 shows values for differential cross-section obtained from the SAID database, which contains previously measured cross sections, and a model for interpolating them in phase space.  

Calculation of viewed fraction depends on the geometry of the target chamber setup, as well as target density, as shown in Figure 25. The density of the target is
greatest in the center of the 1cm diameter target cell tube (where the hydrogen enters) and decreases linearly to the ends, where it is removed by the vacuum pumps.

![Viewed fraction schematic](image)

**Figure 25** Viewed fraction schematic

The paths shown by arrows are those of forward-scattered protons and recoil protons resulting from p-p elastic collisions. For the same forward angle, the vertical lines A and B represent the leftmost and rightmost positions in the target cell where the recoil proton can reach the BGO scintillator. Taking the maximum target density to be an arbitrary value, integrating the triangular target density function between the limits A and B, and dividing by the total area under the target density function, yields the “viewed fraction” of the target available to the BGO detector as a function of forward angle. The viewed fraction function is shown in Figure 26, for a beam energy of 325 MeV.
b.) Measurement of Recoil Counts

The 2-dimensional raw data spectrum of Figure 17 can be projected onto the signal height axis or the forward angle axis. Figure 27 shows the $x$-projection, counts vs. recoil signal height.

Figure 26 Viewed fraction vs. forward angle

Figure 27 Counts vs. recoil signal height, showing energy gate
The vertical line represents a software threshold, which was set to discard counts within the large noise peak on the left. A 2-d forward angle vs. recoil detector pulse height spectrum with this threshold condition applied is shown in Figure 28.

![Figure 28 2-d forward angle vs. recoil energy spectrum, above energy threshold](image)

Figure 29 shows the $y$-projection of Figure 28, a 1-dimensional spectrum of counts vs. forward angle, showing only those counts which pass the 2-d gate of Figure 27. The forward angle axis was divided into bins of 1 degree each.
Since the recoil detector lies below the target cell, detected recoil protons correlate to forward protons in the upper part of the forward array. The forward and recoil protons are coplanar with the beam, in accordance with momentum and energy conservation. Therefore, a correspondence should be seen between the $\phi$ coverage of the recoil detector and the $\phi$ range of the forward-scattered protons. The wire chambers in the forward array provide position information for the particle’s path through the wire chamber. As shown in Figure 4, there are two sets of wire chambers, separated by a known distance. Using the separation distance, and the vertical difference between the particle’s path through the two wire chambers, the forward angle is calculated. The wire chamber 2-d display shown in Figure 30 (WC2 in Fig. 4) shows the density of counts in the forward array arriving in coincidence.
with counts from the recoil detector. The blank area in the center is the beamline tube.

![Figure 30  2-d wire chamber display](image)

By inspection, a rough $\phi$-correlation of counts with the $20^\circ$ $\phi$-coverage of the recoil detector can be seen in the expected downstream region above the beam, but for precision analysis, the actual correlated counts must be separated from the uncorrelated background counts. The wire chamber axes numbers are for distances, in arbitrary units. First, 2-dimensional gates were set by hand around the regions of interest, as shown in Figure 31, the forward angle gate on the left, and the $\phi$-gate on the right. The gates are drawn slightly large, to avoid losing data.
Points that pass these two gate conditions can be projected onto the y-axis of the forward angle vs. recoil energy spectrum, yielding a 1-d spectrum of counts vs. forward angle, as shown in Figure 32.
The process is repeated, this time with the \( \phi \) gate of the same size, but reflected about a horizontal axis to a region containing only uncorrelated background counts, as shown in Figure 33.
The resulting counts vs. forward angle spectrum in Figure 34 shows significantly fewer counts, as expected.

![Figure 34 Background counts vs. forward angle](image)

Figure 34  Background counts vs. forward angle

After subtracting a smoothed version of the Figure 34 background from the counts vs. forward angle 1-dimensional spectrum of Figure 32, the data were ready to be compared to the theoretical prediction\(^9,10\) of the previous section.
C. Comparison of Measured Counts to Theoretical Expectation

Figure 35  Counts vs. forward angle, 325 MeV beam energy

Figure 36  Counts vs. forward angle, 350 MeV beam energy
Summing the measured counts and dividing by the total the expected counts over the forward-$\theta$ ranges shown in Figures 35-37, yields a value of 1.07, or roughly 100% efficiency, recalling the 5% uncertainty in the expected values.
VI. SUMMARY

A.) New Detector Performance

The purpose of this project was to develop a new recoil proton detector for nuclear scattering experiments. There were two principal uses planned for this detector. The first was to use it as a “yes or no” detector, to determine if a proton entering the forward detector array correlates with another proton entering the recoil detector, and therefore results from an elastic collision. The second use for this detector was to monitor the elastic scattering cross sections in order to continuously measure the luminosity. The threshold of detection for the BGO-PD detector was 5 MeV in the WMU accelerator tests, but in the electromagnetically “noisier” environment of the IUCF Cooler, the practical limit was 13 MeV, still below the minimum requirement of 15 MeV. The stopping power was 60 MeV for protons of normal incidence, and increased up to 70 MeV for the recoil protons entering the detector obliquely. This fulfilled the initial specification of a minimum stopping power of 40 MeV. The energy resolution and speed of the detector make it suitable for both of its planned uses. The efficiency is ≈100%, which is standard for scintillation detectors.

In addition, the new detector needed to operate in ultra-high (nanotorr) vacuum, and posses increased radiation hardness, compared to the silicon detectors. Using inorganic scintillator material and a photodiode fulfilled the high-vacuum requirement. Placing the new detector farther from the beam and giving it a correspondingly larger active area reduced the incidence of stray protons without
sacrificing the solid-angle coverage. The original specifications called for detection of protons from $\geq 50\%$ of target (“viewed fraction”), and $\geq 10\% \phi$-coverage. The resulting viewed fraction was $\approx 84\%$, and the $\phi$-coverage $\approx 11\% \ (20^\circ)$

The photodiode is similar to the silicon detectors in its vulnerability to defects caused by protons passing through, but with the new detector, the active area is the relatively radiation-damage resistant BGO material. Extra shielding for the photodiode could further reduce damage, without shadowing the forward detectors.

Since the removal of the silicon detectors from the PINTEX target chamber, the X detectors in the forward detector array have been used to monitor p-p elastic collisions. Four BGO-PD detectors mounted inside the target chamber can now perform that function over a greater solid angle.

B.) Suggestions for Further Improvements

Light transmission from the BGO scintillator crystal to the photodiode could be improved by reducing the index of refraction mismatch between the resin coating of the photodiode ($n=1.5$) and the BGO (2.0). At the time of this project, optical cements of intermediate index of refraction were unavailable. Since these cements are used primarily with photomultipliers, they are made with $n=1.5$, to match that of the glass on the face of the photomultiplier tube.

A photodiode with a larger surface area matched to the BGO crystal end-face may improve the signal, without adding as much extra noise as 2 photodiodes in parallel.

Since the preamplifier characteristics are critical to the quality of the BGO-PD detector signal, a preamp could be made or purchased which is better matched to the task.
VII. APPENDICES

A. PTRIM Program

C Program to find Theta vs. Energy Loss for BGO detector, given incident energy
C Phil Ugorowski 3/16/00
C Fine-tuning for I 8/1/00

INTEGER ITERATIONS,NTH
REAL PI,E,DE,DX,ELOSS,A,Z,B,B2,CONST,M,I,RHO,THICKNESS
REAL MASS,C,M1,M2,M3,M4,M1S,M2S,M3S,M4S,JAC3,JAC4,DTH
REAL ALPHA,N,T4,RECOILMAX,IMIN,IMAX,IINC,A1,A2,A3,RANGE
DIMENSION TITLE(40)

C BGO is Bismuth Germanium Oxide, [ Bi-4 Ge-3 O-12 ]
C 21.05% Bi, 15.79% Ge and 63.16% O
C Bi:Z=83,A=208.98 Ge:Z=32,A=72.59 O:Z=8,A=15.999
C Density is 7.13 g/cm^3 or 7130 Kg/m^3
C A = 208.98*0.2105 + 72.59*0.1579 + 15.999*0.6316 ! Average A of BGO
C Z = 83.0*0.2105 + 32.0*0.1579 + 8.0*0.6316 ! Average Z of BGO
C
Z = 524.0
A = 1245.678
RHO = 7.103 ! Density of BGO in g/(cm)^3
ALPHA = 1.4399766E-13

C Alpha is Fine Structure Constant, e^2/(4*pi*Eo) in Mev*cm
N = 6.022045E+23 ! Avagadro's Number
M = 0.511003 ! Electron mass in MeV/c^2

C I = Z*1.00E-05! Empirical Constant in MeV
THICKNESS = 1.000 ! Thickness of BGO in cm
MASS = 938.280 ! Proton mass in Mev/c^2

C All energies are in MeV

WRITE(*,100)
100 FORMAT(' Highest Recoil Energy? ')
READ(*,110) RECOILMAX

110 FORMAT(E15.5)

115 FORMAT(I5)

WRITE(*,140)
140 FORMAT(' How Many ELOSS Iterations ')
READ(*,115) ITERATIONS

C Let the parameter I vary between IMIN and IMAX, in steps of IINC

WRITE(*,155)
155 FORMAT(' IMIN ')
READ (*,110) IMIN
WRITE(*,165)
165 FORMAT(' IMAX ')
READ (*,110) IMAX
WRITE(*,175)
FORMAT(' IINC ') READ (*,110) IINC

! Steps of DX in ELOSS calculation, in cm
DX = THICKNESS/ITERATIONS
PI = ACOS(-1.0)
I = IMIN

C Fitting Parameters for RANGE
A1 = -0.00872
A2 = 0.00339
A3 = 1.57541E-04

WRITE(*,220)
210 FORMAT(5E15.5)
220 FORMAT(' I ', ' T4 ', ' X ',
1 ' RANGE ', ' ELOSS ')

C Initialize
222 T4 = 1.0

C Bethe-Bloch dE/dx, P. Ugorowski, from Krane, p. 194
225 E = T4
ELOSS = 0.0
X = 0.0
RANGE = A1 + A2*T4 + A3*T4*T4
230 B = SQRT(2.0*E/MASS)
B2 = B*B ! B = v/c
CONST = (ALPHA*ALPHA)*(4.0*PI*Z*N*RHO/(M*A))
E = E + DE ! Reduce the Remaining Energy by DE
ELOSS = ELOSS - DE ! Increment ELOSS by DE -- Note: DE < 0
470 IF (X.GE.THICKNESS) GOTO 600
X = X + DX ! Increment Range by DX in cm
IF (ELOSS.GE.T4) GOTO 500
GOTO 230
500 T4 = T4 + 1.0
IF (T4.GT.RECOILMAX) GOTO 700
GOTO 225
600 WRITE(*,210) I,T4,X,RANGE,ELOSS
700 I = I + IINC
IF (I.GE.IMAX) GOTO 800
GOTO 222
800 STOP
END

B.) TWO Program

C General two-body kinematics routine, nothing fancy.
C Input FOR001.DAT, output FOR002.DAT. PVP
C Last Revised: 14-OCT-85
C 21-MAY-91

REAL M1,M2,M3,M4,M1S,M2S,M3S,M4S,JAC3,JAC4
DIMENSION TITLE(40)
READ(1,10) TITLE
10 FORMAT(40A2)
READ(1,11) M1,M2,M3,M4 ! Rest masses, (MeV):
11 FORMAT(4F10.3) ! Beam, target, final state.
IF(M1+M2) 99,99,2
READ(1,12) T1,TH3CM,DTH,NTH
12 FORMAT(3F10.3,I5)
M1S = M1*M1 ! Masses squared.
M2S = M2*M2
M3S = M3*M3
M4S = M4*M4
E1 = M1 + T1 ! Projectile total energy,
P1 = SQRT(E1*E1 - M1S) ! momentum,
B1 = P1/E1 ! beta.
PI = ACOS(-1.)
C *** CALCULATE C.M. QUANTITIES ***
S = M1S + M2S + 2.*E1*M2
ECM = SQRT(S) ! Total energy in center of mass.
BCM = P1/(E1+M2) ! Beta cm
GCM = (E1+M2)/ECM ! Gamma cm
PCMI = P1*M2/ECM ! Initial cm momentum. (1 & 2)
E3CM = (ECM*ECM + M3S - M4S)/(2.*ECM)
IF (E3CM .LT. M3) GOTO 98
E4CM = ECM - E3CM ! Conservation of energy.
PCMF = SQRT(E3CM*E3CM - M3S) ! Final cm momentum. (3 & 4)
B3CM = PCMF/E3CM ! Individual betas.
B4CM = PCMF/E4CM
C *** CALCULATE DOMEGA3CM/DT ***
DODT = PCMI*PCMF/PI
WRITE(2,20) TITLE
20 FORMAT(1H1///1H0,T10,40A2)
WRITE(2,21)
21 FORMAT(//1H0,T14,'M1',T22,'M2',T30,'M3',T38,'M4',T46,'T1',T54,
1
'P1',T61,'BET1',T69,'ECM',T76,'BETCM',T85,'GAMCM',T93,'PCMI',
2 T101,'PCMF',T108,'DO3CM/DT')
WRITE(2,22) M1,M2,M3,M4,T1,P1,B1,ECM,BCM,GCM,PCMI,PCMF,DODT
22 FORMAT(1H0,T10,6F8.2,F8.4,F8.2,F8.4,F8.3,2F8.2,E11.4,///1H0,T6,
2 'TH3CM TH3L T3L P3L BET3L JACO3 T U'
3 ' TH4L T4L P4L BET4L JACO4 DTH3DT4'/)
RAD = PI/180.
DO 55 K=1,NTH
IF(TH3CM-180.) 50,50,98 ! Max. angle (3) is 180 degrees.
THX = TH3CM*RAD ! First cm angle in radians.
50 DO 55 K=1,NTH
IF(TH3CM-180.) 50,50,98 ! Max. angle (3) is 180 degrees.
THX = TH3CM*RAD ! First cm angle in radians.
C *** CALCULATE LAB QUANTITIES ***
E3 = GCM*(E3CM + BCM*PCMF*COS(THX)) ! Straight Lorentz.
E4 = GCM*(E4CM - BCM*PCMF*COS(THX))
IF(E3*E3-M3S) 55,7,7
IF(E4*E4 - M4S) 55,8,8
P3 = SQRT(E3*E3 - M3S)
P4 = SQRT(E4*E4 - M4S)
B3 = P3/E3
B4 = P4/E4
T3 = E3-M3
T4 = E4-M4
IF(T3*T4) 55,9,9
9 CONTINUE

C *** CALCULATE INVARIANTS ***
T = M2S + M4S - 2.*M2*E4
U = M1S + M2S + M3S + M4S - S - T

C *** CALCULATE LAB ANGLES AND DTH3/DTH4 ***
TH3 = ATAN((PCMF*SIN(THX))/(GCM*(PCMF*COS(THX)+BCM*E3CM)))
TH4 = ATAN((PCMF*SIN(THX))/(GCM*(-PCMF*COS(THX)+BCM*E4CM)))
TH3D = ATAN( (PCMF*SIN(THX+.001))/ (GCM*(PCMF*COS(THX+.001)+BCM*E3CM) ) )
TH4D = ATAN( (PCMF*SIN(THX+.001))/ (GCM*(-PCMF*COS(THX+.001)+BCM*E4CM) ) )
PT = ABS((TH3-TH3D)/(TH4-TH4D))

C *** CORRECT FOR ATAN RETURNING VALUE BETWEEN + OR - PI/2 ***
IF(TH3) 3,4,4
3 TH3 = PI + TH3
4 IF(TH4) 5,6,6
5 TH4 = PI + TH4

C *** CALCULATE JACOBIANS DOMEGAL/DOMEACM ***
6 THY = PI - THX
IF(THX) 32,31,32 ! Don't divide by zero.
31 JAC3 = 999.
GOTO 33
32 JAC3 = SIN(TH3)**3*GCM*(1. + BCM*COS(THX)/B3CM)/SIN(THX)**3
33 IF(THY) 35,34,35
34 JAC4 = 999.
GOTO 39
35 JAC4 = SIN(TH4)**3*GCM*(1. + BCM*COS(THY)/B4CM)/SIN(THY)**3
39 TH3 = TH3/RAD
TH4 = TH4/RAD
WRITE(2,30)TH3CM,TH3,T3,P3,B3,JAC3,T,U,TH4,T4,P4,B4,JAC4,PT
30 FORMAT(3X,F8.2,F8.3,2F7.1,2F8.4,2(1X,E11.4),F8.3,2F8.4,2F8.4,F8.3)

55 TH3CM = TH3CM + DTH ! Next angle
98 CONTINUE
GO TO 1
99 CONTINUE
END

C.) TWO-PTRIM Program

C --------------------------------------------------------

C

C

C 65
C Program to find Theta vs. Energy Loss for BGO detector, given incident energy
C Phil Ugorowski 3/16/00
C Fine-tuning for I 8/1/00

INTEGER ITERATIONS,NTH
REAL MASS,C,M1,M2,M3,M4,M1S,M2S,M3S,M4S,JAC3,JAC4,DTH
REAL ALPHA,N,T4,A1,A2,A3,RANGE
DIMENSION TITLE(40)

C BGO is Bismuth Germanium Oxide, [ Bi-4 Ge-3 O-12 ]
C 21.05% Bi, 15.79% Ge and 63.16% O
C Density is 7.13 g/cm^3 or 7130 Kg/m^3
A = 1.245678E+03 ! Atomic Weight of BGO
Z = 5.240E+02 ! Atomic Number of BGO
RHO = 7.103 ! Density of BGO in g/(cm)^3
ALPHA = 1.4399766E-13

C Alpha is Fine Structure Constant, e^2/(4*pi*Eo) in Mev*cm
N = 6.022045E+23 ! Avagadro's Number
M = 0.511003 ! Electron mass in MeV/c^2
I = 24.09 ! Empirical Constant in MeV
THICKNESS = 1.000 ! Thickness of BGO in cm
MASS = 938.280 ! Proton mass in MeV/c^2
C All energies are in MeV, all masses are in MeV/c^2

C Fitting Parameters for RANGE
A1 = -0.00872
A2 = 0.00339
A3 = 1.57541E-04

C---------------------------------------------------------------
C General two-body kinematics routine, nothing fancy.
C Input FOR001.DAT, output FOR002.DAT. PVP
C Last Revised: 14-OCT-85
C 21-MAY-91
C Added 7/31/00 by P. Ugorowski
1 READ(1,10) TITLE
10 FORMAT(40A2)
READ(1,11) M1,M2,M3,M4 ! Rest masses, (MeV):
11 FORMAT(4F10.3) ! Beam, target, final state.
IF(M1+M2) 99,99,2
2 READ(1,12) T1,TH3CM,DTH,NTH,ITERATIONS
12 FORMAT(3F10.3,I5,I9) ! Masses squared.
DX = THICKNESS/ITERATIONS ! Normal path length component
C DL = Actual path length
M1S = M1*M1
M2S = M2*M2
M3S = M3*M3
M4S = M4*M4
E1 = M1 + T1 ! Projectile total energy,
P1 = SQRT(E1*E1 - M1S) ! momentum,
B1 = P1/E1  !  beta.
P1 = ACOS(-1.)

C *** CALCULATE C.M. QUANTITIES ***
S = M1S + M2S + 2.*E1*M2
ECM = SQRT(S)  !  Total energy in center of mass.
BCM = P1/(E1+M2)  !  Beta cm
GCM = (E1+M2)/ECM  !  Gamma cm

PCMI = P1*M2/ECM  !  Initial cm momentum.  (1 & 2)
E3CM = (ECM*ECM + M3S - M4S)/(2.*ECM)
IF (E3CM .LT. M3) GOTO 98
E4CM = ECM - E3CM  !  Conservation of energy.
PCMF = SQRT(E3CM*E3CM - M3S)  !  Final cm momentum.  (3 & 4)
B3CM = PCMF/E3CM  !  Individual betas.
B4CM = PCMF/E4CM

C *** CALCULATE DOMEGA3CM/DT ***
DODT = PCMI*PCMF/PI
WRITE(2,20) TITLE
20 FORMAT(1H1///1H0,T10,40A2)
WRITE(2,21)
21 FORMAT(//1H0,T14,'M1',T22,'M2',T30,'M3',T38,'M4',T46,'T1',T54,
1 'P1',T61,'BET1',T69,'ECM',T76,'BETCM',T85,'GAMCM ',T93,'PCMI',
2 T101,'PCMF',T108,'DO3CM/DT')
WRITE(2,22) M1,M2,M3,M4,T1,P1,B1,ECM,BCM,GCM,PCMI,PCMF,DODT
22 FORMAT(1H0,T10,6F8.2,F8.4,F8.2,F8.4,F8.3,2F8.2,E11.4,///1H0,T6,
2 'TH3CM   TH3L   T3L   T   ',
3 '   TH4L   T4L   X   RANGE   ELOSS'/)
RAD = PI/180.
DO 55 K=1,NTH
IF(TH3CM-180.) 50,50,98  !  Max. angle (3) is 180 degrees.
50 THX = TH3CM*RAD  !  First cm angle in radians.
55 CONTINUE

C *** CALCULATE LAB QUANTITIES ***
E3 = GCM*(E3CM + BCM*PCMF*COS(THX))  !  Straight Lorentz.
E4 = GCM*(E4CM - BCM*PCMF*COS(THX))
IF(E3*E3-M3S) 55,7,7
7 IF(E4*E4 - M4S) 55,8,8
8 P3 = SQRT(E3*E3 - M3S)
P4 = SQRT(E4*E4 - M4S)
B3 = P3/E3
B4 = P4/E4
T3 = E3-M3
T4 = E4-M4
IF(T3*T4) 55,9,9
9 CONTINUE

C *** CALCULATE INVARIANTS ***
T = M2S + M4S - 2.*M2*E4
U = M1S + M2S + M3S + M4S - S - T

C *** CALCULATE LAB ANGLES AND DTH3/DTH4 ***
\[
\begin{align*}
\text{TH3} &= \text{ATAN}\left(\frac{\text{PCMF} \cdot \text{SIN}(\text{THX})}{\text{GCM} \cdot (\text{PCMF} \cdot \text{COS}(\text{THX}) + \text{BCM} \cdot \text{E3CM})}\right) \\
\text{TH4} &= \text{ATAN}\left(\frac{\text{PCMF} \cdot \text{SIN}(\text{THX})}{\text{GCM} \cdot (-\text{PCMF} \cdot \text{COS}(\text{THX}) + \text{BCM} \cdot \text{E4CM})}\right) \\
\text{TH3D} &= \text{ATAN}\left(\frac{\text{PCMF} \cdot \text{SIN}(\text{THX} + .001)}{\text{GCM} \cdot (\text{PCMF} \cdot \text{COS}(\text{THX} + .001) + \text{BCM} \cdot \text{E3CM})}\right) \\
\text{TH4D} &= \text{ATAN}\left(\frac{\text{PCMF} \cdot \text{SIN}(\text{THX} + .001)}{\text{GCM} \cdot (-\text{PCMF} \cdot \text{COS}(\text{THX} + .001) + \text{BCM} \cdot \text{E4CM})}\right) \\
\text{PT} &= \text{ABS}\left(\frac{\text{TH3} - \text{TH3D}}{\text{TH4} - \text{TH4D}}\right)
\end{align*}
\]

**C**  
*** CORRECT FOR ATAN RETURNING VALUE BETWEEN + OR - PI/2 *** 

\[
\begin{align*}
\text{IF}(\text{TH3}) & \text{ 3,4,4} \\
\text{TH3} &= \pi + \text{TH3} \\
\text{IF}(\text{TH4}) & \text{ 5,6,6} \\
\text{TH4} &= \pi + \text{TH4}
\end{align*}
\]

**C**  
*** CALCULATE JACOBIANS DOMEGAL/DOMEGACM *** 

\[
\begin{align*}
\text{THY} &= \pi - \text{THX} \\
\text{IF}(\text{THX}) & \text{ 32,31,32} \text{ ! Don't divide by zero.} \\
\text{JAC3} &= 999. \\
\text{GOTO} 33 \\
\text{JAC3} &= \text{SIN}(\text{TH3})**3 \cdot \text{GCM} \cdot (1. + \text{BCM} \cdot \text{COS}(\text{THX}) / \text{B3CM}) / \text{SIN}(\text{THX})**3 \\
\text{IF}(\text{THY}) & \text{ 35,34,35} \\
\text{JAC4} &= 999. \\
\text{GOTO} 39 \\
\text{JAC4} &= \text{SIN}(\text{TH4})**3 \cdot \text{GCM} \cdot (1. + \text{BCM} \cdot \text{COS}(\text{THY}) / \text{B4CM}) / \text{SIN}(\text{THY})**3 \\
\text{TH3} &= \text{TH3} / \text{RAD} \\
\text{TH4} &= \text{TH4} / \text{RAD}
\end{align*}
\]

**C**  

=================================================================

**C**  
Bethe-Bloch dE/dx, P. Ugorowski, from Krane, p. 194

\[
\begin{align*}
\text{E} &= T4 \\
\text{ELOSS} &= 0.0 \\
\text{X} &= 0.0 \\
\text{RANGE} &= A1 + A2 \cdot T4 + A3 \cdot T4 \cdot T4 \\
\text{DL} &= \text{DX} / \text{SIN}(\text{TH3L}) \\
\text{B} &= \text{SQRT}\left(\frac{\text{E} + \text{E}}{\text{MASS}}\right) \\
\text{B2} &= \text{B} \cdot \text{B} \text{ ! B = v/c} \\
\text{CONST} &= (\text{ALPHA}^2 \cdot \text{ALPHA}) \cdot (4.0 \cdot \text{PI} \cdot \text{Z} \cdot \text{N} \cdot \text{RHO} / (\text{M} \cdot \text{A})) \\
\text{DE} &= \left(\text{CONST} / \text{B2}\right) \cdot \left(\text{LOG}\left(2.0 \cdot \text{M} \cdot \text{B2} / 1\right) - \text{LOG}\left(1 - \text{B2} - \text{B2}\right) \cdot \text{DL}\right) \\
\text{E} &= \text{E} + \text{DE} \text{ ! Reduce the Remaining Energy by DE} \\
\text{IF} (\text{E.LT.}(0.0)) & \text{ GOTO 500} \\
\text{ELOSS} &= \text{ELOSS} - \text{DE} \text{ ! Increment ELOSS by DE -- Note: DE < 0} \\
\text{IF} (\text{X.GE.RANGE}) & \text{ GOTO 500} \\
\text{IF} (\text{X.GE.THICKNESS}) & \text{ GOTO 500} \\
\text{X} &= \text{X} + \text{DX} \text{ ! Increment Range by DX in cm} \\
\text{GOTO} 230 \\
\text{WRITE}(2,30)\text{TH3CM,TH3,T3,T,Th4,T4,X,RANGE,ELOSS} \\
\end{align*}
\]

=================================================================

**C**  

\[
\begin{align*}
\text{FORMAT}(3X,F8.2,F8.3,F7.1,1X,E11.4,F8.3,F8.4,3E15.5) \\
\text{TH3CM} &= \text{TH3CM} + \text{DTH} \text{ ! Next angle} \\
\text{CONTINUE} \\
\text{GO TO 1} \\
\text{CONTINUE}
\end{align*}
\]

END
Note: The empirical constant (I) was found by varying its value and comparing the predicted stopping power to that predicted by SRIM$^{11}$
VIII. REFERENCES


[7] See Appendices A.-C. Expected IUCF Data were generated by TWO-PTRIM, which was built up from TWO, written by P. Pancellia, and PTRIM, written by P. Ugorowski


