“Phoswich Wall”: A charged-particle detector array for inverse- kinematic reactions with the Gretina/GRETA γ -ray arrays

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Abstract

A high-efficiency, forward-hemisphere detector system for light charged particles and low- Z heavy ions, as obtained in an accelerator experiment, is described. It consists of four 8x8 pixel multianode photomultiplier tubes with 2.2-mm thick CsI(Tl) and 12- μ m thick fast-plastic scintillation detectors. Its phoswich structure allows individual Z resolution for ^1H , ^4He , ^7Li , $^4\text{He}+^4\text{He}$, ^9Be , ^{11}B , ^{12}C , and ^{14}N ions, which are target-like fragments detected in strongly-inverse kinematics. The device design has been optimized for use with a 4π γ -ray array, and the main applications are transfer reactions and Coulomb excitation. A high-angular resolution for the detection of the target-like fragments is achieved which permits angular distributions to be measured in the rest frame of the projectile-like fragment with a resolution of $\sim 2^\circ$.

Keywords:

Inverse-kinematic reactions, Phoswich technique, Multianode detector, Pulse-shape discrimination, ASIC-chip readout

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1. Introduction

The γ -ray detection capability of the present-generation 4π arrays, like Gammasphere, [1] has been enhanced greatly by inserting auxiliary detector systems in the experimental setup. Early examples are the Dwarf Ball, the Dwarf Wall [2] and the Microball [3], aimed at detecting light-charged particles with a nearly 4π solid-angle coverage. Another example is HERCULES [4], aimed at selecting evaporation-residue trans-lead nuclei in the presence of a large fission background. These arrays have been designed for normal-kinematic fusion reactions, in which the heavy-ion projectile is lighter than the target. For binary reactions such as Coulomb excitation (Coulex) and nucleon transfer, and typically with a symmetric projectile-target combination, CHICO [5] played an important role as another auxiliary detector for Gammasphere. These detector combinations have been very successful in delineating weak sequences, indicative of excitation modes and/or exotic shapes at high spin, of many nuclei across the chart of nuclides.

In recent years great success has been made in accelerating radioactive projectiles of both neutron-rich and proton-rich species, known as rare-isotope beams (RIB's). In these accelerator experiments the projectile is usually heavier than the target and the structural information desired relates to the projectile or a projectile-like fragment (PLF). In addition to the PLF level structure (level energies, spins, and parities), spectroscopic information of interest includes asymptotic normalization coefficients, spectroscopic fac-

tors, lifetimes, and $B(\sigma\lambda)$ values. There are two classes of RIB experiments, using either “fast” or reaccelerated beams. The latter have energies of 4-7 MeV/u, which are at least a factor of 10 lower than the “fast” beam energies. Accordingly, “fast” and reaccelerated beam experiments are associated with considerably different degrees of forward focussing of the reaction products. In the present work reaccelerated beams and the instruments useful in this class of experiments are mentioned, in particular the recently built charged-particle detection devices, used in binary-reaction studies, such as HELIOS [6], ORRUBA [7] and CHICO-2 [8]. The latter two can be inserted in Gammasphere, Digital Gammasphere [9], or Gretina [10]. These detectors have their advantages and limitations as is also the case for the Phoswich Wall (PW), the new device that is discussed hereafter.

Benchmark experiments for the PW are found in Refs. [11, 12]. In those experiments, single-nucleon transfer, for example in the $^{13}\text{C}(^{134}\text{Te}, ^{135}\text{Te})^{12}\text{C}$ and $^9\text{Be}(^{136}\text{Te}, ^{137}\text{Te})^8\text{Be} \rightarrow 2\alpha$ reactions, have been studied by measuring correlations between target-like fragments (TLF’s) and PLF γ rays. Specifically, particle- γ and particle- γ - γ coincidences have been recorded, using a setup that comprised a CsI(Tl) and a Ge array. Another type of experiment that should benefit from the PW uses break up of weakly bound nuclei like ^7Li as targets. Here triton transfer to the projectile is of interest. This reaction has been used, to some extent, in normal kinematics (see Refs. [13, 14]). Some of the key issues in both types of experiments are: (i) the ability to study strongly inverse-kinematic reactions with high efficiency, and (ii) a high degree of selectivity for various reaction channels. The latter requirement ensures that a variety of targets can be used and thus different reaction exit

channels can be exploited.

To elaborate on these points, *first* note that a high resolution γ -ray array is often required due to the high density of PLF excited states. This is the case for the nuclei in the nickel region and heavier. *Second*, when using strongly inverse-kinematic reactions, experimental limitations arise from the fact that the small-angle angular distributions in the PLF rest frame correspond to large laboratory angles for the TLF's ($\theta_{Lab,TLF}$ approaching 90°). At these angles, however, the energies of the TLF are low and in some cases may prohibit the detection of the fragment. The PLF's span is a very limited angular range in the laboratory and, thus, are not detected and exit the detector system. In fast-beam experiments, the PLF's are detected in a spectrograph system downstream, and represent a special case: only reaction-channel identification is provided. In contrast, the present method provides the information from detecting the energy, and polar (θ), and azimuthal (ϕ) angles of the TLF as accurately as possible, in order to determine detailed properties of the PLF. *Third*, in transfer-reaction studies one often has to deal with the significantly stronger Coulex channel and it may be desirable to suppress Coulex by gating uniquely on the TLF. This is possible for some projectile-target combinations (neutron transfer from a ^9Be target to a projectile and proton transfer or pickup by the PLF).

The PW helps minimize or eliminate most of the difficulties discussed above. The PW was designed for optimal performance in strongly inverse-kinematic reactions. Near-symmetric reactions could also be accommodated; in particular, certain fusion-evaporation reactions could benefit from the PW.

The Phoswich Wall consists of an array of four multianode photomul-

tiplier tubes (PMT's). Each has 8×8 anode pixels and 52×52 mm² outer dimensions, and an active area of 49×49 mm² (Hamamatsu H8500). The active area is covered by a 2.2-mm thick CsI(Tl) scintillator with a front layer of ~ 12 - μ m (~ 1.2 -mg/cm²) thick fast-plastic scintillator. The PMT's have been arranged in a tilted geometry and can cover the forward range of angles $\theta_{Lab,TLF} = 10^\circ$ to 72° . The arrangement fits in a small scattering chamber that can be placed in the central cavity of the Gammasphere or Gretina array.

The signal processing has the following main features. The pixel signals are split and one branch is digitized by a set of 32 8-channel "pulse-shape-capable" ASIC chips (similar to the one of Ref. [15]). The second branch is processed by constant-fraction discriminators (CFD's) and is used to provide the trigger to the charge integrating chips. Three gates and their delays are applied: one for the fast scintillator A and two that sample the CsI(Tl) part of the signal and are called "early" B and "late" C , respectively. In addition, a timing signal T is provided in the data stream. The device has a VME based acquisition system that allows for interfacing with an array like Gretina.

The geometrical design of the PMT together with the finite thickness of the detector layers leads to a larger signal from the anode pixel *below* the position hit by a particle, and to smaller signals from the neighboring faces, edges, and corner pixels. This effect, termed "cross talk" (CT), is optical in nature. The analysis takes advantage of the fraction of the CT signals to each face-neighbor pixel to derive sub-pixel position resolution: information within 1×1 mm² out of the 6.08×6.08 mm² pixel size can be

obtained. This translates into an angular resolution of $\Delta\Theta_{CoM,PLF} \sim 2^\circ$ for the angular distribution of the PLF in its rest frame.

2. The detection system

2.1. Design requirements

The design criteria for a high-efficiency charged-particle detection device are based on the physics requirements that it will address. In the present case the reaction types of primary interest are transfer and Coulex binary reactions in strongly inverse kinematics (like those discussed in Sec. 1). In order to achieve a good selectivity for a variety of excited states in a given nucleus, particle- γ coincidences must be measured. Thus, the device is designed for optimum use in conjunction with Gammasphere or Gretina/GRETA. This means that the performance of the γ -ray array should not be affected much, which requires that the inserted mass be minimal to avoid degradation in the γ -ray response due to low-energy absorption and Compton scattering.

The detailed design requirements are listed below:

- (i) *Good light charged-particle identification (PID)*: A separation of α particles and protons down to energies of a few MeV should be achievable.
- (ii) *Z resolution for low-Z and low-kinetic energy ions*: The particles and ions of interest are ^1H , ^4He , ^7Li , ^9Be , ^{11}B , ^{13}C , and ^{14}N . Typical reactions for which such Z resolution ought to be achieved are $^{13}\text{C}(^{136}\text{Xe}, ^{137}\text{Xe})^{12}\text{C}$ or $^{11}\text{B}(^{136}\text{Xe}, ^{137}\text{Cs})^{10}\text{Be}$.
- (iii) *Large solid angle coverage*. For strongly inverse-kinematic reactions an $\approx 1.5\pi$ coverage of the forward hemisphere is useful (see Sec. 2.2.1).

(iv) *Discrimination between transfer products and Coulex in selected cases:*

The selected cases depend on the choice of the target. For example, in the reaction ${}^9\text{Be}({}^{136}\text{Xe}, {}^{137}\text{Xe}){}^8\text{Be} \rightarrow 2\alpha$ with nearly immediate break up of the ${}^8\text{Be}$ into two α particles, gating on the 2α channel eliminates Coulex γ rays. Other possibilities may involve proton-transfer reactions like ${}^{11}\text{B}({}^{136}\text{Xe}, {}^{137}\text{Cs}){}^{10}\text{Be}$ where one should be able to eliminate the Coulex lines by appropriate particle gating provided that a distinction between ${}^{11}\text{B}$ and ${}^{10}\text{Be}$ can be made.

(v) *Compact size and small total mass:* This is needed to reduce degradation of the γ -ray spectra due to the Compton background and maintain a high Ge γ -peak efficiency. The device should be small enough to fit in the cavity of Gretina and Gammasphere.

(vi) *Good TLF position resolution:* This will make possible detailed angular-distribution studies for the PLF's in their rest frame by virtue of the binary nature of the reactions of interest.

(vii) *Good timing resolution:* For accelerators that provide beam timing with ~ 1 ns pulse width, it should be possible to identify low-energy charged particles by time of flight, provided that there is a considerable flight path (~ 5 cm target to detector distance).

(viii) *High segmentation:* This is crucial for angular distributions of the PLF in its rest frame. A resolution $\Delta\theta_{Lab,TLF}$ of $\sim 1^\circ$ (corresponding to $\Delta\Theta_{CoM,PLF} \sim 2^\circ$) should be achievable for a $\Theta_{CoM,PLF}$ range from $\sim 30^\circ$ to $\sim 160^\circ$.

(ix) *Good gain stability with counting rate, temperature and time:* This is important for high-quality data.

- (x) *Radiation hardness:* Radiation damage due to the Rutherford scattering of the light TLF's that can seriously affect the large-angle portion of the detection system.
- (xi) *Versatility:* The device should be compatible with an upstream plunger assembly. This will allow for life-time measurements by the recoil-distance method.

The above requirements limit the choice of detector material. Since this device is designed for reactions at projectile energies of $\sim 4\text{-}7$ MeV/u the requirement of Z identification for light TLF's essentially eliminates Si as the choice material. Very thin, position sensitive, large-area Si wafers (for ΔE measurements) are not easy to fabricate, are fragile, and may suffer radiation damage. As an example, in the 560 MeV $^{136}\text{Xe} + ^{13}\text{C} \rightarrow ^{137}\text{Xe} + ^{12}\text{C}$ reaction a typical 65- μm thick Si stops ≤ 51 MeV ^{12}C for $\theta_{Lab,TLF} \lesssim 58^\circ$, which requires $\Theta_{CoM,PLF}$ to be larger than 65° . In contrast, the PW allows the identification of ^{12}C to $\sim 72^\circ$, with the smallest $\Theta_{CoM,PLF}$ being 40° (8.9 MeV ^{12}C ions stop in 1.15 mg/cm² fast plastic).

The phoswich arrangement of the present device consists of 2.2-mm thick CsI(Tl) scintillators (E detectors), in front of which are 1.13 - 1.50 mg/cm² fast-plastic scintillators (ΔE detectors). The CsI(Tl) thickness is sufficient to stop the TLF products of interest. It contributes to the optical CT between the central-hit pixel and its neighbor pixels, but it is minimized by the material thickness. As with the Microball, the thallium concentration is 1200 ppm. This provides excellent PID resolution by pulse shape discrimination (PSD) between α particles and protons. However, CsI(Tl) does not have PID capability for light heavy ions with $Z > 3$ at the low energies that are antic-

ipated in the present applications. Therefore, the fast-plastic scintillator is important, since it provides additional selectivity for the TLF ions according to their atomic number Z .

The CsI(Tl) scintillator has two decay components: a short one with a decay time $\tau = 0.4 - 1.0 \mu\text{s}$, and a long one with $\tau = 7 \mu\text{s}$. It is the long one that provides a counting-rate limitation due to pileup. In this instance, the present concept is different from the Microball. In that case the so-called tail gate was placed at $8 \mu\text{s}$ (as a consequence of the photodiode readout) [3]. Since PMTs are used here, the “late” $1.8\text{-}\mu\text{s}$ wide gate is placed at $1.0 \mu\text{s}$ (closing at $2.8 \mu\text{s}$), as a condition for optimum PID. Consequently, about three times the counting rate can be taken, for the same amount of pileup per unit solid angle, as for the Microball. Since pileup is now less severe and the PW is more segmented than the Microball, a decrease in segmentation with increasing θ (like the Microball) is not required.

The thickness of the CsI(Tl) scintillator has additional implications for the performance of the device discussed hereafter. For pixels at the shortest distance from the target, protons and α -particles with energies up to 21.7 and 85.6 MeV, respectively, are stopped neglecting the small energy loss due to the fast-plastic scintillators. For particles at larger angles the CsI(Tl) thickness increases from 2.2 to 3.3 mm, where the proton and α -particle ranges correspond to maximum energies of 29 and 115 MeV, respectively.

The minimum and maximum angles at which the TLF can be detected are determined as follows. (a) The minimum energy of a TLF that can be detected and identified translates into an upper-limit angle. (As 90° is approached the TLF energy goes below the detection limit, i.e., the TLF stops

Figure 1: Kinematics plot for the $^{136}\text{Xe}+^{13}\text{C}\rightarrow^{137}\text{Xe}+^{12}\text{C}$ reaction at 560 MeV with ^{137}Xe and ^{12}C in their ground state (thin lines), and the products sharing 2.0-MeV (dashed lines), and 6.439-MeV excitation energy (thick lines). The blue lines are the detected TLF energies in MeV as a function of the TLF laboratory angle. The red lines are the ^{137}Xe angles in the PLF rest frame for the same abscissa quantity. The vertical arrows indicate the minimum and maximum TLF laboratory angles covered by the detector. The vertical line with the arrow pointing to the right indicates the range of $\theta_{\text{Lab,TLF}}$ for “safe” Coulomb excitation (see text).

in the ΔE detector). (b) At the forward TLF angles the corresponding kinetic energy becomes so high that thicker ΔE and E detectors are needed to stop the particles. However, such thicker ΔE detectors would stop the TLF's detected at large angles and thus forbid PID of those fragments. Clearly, a compromise is needed with some flexibility for the choice of the fast-plastic thickness. In the present device very thin fast-plastic scintillators appear to be adequate. For the E detectors in the phoswich arrangement CsI(Tl) with 2.2-mm thickness appears to be a good compromise: it can stop any light heavy-ion fragment of interest as well as the α particles and protons from most of the reactions. The limited intrinsic energy resolution of CsI(Tl), compared with Si, is not a major impairment because the kinematic-broadening contribution to the peak width is significant. This diminishes the advantage of the intrinsic energy resolution of Si.

2.2. Characteristics of the Phoswich Wall

2.2.1. Kinematics and geometry considerations

The PW was designed for strongly inverse-kinematic reactions, but it is also useful for more symmetric reactions. Kinematics strongly depend on the Q values of the binary reactions, and two reactions have been chosen as examples. The first one is a neutron transfer to the PLF, namely

$$^{136}\text{Xe} + ^{13}\text{C} \rightarrow ^{137}\text{Xe} + ^{12}\text{C}, E_{lab} = 560 \text{ MeV}, \quad (1)$$

$$Q_{gg} = -0.921 \text{ MeV}. \quad (2)$$

Here Q_{gg} is the Q value for the ground-state to ground-state reaction. Two cases are considered: (i) an excitation of the PLF, leading to the population of states in the 2-MeV energy range (e.g. the $13/2^+$ state at 1753 keV [12]),

and (ii) an additional excitation of the TLF at 4.439 MeV (2_1^+ state state in ^{12}C [16]). Figure 1 shows the important kinematics parameters $\theta_{Lab,TLF}$, $E_{Lab,TLF}$ (both measured), and $\Theta_{CoM,PLF}$ (derived). The $E_{Lab,TLF}$ value can also be calculated from kinematics for comparison.

Figure 2: Similar to Fig. 1, but for the reaction $^{136}\text{Xe} + ^{11}\text{B} \rightarrow ^{137}\text{Cs} + ^{10}\text{Be}$. The solid and dashed lines correspond to the ground and an excited state at 2 MeV, respectively.

The TLF kinetic energy for a 2-MeV excitation of the PLF [case (i)] and the ground-state reaction differ by about 3.7 MeV throughout the TLF energy span. The most forward $\Theta_{CoM,PLF}$ angle covered is 38.1° for a 2-MeV excitation and 41.2° for the ground state. The corresponding minimum ki-

Figure 3: Comparison of TLF energy spectra calculated for 560 MeV ^{136}Xe on ^{11}B . The solid curves are for TLF's in their ground states and the reactions are from top to bottom: proton transfer to the target (green, $Q_{gg} = 6.03$ MeV), Rutherford scattering (solid red, $Q_{gg} = 0$), proton pick up by the ^{136}Xe projectile leading to the ^{137}Cs ground state (solid blue, $Q_{gg} = -3.82$ MeV), and neutron pickup by the projectile (black, $Q_{gg} = -7.42$ MeV). The dashed curves are for the TLFs at 2 MeV of excitation and the same reaction channels.

netic energies for the TLF are 21.1 and 17.8 MeV for the ground and 2-MeV states, respectively. For the indicated range of detection there is only one kinematic solution unless the excitation energy exceeds ~ 3.5 MeV [case(ii)]. Here only the high-energy branch of the $E_{Lab,TLF}$ parameter and the corresponding $\Theta_{CoM,PLF}$ values are considered; the low-energy branch would be below the detection threshold. The TLF kinetic energies for an additional excitation (leading to $Q = -7.36$ MeV) and a 2-MeV excitation of the TLF differ by more than 7 MeV. The differences in the kinetic energies allow for selection of the events corresponding to a PLF excitation by appropriate gating.

For a reaction like the present one, the PLF rest frame angular distribution is calculated to span from $\sim 38^\circ$ to $\sim 160^\circ$. This ought to be sufficient for measuring the angular distribution.

From the slope of the $\Theta_{CoM,PLF}$ vs. $\theta_{Lab,TLF}$ function it is clear that for a 1° resolution in $\theta_{Lab,TLF}$ one obtains $\sim 2^\circ$ resolution in $\Theta_{CoM,PLF}$. Consequently the desired PLF rest-frame angular resolution determines the required TLF $\Delta\theta$, which leads to the required position resolution in mm for the detection system (~ 1 mm for 55-mm target to detector distance).

The phoswich arrangement offers the opportunity to study proton transfer and pickup reactions. This is discussed in a second example, namely

$$^{136}\text{Xe} + ^{11}\text{B} \rightarrow ^{137}\text{Cs} + ^{10}\text{Be}, E_{lab} = 560 \text{ MeV}, \quad (3)$$

$$Q_{gg} = -3.823 \text{ MeV}. \quad (4)$$

In Fig. 2 the kinematics for this reaction are presented, but only the ground state of the PLF, ^{137}Cs , and an excitation of 2 MeV are considered.

Note that the double-kinematic solution is present now due to a more negative Q value for 2 MeV excitation. It is worth pointing out that a 2-MeV excitation leads to an ~ 4 MeV difference in the TLF kinetic energy for all angles.

The PW allows for simultaneous measurements of transfer and Coulex reactions. In the case of Coulex, the bombarding energy should not exceed 85% of the Coulomb barrier (“safe” Coulex). Here the key parameter is the value $\theta_{Lab,TLF}$ above which “safe” Coulex occurs. In Figures 1 and 2 the vertical long lines with the arrow pointing to the right indicate the respective “safe” $\theta_{Lab,TLF}$ angle for ^{13}C and ^{11}B targets and a 560 MeV ^{136}Xe beam: $\theta_{Lab,TLF} > 55^\circ$ (^{13}C) and $> 40^\circ$ (^{11}B). If more Coulex data are needed, then lowering the projectile energy increases the angular range for safe Coulex.

It is interesting to plot the observable kinetic energies for single nucleon transfer, elastic scattering and Coulex reactions as a function of the TLF angles. Such a comparison is presented in Fig. 3 for the $^{136}\text{Xe}+^{11}\text{B}$ reaction. As indicated in the legend, TLF products corresponding to PLFs in their ground state (solid lines) and an assumed excitation energy of 2 MeV (dashed lines) are considered. For TLF angles between 10° and 40° the spread in kinetic energy for the various reactions seems to be sufficiently large to allow event-by-event gating and, thus, suppress unwanted channels. Note that by requiring a coincidence between TLF’s and γ rays the ground states are suppressed. The strong elastic Rutherford scattering is then also suppressed and it will appear in the data only as random coincidences. However, this does not reduce the counting-rate load of the detectors. Recording only coincidences provides cleaner angular distributions for the channels of interest.

It should be noted that for single-nucleon transfer the difference in kinetic energy between reactions is due to the Q values and the different masses involved. These differences are magnified at the forward angles (by a factor of ~ 2.7), but are closer at $\sim 70^\circ$.

It is worthwhile to compare the angular resolution $\Delta\theta$ of the PW with that of the Microball. As an example, the 3rd ring of the Microball is chosen: $\theta = 32 \pm 8^\circ$ (half angle $\Delta\theta = 8^\circ$). In the PW $\Delta\theta = 2.8^\circ$ to 3.5° (half angle) for a pixel: subpixel position resolution (see Sec. 2.6) is ignored in this comparison.

2.2.2. Mechanical and cabling of the Phoswich Wall

A photograph of the Phoswich Wall is shown in Fig. 4. The four multianode PMT's are mounted in a tilted geometry, which provides optimal solid angle coverage. The PMT's are held by four square frames made of black Delrin, which in turn are connected to the support plate by four legs, all made of Al. The square hole around the exiting beam can be opened by moving the Al legs to different positions on the support plate, in a way that preserves the tilted maximum packing at each new distance from the target. Opening the exit hole increases both the minimum and maximum angles, $\theta_{\min}$ and $\theta_{\max}$. However, the outer angle $\theta_{\max}$ does not increase as much as $\theta_{\min}$ in the present geometry. The shortest and longest distances of the detector plane from the target are 43.4 and 67.8 mm (for $\delta = 15$ mm), respectively (see Eqs. 10 to 18 below).

The four white Delrin square frames serve to hold down the ΔE detectors. Their opening is the same as the active photocathode area of 49×49 mm². The corresponding dimensions of the CsI(Tl) and fast-plastic scintillators

Figure 4: Front view of the Phoswich Wall. The central red dot shows the target position with the incident beam indicated by the red arrow above the target position. The square frames (made of white Delrin) with a $49 \times 49 \text{ mm}^2$ opening support the edges of the fast-plastic ΔE detectors. The high voltage cables (red) and the support plate onto which the PMT's are mounted are recognizable.

Figure 5: Side view of the Phoswich Wall scattering chamber. The position of the target holder, and the HV and signal-cable feedthroughs are highlighted. The 32-channel multi-pin signal cables are firmly attached to the exit beam line with the highest packing possible.

are $50 \times 50 \text{ mm}^2$. From each PMT four short cables bring the 64 signals and grounds to a feedthrough PC board, which also acts as the vacuum seal.

The signal cables outside the scattering chamber are seen in the photograph of Fig. 5. For example, the four cables from the bottom detector are recognizable. The feedthrough connectors are tilted to minimize the required opening in Gammasphere or Gretina/GRETA to bring 256 signals out. The multi-pin cables from the chamber to the electronics rack are 4.8 m long and have individual shielded signal and ground wires. The complete electronics setup fits in single rack about 2-m tall.

2.3. Gain matching and source calibrations

In addition to the properties of the detectors, the performance of the system is also determined by the geometry of the PMT's. The pixel sizes are $6.08 \times 6.08 \text{ mm}^2$ and the anode sizes $5.8 \times 5.8 \text{ mm}^2$ (0.28 mm inter-anode spacing). The distance between cathode and anode is not specified by the manufacturer and, thus, is neglected in the discussion. The glass-window thickness is 1.5 mm. In addition 2.2 mm is included for the CsI(Tl) giving a distance of 3.7 mm to the photocathode. A low-energy heavy ion or an α particle will stop within a small fraction of a mm, but the scintillator light is emitted in all directions. Hence the pixel below the central hit and the face- and corner-neighboring pixels are illuminated. This "cross talk" is part of the response of the detector to a single particle. Typically, multiplicities of about 9 per detected particle are obtained, as determined by α -source measurements. The usefulness of the CT is discussed in Sec. 2.6.

A complication that must be addressed is the variation in gain between pixels. While neighbor pixels vary in gain by $\lesssim 25\%$, in the entire PMT the

minimum and maximum gain can vary by a factor of two. Even with the $\lesssim$ 25% pulse-height variation between neighbors, the central-hit pixel cannot be identified in a single event unless the gains are matched. Then, the largest pulse height gives the central hit. In fact, the pulse-height distribution from a monoenergetic α -particle source is nearly flat. It was found that by placing a mask with an opening of $5.0 \times 5.0 \text{ mm}^2$ on every pixel one can easily identify the α peaks. Two sources were used: (a) ^{252}Cf with an α group at 6.112 MeV and two groups of fission fragments, and a distribution of β^- particles; (b) ^{232}U with many α -particle energies including a high-energy one at 8.785 MeV and a weakly seen group of β^- particles.

Three PSD gates must be placed for the phoswich-detector signal and they require separate gain matching and calibrations for each pixel. Figure 6 shows an example oscilloscope trace of a PW signal showing mainly the fast component from a fission fragment of ^{252}Cf . The gates and their delays are derived from the CFD trigger pulse and have the following values: delay 15 ns and width 50 ns (*A*), delay 68 ns and width 280 ns (*B*), and delay 1000 ns and width 1800 ns (*C*).

The nonlinearity of the CsI(Tl) for α particles makes energy calibrations with two low-energy α particles difficult, but it can be done (see Sec. 2.4). However, good gain matching can be done with the 8.785-MeV α line from ^{232}U through the thin plastic scintillators. The fast-plastic scintillators are typically 1.13-1.50 mg/cm² thick. The energy-loss variation for the thin scintillators due to the variation of their thickness or with angle is very small for nearby pixels (typically $\pm 0.5\%$), i.e., within the uncertainty of the calibration. Since a single-energy α source is used for gain matching the

Figure 6: Oscilloscope trace focussing on the fast signal from a ^{252}Cf fission fragment and the corresponding 50-ns wide gate A. The “early” gate B is partially seen, but the “late” gate C is off scale. The amplitude for B is about 20% of that from A.

channel number for zero energy has been determined by the channel near the noise from relatively low thresholds used for this purpose. Note that the input channels of the digitizing chips are AC coupled, consequently pedestals from a measurement with 50- Ω terminators at the input cannot be used.

Figure 7: Maps for the (A, B) (left) and (B, C) combinations (right) taken with a ^{232}U α source for a pixel in detector 3. The minimum and maximum of the z axis are set at 50 and 1, respectively. See the text for explanation of the various panels.

The data were sorted into three sets of two-dimensional maps correspond-

ing to the gate combinations (A, B) , (A, C) , and (B, C) . Two-dimensional software gates are placed on the (A, B) and (B, C) maps to provide the information needed for gain matching each set of parameters A , B , and C for each detector. The best energy resolution is obtained for the gate- B spectra. The (B, C) and the (A, C) maps provide the best separation between protons and α particles. The (A, B) or (A, C) maps provide Z separation between the TLF fragments of interest with $Z = 1$ to 6. Despite the fact that the B parameter in the (A, B) maps has better energy resolution, often the (A, C) maps separate somewhat better the TLF's by their Z . The PW system does not allow mass-number separation. The exception is ${}^8\text{Be}$, which is distinguished from ${}^{9,10}\text{Be}$ by its decay into two tightly correlated α particles. In all other cases, isotopic separation relies on the identification with representative γ rays.

Selecting the largest pulse height suppresses all CT and gives single α -peak spectra from sources. The intervening thin-plastic scintillator absorbs a small amount of energy, and somewhat degrades the energy resolution of the CsI(Tl) scintillator. A typical energy resolution for the B component is $\sim 4\%$ RMS or $\sim 10\%$ FWHM for the $\sim 7.6\text{-MeV}$ α peak from ${}^{232}\text{U}$ through a 1.15 mg/cm^2 fast plastic [see panels (c) and (f) in Fig. 7].

It is possible to improve the energy resolution by about 30% by adding the face-neighbor pulse heights to the central pixel, which approximately doubles the PH of the central pixel. However, this procedure destroys the gain matching and energy calibration of the edge and corner pixels, where one or two neighbors are missing. One can compensate for the missing neighbor pulse height by taking advantage of the positioning algorithm (see Sec. 2.6).

The latter procedure could retain the gain matching but not the calibration and recalibration is required. An additional complication arises from the fact that for low energy particles occasionally one of the face neighbors in an interior pixel may also be missed (below the discriminator threshold) and this cannot be reliably corrected.

Figure 7 shows sets of (A, B) and (B, C) maps taken with a ^{232}U source with $5.0 \times 5.0 \text{ mm}^2$ masks. Panels (a) and (d) show the data after gain matching and include large amounts of CT. Panels (b) and (e) show the data after gain matching when the largest pulse height was selected, thus eliminating the CT. Panels (c) and (f) show the data after the face-neighbor pulse heights are added to the central-pixel pulse height; the data have been recalibrated. It is worth noting that in panel (a) the CT from the high-energy α lies on the left of the lower energy group of α particles. It is seen from panels (a) and (b) or (d) and (e) that the energy resolution does not change when the largest pulse height is plotted. The improvement in energy resolution from adding in the neighbor pulse heights is evident from comparisons of panel (b) with (c) and (e) with (f). While the energy resolution in (f) is superior to that in (e) the PID resolution improves only a little. In contrast panel (c) shows large improvements in both the energy and the PID (or Z) resolution. The latter is due to the significant improvement in the energy resolution of the gate- A signal. The ratio of the counts in panels (a) and (c) is about 8.6, indicating that the central pixel and 7 of the neighboring pixels fired, implying that on average one corner neighbor missed. This is because the corner-neighbor pulse heights are lower than those of the face neighbors and could lie below the CFD threshold. In all cases shown the gains are 18 keV/channel for A ,

9 keV/channel for B , and 13.5 keV/channel for C .

The overall energy resolution in any pixel is the quadratic average of the intrinsic resolution and that from the kinematic broadening. In many instances these contributions may be comparable.

It should be pointed out that the α -source calibrations are mainly useful for the gain matching. The full calibration for the TLF's and α particles should be done relative to protons, which have a linear response of pulse height with energy (see Sec. 2.4).

The response of the PW to β^- particles, α particles and fission fragments is illustrated in Fig. 8. The top panel shows an (A, B) plot where the face neighbor PH have been added in. In addition to the separation of the main groups the light and heavy fission-fragment groups appear separated. The bottom panel shows the corresponding (B, C) plot. Here the fission fragments appear below the α group. This is due to energy loss of the fission fragments in the fast plastic and light quenching in the CsI(Tl).

2.4. Response to low Z elements

An investigation of the PW's response to low- and medium-energy α particles and light-heavy ions needs to be conducted in order to characterize further its performance. A typical experiment with the PW and a γ -ray array requires to detect α particles and protons as well as at least one of the following species: ${}^6,7\text{Li}$, ${}^9,10\text{Be}$, ${}^{10,11}\text{B}$, ${}^{12,13}\text{C}$, or ${}^{13,14}\text{N}$. As shown below, single- Z resolution for all but the lowest laboratory energies will be possible.

The expected laboratory energies cover a range from ~ 10 MeV, when TLF's stop in the plastic, to ~ 160 MeV, when the forward-angle TLF's hit the detector. This requires a large dynamic range of energies, which defines

Figure 8: Maps of electrons, α particles and fission fragments from a ^{252}Cf source. The data were taken with CsI(Tl) and fast plastic scintillators in place. The top and bottom panels show (A, B) and (B, C) maps, respectively. In the (A, B) map the fission fragment groups are resolved. See text for more details.

Table 1: Projectiles and their energies in MeV used in the elastic-scattering measurements with an ^{197}Au target.

^4He	^7Li	^{11}B	^{12}C	^{14}N
10	12	12	20	24
15	18	14	28	33
19	24	20	36	42
23	30	29	45	51
27	36	37	54	60
		45	63	
		54		

the needed HV and amplifier-gain settings. A related point of concern is the magnitude of the CsI(Tl)-scintillator pulse height as a function of incident energy. In general, only the proton response is linear. For ^4He and species with higher Z non-linearity occurs with energy, which increases with atomic number. Therefore, one should determine the CsI(Tl) response as a function of energy and for each Z of interest. A three-point proton-energy calibration can be made by measuring elastic and inelastic scattering of 14-MeV protons on ^{12}C from the ground-, 4.439-, and 9.641-MeV states of ^{12}C , respectively. It is advantageous to measure the response (pulse height) for each Z expressed in terms of equal pulse height of protons of known energy.

In order to address these issues and obtain calibrations of relevant TLF's relative to proton energy, comprehensive elastic-scattering measurements were carried out at the University of Notre Dame FN tandem accelerator. The scattering measurements were made with beams of ^4He , ^7Li , ^{11}B , ^{12}C ,

and ^{14}N ions, with various energies, scattered off a thin ^{197}Au target. The beam energies employed are listed in Table 1. Also 12- and 14-MeV protons were scattered off a thin ^{12}C target.

At the beam energies employed in the Notre Dame measurements the ions just pass through the thin plastic. In the inverse-kinematic experiments such low-energy light-heavy ions are found at the large $\theta_{Lab,TLF}$ angles. To demonstrate the Z resolution at the lowest possible TLF laboratory energies the maps of the gate combinations (A, B) or (A, C) are important. Somewhat better Z resolution is obtained with the (A, C) maps at low energies. For higher energies a comparison for the best separation is warranted.

Figure 9 shows (A, C) maps of ^4He , ^7Li , ^{11}B , and ^{14}N ions for the projectile energies listed in Table 1. The energies deposited in the CsI(Tl) and fast-plastic detectors for the points in Fig. 9 are listed in Table 2. For the chosen pixel the fast plastic is 1.147-mg/cm² thick (or 1.482 mg/cm² corrected for the tilt). The counts histogrammed in panel (a) correspond to the highest pulse height. Good Z resolution is seen except at the lowest energies. However, at higher energies the Z lines diverge somewhat and allow single- Z separation. When the face-neighbor and central pixel pulse-heights are added the Z resolution improves, as can be seen in panel (b) of Fig. 9. For the A - and C - axes the channel labels have arbitrary scales, however, the same data were sorted and the z axis in both panels has the same scale (maximum 14, minimum 1.1 counts). The data labeled ^1H , from the reaction $^{197}\text{Au}(\alpha, p)^{200}\text{Hg}$ at 27 MeV, are superimposed. Here the statistics were too poor to resolve the ground and first two excited states in ^{200}Hg . The α particles from the latter reaction have been removed for clarity, since the

elastic scattering is too weak to give a single-energy elastic-scattering point with the statistical quality of the lower-energy points.

For the reactions of interest, significantly higher energies than those of Fig. 9 will be observed, and the present measurements can be used to adjust the overall gain of the system to accommodate the highest energy prior to carrying out the actual experiments. The maximum energy that is needed for an experiment can be set in two ways. First, the high voltage (HV) can be adjusted accordingly. However, this destroys the energy calibrations needed for gain matching and influences the CFD thresholds that have to be re-adjusted. Second, the gains can be changed by factors of 2 or 2.5 among various settings that can be applied to the chip boards for the A , B , and C parameters separately. The disadvantage of such changes is that they interfere with the low-energy offsets for each pixel. Then channel by channel adjustment must be done, since low pulse heights for some pixels could be cut. To avoid these difficulties for a fixed voltage several chip-gain settings should be set and calibrated with two α sources that cover the energy range needed.

The lowest energies, considered in Fig. 9 and listed in Table 2, are close to the values where the ions stop in the plastic, which are: 2.695, 4.907, 9.345, 13.916 MeV for ^4He , ^7Li , ^{11}B , ^{14}N , respectively. With its 1.482-mg/cm² thickness, the plastic is for the lower-energy ^{11}B and ^{14}N ions more like an E than a ΔE detector.

It is interesting to compare the nonlinearity in energy and Z for the ions shown in Fig. 9(b). The worst case would be for ^{14}N . For the CsI(Tl), the ratio of highest to lowest energy is $50.23/8.46 = 5.94$. The ratio should be

Figure 9: Maps of the (A, C) gate combination for ^1H , ^4He , ^7Li , ^{11}B , and ^{14}N ions with the projectile energies listed in Table 1. Panel (a) shows the map obtained for the largest pulse height. Panel (b) shows the same type of maps after the face-neighbor pulse heights are added in. In both panels, the same Z -axis scale is used (maximum 14, minimum 1.1 counts). The improvement in Z resolution in panel (b) is apparent. The numbers next to the top points in (b) are the energies in MeV the particles deposite in the CsI(Tl). The lines in (a) and (b) join the groups for each ion and are drawn to guide the eye. The data points labeled ^1H are from the reaction $^{197}\text{Au}(\alpha, p)$ at 27 MeV.

Table 2: Energies in MeV deposited in the CsI(Tl) E , and the plastic ΔE detectors, and total incident energy for the ions indicated. The entries for a given ion and the detectors correspond to the projectile energies for the same species in Table 1. The values are for pixel 145 at $\theta_{Lab} = 41.57^\circ$ and $\phi_{Lab} = -144.25^\circ$.

^4He			^7Li		
CsI	ΔE	E_{inc}	CsI	ΔE	E_{inc}
8.94	0.87	9.81	8.78	2.76	11.54
14.2	0.62	14.82	15.5	1.98	17.48
18.3	0.50	18.80	21.9	1.54	23.44
22.3	0.44	22.74	28.0	1.27	29.27
			34.1	1.11	34.21
^{11}B			^{14}N		
CsI	ΔE	E_{inc}	CsI	ΔE	E_{inc}
1.00	9.98	10.98	8.46	13.7	22.16
3.40	9.56	12.96	20.0	10.9	30.90
11.5	7.40	18.90	30.5	9.19	39.69
22.2	5.53	27.73	40.5	7.87	48.37
31.0	4.51	35.51	50.2	6.92	57.12
39.7	3.77	43.47			
48.9	3.25	52.14

Figure 10: Light-quenching curves for CsI(Tl), for the ions indicated, as a function of proton energy in MeV, obtained from the proton calibration at the same pulse height. The data are taken for pixel 54. The ^9Be points are from an interpolation using the ^7Li and ^{11}B data points. The lines join the values obtained from fits at the data- point energies.

compared with the corresponding PH ratio of $350/50 = 7.0$. The ratio of the ratios is 1.18 [similar ratios are found if (A, B) maps are used]. For the plastic, the ratio of the highest to lowest deposited energy is $6.92/13.66 = 0.507$, while the the value of the corresponding PH ratio is $5000/2500 = 2$. The ratio of the ratios is $0.507/2 = 0.25$. So for the plastic the PH anticorrelates with the deposited energy. However, if the PH ratio is compared with ratio of the incident energies, i.e., $(50.23+6.92)/(8.46+13.66) = 2.58$, then the ratio of the ratios is $2.58/2.0 = 1.29$, which is close to the ratio of 1.18 obtained for the CsI(Tl) detector.

It should be also noted that in the (B, C) maps protons and α particles are well separated at very low energies. The same is true for the (A, B) and (A, C) maps (see Fig. 9). In addition, in the (B, C) maps (not shown) α particles and ${}^7\text{Li}$ ions are also separated for $E_{Li} \gtrsim 22$ MeV corresponding to $\gtrsim 24$ MeV of incident energy. In contrast, at $E_{Li} = 8.8$ MeV in the (A, C) map of Fig. 9(b) (incident energy = 11.5 MeV) ${}^7\text{Li}$ cannot be completely separated from ${}^4\text{He}$.

It is important to quantify the quenching in the CsI(Tl) for ions with $Z = 2$ to 7 in the appropriate energy range. Figure 10 shows a plot of the ion energies in CsI(Tl) as a function of the proton energy. These energies were obtained from the proton calibrations at the same pulse height. The data, for a representative pixel (pixel 54), are obtained from the B gate, which give the best energy resolution. Similar graphs should apply for all the pixels in the array assuming that all CsI(Tl) detectors have the same quenching curves. The curves shown represent least-square fits to the function

$$E_{particle}(E_p) = a E_p + b (E_p)^c. \quad (5)$$

This function is valid for $E_p \geq 0$, and the coefficients a, b, c for these fits are listed in Table 3. For example, the procedure for obtaining the ${}^7\text{Li}$ energy is as follows. A hit by this particle leads to a pulse height x_{Li} in pixel 54 from which the proton equivalent energy $E_p = 0.1105 + 0.0056687 x_{Li}$ (the proton calibration curve) is derived. Then Eq. 5 is used with the ${}^7\text{Li}$ coefficients from Table 3 to find the ${}^7\text{Li}$ energy $E_{particle}(E_p)$ deposited in the CsI(Tl) detector. For other pixels, only the proton calibration changes, which is used to get E_p in MeV. To obtain the incident energy the latter energy should be corrected for the energy loss through the plastic at that pixel position, considering the angle dependence of the plastic thickness. The advantage of the functional form of Eq. 5 is that it allows for a reasonable extrapolation to higher energies; it also helps estimating the gains needed for each planned experiment.

Table 3: Coefficients for the light-quenching curves in CsI(Tl) (Eq. 5) for the ions listed.

Ion	a	b	c
${}^4\text{He}$	0.42649	0.8561	0.8813
${}^7\text{Li}$	0.6795	2.1228	0.6389
${}^9\text{Be}$	0.9809	2.2700	0.6145
${}^{11}\text{B}$	1.2823	2.3365	0.5901
${}^{12}\text{C}$	0.9758	3.4091	0.7070
${}^{14}\text{N}$	1.9266	1.9076	0.6903

If the energy calibration must be changed, then a new calibration run with 12- or 14-MeV protons scattered off ${}^{12}\text{C}$ is sufficient. This enables the determination of the calibration for the TLF's with $Z = 2$ to 7. The strong

forward focussing of the Rutherford scattering and the small opening angle of the PW require very low proton-beam intensities in order to avoid accidental summing with signals in the nearest face neighbors. This is important for the pixels around the beam. It may require long runs to collect enough statistics for the pixels at large angles.

To avoid the above difficulties an alternative calibration method is devised, using two α sources, ^{252}Cf ($E_\alpha = 6.112$ MeV) and ^{232}U ($E_\alpha = 8.784$ MeV). For example, for pixel 145 energies of 4.815 and 7.836 MeV, respectively, are deposited in the CsI(Tl) detector, as the particle has to pass the plastic detector. Their proton-equivalent energies are obtained by numerically inverting Eq. 5 for ^4He giving $E_1 = 4.192$ and $E_2 = 7.092$ MeV, respectively. Using the latter two values, the proton-calibration equation becomes

$$E(x) = a + b \cdot x, \text{ with} \quad (6)$$

$$a = E_2 - b \cdot x_2, \quad b = \frac{(E_2 - E_1)}{(x_2 - x_1)}, \quad (7)$$

where E_1, E_2 are the proton-equivalent energies relative to the α -particle energies, and x_1, x_2 are the α -particle calibration pulse heights, respectively. In turn, any TLF particle with $Z \leq 7$ that has a $\text{PH} = x_{\text{particle}}$ will have a proton-equivalent energy $E(x_{\text{particle}})$ given by Eq. 6, and an energy given by Eq. 5, with $E_p = E(x_{\text{particle}})$ using the appropriate values of the coefficients listed in Table 3.

Since the plastic scintillator is used for PID only, it need not be calibrated. The incident TLF energies are obtained by correcting for the energy loss through the plastic and for the target thickness for each pixel position in an

event-by-event procedure.

2.5. Position determination of detector hits

In experiments with the Phoswich Wall each pixel acts as an individual detector. The tilted geometry (cf. Fig. 4) can be described by an appropriate choice of a coordinate system for each detector, i.e., transformations are needed that bring each interaction point to polar or Cartesian coordinates with the Z axis along the beam direction. The detector geometry is defined in Cartesian coordinates (x, y) on the plane of each detector with the x axis going from left to right (see the top detector No. 1 in Fig. 4), and the y coordinate going from bottom to top. The key design parameters are given in Eqs. 8 and 9, where L is the length of the square detector edge, R_0 is the maximum radius when there is no side overlap (parameter $\delta = 0$), Ψ is the angle between the normal to the detector plane and the beam axis, and δ is a linear displacement length. Only the parameter δ can be varied with steps of 2.5 mm. One can adjust the opening of the exit hole by translating the detectors along an axis perpendicular to the beam and moving this axis closer or farther from the beam ($\delta = 0$ and 17.5 mm correspond to the maximum and minimum sizes of the exit hole, respectively).

$$L = 49 \text{ mm}, R_0 = 55 \text{ mm}, \Psi = 50.6^\circ, \quad (8)$$

$$\delta = 0.0 \text{ to } 17.5 \text{ mm}. \quad (9)$$

Equation 10 gives the perpendicular distance from the target point to the plane of each detector.

$$R_p = R_0 - \delta \sin \Psi. \quad (10)$$

Equations 11 to 13 give the Cartesian coordinates about the beam axis for an (x, y) point on the surface of the top detector (detector 1).

$$X(x, y) = (L/2 - x + \delta), \quad (11)$$

$$Y(x, y) = R_0 \sin \Psi - (L/2 - y) \cos \Psi - \delta, \quad (12)$$

$$Z(x, y) = R_0 \cos \Psi + (L/2 - y) \sin \Psi. \quad (13)$$

The corresponding spherical polar coordinates are given by Eqs. 14 to 17. Here $\phi_1(x, y)$ is defined to be consistent with the right-handed system of Eqs. 14 to 17. The $Z(x, y)$ axis coincides with the beam direction. For two consecutive detectors, e.g. 1 and 2, $\phi_1(x, y)$ is replaced by $\phi_2(x, y)$ according to Eq. 17.

$$r(x, y) = \sqrt{X(x, y)^2 + Y(x, y)^2 + Z(x, y)^2}, \quad (14)$$

$$\theta(x, y) = \cos^{-1} \left(\frac{Z(x, y)}{r(x, y)} \right), \quad (15)$$

$$\phi_1(x, y) = \tan^{-1} \left(\frac{Y(x, y)}{X(x, y)} \right), \quad (16)$$

$$\phi_n(x, y) = \phi_{n-1}(x, y) - \pi/2, \quad n = 2, 3, 4. \quad (17)$$

When $X(x, y)$ becomes negative (for large x values and any y), then π must be added to Eq. 16 to make $\phi_1(x, y)$ positive, whereas ϕ_2, ϕ_3 , and ϕ_4 obtained by rotation via Eq. 17 can assume negative values. This is necessary for the subscript n in Eqs. 19 to 24 to label properly the coordinates for each detector n . The angle θ is the same for all detectors.

Equation 18 defines the angle, $\chi(x, y)$, of the line from the target to a point (x, y) on the detector and the line perpendicular to the detector face. This expression is needed in order to calculate the increased thickness of the ΔE , the E detectors or of any absorber in front of a detector according to the pixel (x, y) position.

$$\cos \chi(x, y) = \frac{R_p}{r(x, y)}. \quad (18)$$

Equations 19 to 21 give the coordinates (X_u, Y_u, Z_u) of the unit vector at $[r, \theta, \phi]$ for directional cosine calculations. Here n ($n = 1, 2, 3, 4$) is representative for a detector.

$$X_{u,n}(x, y) = \sin \theta(x, y) \cos \phi_n(x, y), \quad (19)$$

$$Y_{u,n}(x, y) = \sin \theta(x, y) \sin \phi_n(x, y), \quad (20)$$

$$Z_{u,n}(x, y) = \cos \theta(x, y). \quad (21)$$

The Cartesian coordinates with the Z axis along the beam direction for points on detectors 1 to 4 are obtained from Eqs. 22 to 24.

$$X_n(x, y) = r(x, y) X_{u,n}(x, y), \quad (22)$$

$$Y_n(x, y) = r(x, y) Y_{u,n}(x, y), \quad (23)$$

$$Z_n(x, y) = r(x, y) Z_{u,n}(x, y). \quad (24)$$

The solid angle subtended by a pixel with an area A_{pix} at the detector coordinates (x, y) is determined by a fraction $F(x, y)$ of 4π which leads to

$$\begin{aligned} \Delta\Omega(x, y) &= F(x, y) 4\pi = \frac{A_{pix}(x, y) \cos \chi(x, y)}{4\pi r(x, y)^2} 4\pi \\ &= \frac{A_{pix}(x, y) \cos \chi(x, y)}{r(x, y)^2} \text{ msr}, \end{aligned} \quad (25)$$

where $\cos\chi(x, y)$ corrects the pixel area for the tilt off the perpendicular. Equation 25 is crucial for cross-section calculations: it provides the solid angle at any point (x, y) on each detector.

The above transformations assume that the interaction radii in Eq. 10 correspond to the front of the CsI(Tl) detector. In the analysis these have to be adjusted event-by-event, as the more penetrating particles will have larger radii since they stop at some depth below the surface of the CsI(Tl). For the reactions of interest, the ranges of the low- Z PLF's in the CsI(Tl) are smaller than 1.0 mm. This indicates a small change in radii, causing a change in $\theta_{Lab,TLF}$ smaller than 0.1° - 0.6° (depending on $\theta_{Lab,TLF}$).

The plots in Fig. 11 are important for understanding the variation of $\Delta\Omega(x, y)$ with position (x, y) within each detector. This relationship is indicated by the red points labeled as msr/pixel. The largest solid angle coverage per pixel (efficiency) is at the sixth point in x and the sixth row in y of the detector, where the normal of the detector area pointing to the target position is located. This response function was duplicated by an α -source measurement at the target position, see the blue points, labeled Counts/pixel, in Fig. 11. Note that the pixels in row and column (1,0), (1,1) and (2,0) are partially shielded from the source by the neighboring detector, and as a result the counts for those pixels are lower.

The Appendix A gives the average values of the angles $\langle\theta^\circ\rangle$ and $\langle\phi_1^\circ\rangle$ for detector 1, where the average has been calculated over the the pixel area (no mask) and for a value $\delta = 15$ mm. In addition, the Appendix A lists the angle $\langle\chi^\circ\rangle$ and the relative efficiency $\langle\varepsilon\rangle$, normalized to 1 for the maximum. These efficiencies can be converted to msr/pixel by multiplying by 19.615

(see red points in Fig. 11 for a plot of the msr/pixel).

In an in-beam experiment the elastic scattering for the TLF has the highest cross section and, thus, is a measure of the maximum counting rate that can be sustained by the detector. For a typical reaction like $^{136}\text{Xe} + ^{13}\text{C}$ at 560 MeV, the ^{13}C elastic scattering has the highest cross section in the 8th row (largest $\theta_{Lab,TLF}$). This is shown by the black points in Fig. 11, which have a maximum value of 7.05 b/sr. However, the tilt of each pixel relative to the perpendicular to the detector reduces the counting rate, because the pixel area is reduced. Thus, the product $\Delta\Omega(x, y) \sigma_{Elastic}(x, y)$ flattens out for each row, as seen by the green data points labeled mb/pixel in Fig. 11. A maximum (58.0 mb/pixel) is obtained in the 8th row and a minimum (2.65 mb/pixel) in the 1st row. Due to the nature of inverse kinematics the largest $\theta_{Lab,TLF}$ angle corresponds to the highest yield and $\sigma_{Elastic}$, but to the lowest kinetic energy of the elastics. Conversely, the smallest angle $\theta_{Lab,TLF}$ is associated with lowest cross sections and the highest kinetic energy.

Of course $\Delta\Omega(x, y)$ also gives the solid angle, and thus the efficiency, for any subpixel of size $A_{pix}(x, y)$ on the detector plane. The coordinates within the pixel are represented by (x, y) .

2.6. Sub-pixel positioning

The CT information from the response of the central pixel and its neighbors can be used to derive the sub-pixel hit position. This position information is beneficial for two reasons. Firstly, a high $\Delta\Theta_{CoM,PLF}$ resolution is desirable for the angular distributions of the PLFs in their rest frame. Secondly, the energy resolution for detecting any ion can be improved by deriving the energy at each angle from the $\theta_{Lab,TLF}$ angle alone. At the high-

Figure 11: The variation of the solid angle of one detector of the Phoswich Wall. The plotted quantities are given as a function of x for each row that increases along the y axis from bottom to top. The red curve gives the solid angle per pixel in msr/pixel. The black points give the TLF Rutherford scattering cross sections, in b/sr, for 560 MeV $^{136}\text{Xe}+^{13}\text{C}$. The points in green give the same quantity in mb per pixel. The points in blue give scaled experimental data from an α peak in counts per pixel. Their shape duplicates that of the red points.

est energies the intrinsic resolution and the kinematic broadening contribute almost equally to the overall resolution, whereas at the lowest energies the kinematic broadening dominates the resolution.

Figure 12: Position algorithm giving the sub-pixel position in mm as a function of the crosstalk fraction. The numbers assigned to the data points represent the size in mm of the masks used. For example, the points labeled 2 correspond to $3.04+1.0$ and $3.04-1.0$ mm. The points at 0 and 6.08 mm are from data taken without a mask. For the central pixels only the curve between 3.04 and 6.08 mm is used, while for the edge and corner pixels the complete curve is needed. See text for details.

A representative plot of the position within a pixel as a function of the CT fraction is shown in Fig. 12. The fraction of CT to a face-neighbor pixel (left, right, up, down) varies between the values of ~ 0.15 and 0.50 . The

position in mm , given by the function $mm(f)$ where f is the CT fraction, can be accurately determined as follows. A set of five masks that cover all but a certain central area of each pixel were fabricated. The opening areas were 1.0×1.0 , 2.0×2.0 , 3.0×3.0 , 4.0×4.0 , and 5.0×5.0 mm². Using a single-energy source, data were taken with each mask for all 4 detectors.

Concentrating on the response to the right-face neighbor CT, for each mask the spectra of the CT fraction f_n have a nearly rectangular shape. The lower edge, which is farther from the right face neighbor, corresponds to a low CT fraction ($f_{low,n}$), and the upper edge, which is closer to the right-face neighbor, corresponds to a high CT fraction ($f_{hi,n}$). These edges give the fractions $f_{low,n}$ and $f_{hi,n}$, which correspond to distances of $3.04 - \text{mask}_n/2$ and $3.04 + \text{mask}_n/2$ mm from the left edge of the pixel, where the mask_n values are in mm. The use of the index n ($n = 1, 2, 3, 4, 5$) indicates that the fractions f are determined from each mask. The data points above and below the middle position of 3.04 mm are marked according to the mm size of each mask. The points at 0.0 and 6.08 mm are obtained without a mask. An empirical function which fits the data well, is given by Eq. 26.

$$mm(f) = a \left(2 - \frac{1}{f} \right) + b (f - 0.5) + 6.08, \quad (26)$$

$$\text{with } f_{\min} \leq f \leq 0.5, \text{ and } mm(f_{\min}) = 0.$$

This function satisfies the boundary condition at the 6.08-mm edge of the pixel, where the CT fraction is 0.50. The data are fitted by a least-square procedure. The resulting fit is the curve in Fig. 12 with the parameters $a = 0.4704$ and $b = 10.818$. The parameter f can be determined within an error margin of 4%, leading to a maximum uncertainty of 0.26-mm in the

mm position (error bars in Fig. 12). The maximum uncertainty for $\Delta\theta_{Lab}$ (present data) is obtained for the distance from the source to the detector plane (e.g. $R_p = 43.4$ mm for $\delta = 15$ mm, cf. Eqs. 8 - 10). Here, a 1-mm position resolution translates into $\Delta\theta_{Lab} = 1.32^\circ \pm 0.33^\circ$. The smallest uncertainties for $\Delta\theta$ occur near the edges of the detector.

Figure 13: Single-pixel hit distribution measured with a 4.8×4.8 mm² mask. The square in blue indicates the edge of the mask. The estimated widths of the covered part of the pixel are indicated by the red numbers and symbols.

The hit pixel is given by the largest pulse height within a cluster of nine pixels. The procedure to find the position within the pixel is as follows. The face-neighbor PH fractions are labelled as f_L , f_R , f_U , f_D for left, right, up, and down, respectively. For example, if $f_R > f_L$ and $f_U > f_D$ then the hit

is in the right-top quadrant of the hit pixel. Similar comparisons determine any hit quadrant. Furthermore, if $f_R > f_L$ then the right-face algorithm is used to give a better position $mm_x(f_R)$ based on Eq. 26. Similarly, if $f_D > f_U$ then again the down algorithm based on Eq. 26 gives the $mm_y(f_D)$ position from the bottom to the top of the pixel. Here the subscripts x and y for mm indicate the distances in the x and y direction in the pixel, respectively. Similarly, if $f_L > f_R$ and $f_U > f_D$ then the origins given by the algorithm are reversed. The quantities $[mm_x, mm_y]$ via Eq. 26 provide the coordinates (x, y) for Eqs. 14-25. These equations give the $X(x, y)$, $Y(x, y)$, and $Z(x, y)$ or the $r(x, y)$, $\theta(x, y)$, and $\phi(x, y)$ values that are relevant for the physics quantities to be measured. The coordinates (x, y) for each of the four detectors are related to the sub-pixel coordinates $[mm_x, mm_y]$ via Eq. 27.

$$x = (i - 1) 6.08 + mm_x, \quad y = (j - 1) 6.08 + mm_y. \quad (27)$$

Here (i, j) are the column and row indices of the hit pixel, with i, j taking values $1, 2, \dots, 8$.

Due to small inaccuracies in positioning the masks, it was found that the parameters a and b differ somewhat among the four faces. To compensate for this, the left-right and up-down parameters were then averaged.

The positioning within the edge and corner pixels needs special attention, since one or two face-neighbor pixels are missing. For example, if the left neighbor is missing, then the algorithm for the right face neighbor must be used for both the right and left halves of the pixel. If $f_R < 0.28$ (approximate CT fraction at the center) then the lower portion of the curve is used for positions between 0 and 3.04 mm. There, the range of the CT fraction is

$0.28 - 0.15 = 0.13$, which is about 40% smaller than the range of the half to the neighbor face of $0.50 - 0.28 = 0.22$. This leads to a less accurate positioning in the outer half of an edge pixel. For the corner pixels, the algorithms of the two neighbors must be used.

An example of the hit pattern within one pixel is provided in Fig. 13. It shows the distribution of hits within one pixel for a $4.8 \times 4.8 \text{ mm}^2$ mask. The absence of counts at the edges is evident; the widths of these regions are indicated in red. This suggests that positioning is possible with a precision of less than 1 mm. However, at that level the contribution from the beam size may become important.

The present positioning method based on nearest face-neighbor CT fractions should be independent of the pulse heights; this is suggested by the optical origin of the CT. This was confirmed by measuring the position algorithm for the light and heavy fission fragments from ^{252}Cf , which according to Eq.8, have very different pulse heights. (Including the corner neighbors of a central-hit pixel is hard to justify, since their pulse heights are small, and below the detection threshold for low-energy particles.)

At higher energies the detector response may include the second face neighbors. The need of a large dynamic range in an experiment with this device forbids reducing second face-neighbor response by increasing the CFD thresholds indiscriminately to cut small pulse heights. This suggests judiciously increasing the thresholds for pixels at small $\theta_{Lab,TLF}$ angles, where $E_{Lab,TLF}$ is very high, in order to reduce second face neighbor CT.

The present positioning method is superior to calculating 2-dimensional centroids. That method is based on amplitudes only and is used in γ -ray

imaging (see e.g. Ref. [17]). First, the CT of the multianode PMT can only be significantly reduced at the expense of solid-angle coverage (e.g. using a pixilated detector array with comparatively small pixels [17]). Secondly, the centroid method may fail when the hit is in the outer half of the PMT edge or corner pixels. The H8500 PMT has 24 edge and 4 corner pixels (28 out of 64) for which the present method provides the sub-pixel position.

3. Signal processing and readout

This section describes the electronics hardware, the software control, the process and setting system parameters, and the off line presorting routines of the data.

3.1. Electronics hardware

A block diagram of the signal processing and data acquisition system is shown in Fig. 14. The various components of the system are discussed hereafter.

3.1.1. The amplifier-splitter-delay modules (ASD)

The 256 detector channels are read out through 16 multi-wire ribbon cables, which are connected to the inputs of the two ASD modules. There the signals are amplified (fast amplifiers) and subsequently split in two outputs. The output to the CFD is AC coupled at the ASD, and the output to the chips is AC coupled at the chips. The ASD's provide, in principle, the option of using chip delays for the linear signals or external cable delays. Since the original fast-plastic signals have very short rise and fall times (2-3 ns) chip delays are not suitable; they would greatly reduce the fidelity of these signals.

Therefore, 70-ns cable delays (RG-174 cables) are used for the linear signals that are then connected to the PSD boards that control the PSD chips. The delay cables are housed in a 20-cm tall rack bin. These shielded 34-wire cables have individual 50- Ω wires for signal and ground. The 16 delay-ribbon cables fit in one bin. Prior to entering the chip boards the linear signals are fed into 16 multiplexer boards that connect to the chip boards.

3.1.2. The multiplexer boards

Each of the linear-signal multiplexer boards receives 16 signals from the CFD (not shown in Fig. 14) and 16 linear signals from the ASD modules. In addition to passing the linear signals to the chip boards, the multiplexer provides Lemo outputs of a selected individual trigger and the corresponding linear signal. This allows for inspection and live adjustment of the discriminator levels. The channel selection is done with the aid of a microcomputer that provides selection of the channel of interest via a Graphical User Interface (GUI). The GUI optionally enables or disables the multiplexer output. The presence of the multiplexer boards does not influence the quality of the linear signals.

3.1.3. The constant-fraction discriminators

The CFD's are 32-channel discriminator modules from Pico systems [18]. These are single-width CAMAC modules. Each channel is a true constant-fraction discriminator implemented in a low-power CMOS logic. Input and output have 68-pin 3M-KEL high-density ribbon-cable connectors. The output is provided in Low Voltage Differential Signaling (LVDS) form. The CFD delays are individual plug-in tapped delay lines in a Single In-line package

(SIP) case, and provide 5 taps between 20% and 100% of the full delay range. The thresholds can be set by computer control through the CAMAC bus in 1024 steps, roughly covering 0 to -200 mV. For each group of 16 channels, multiplicity and OR outputs are provided. There is also a way to mask individual channels, although the current version of the control GUI always enables all channels.

Since fast scintillators are used, the cross-over delays are set at 6 ns. The LDVS gates are converted to CMOS (5V) logic-level signals via 16-channel conversion boards that are connected to the top of the PSD boards.

The CFD signals provide both the start of charge integration in the chips and the timing output for each channel. The CFD modules are controlled by a separate microprocessor: a control GUI allows setting the thresholds with sliding bars, and storing the threshold values in a file.

3.1.4. The chip boards and the mother board

The heart of the acquisition system is a set of 32 8-channel ASIC PSD chips [15]. Two chips are attached to each chip board. There are 16 chip boards, with eight 16-bit ADC's on each board (4 per chip for the A, B, C, T parameters). They digitize the voltages provided by the charge integrating chips (8 independent channels per chip). Only the upper 13-bit linear-signal information is used in the output. The chip boards are plugged into the motherboard. The motherboard receives the chip parameters from a Xilinx Logic Module (XLM) [19] that resides in the VME crate and passes them to the chips. The parameters are: (a) zero offsets for each channel of the A -, B -, and C -gate parameters; (b) gate-delay values for each chip board for each parameter A, B, C ; (c) gate-width values for A, B, C ; and (d) gain

settings to each chip board for A , B , and C (discussed in Sec.3.2.2). Some optimal values for the delays and widths of the gates for the A , B , C gates were given in Sec. 2.3. In addition to the values of A , B , C the timing signal of each event T is sent to the XLM module for storage. The time range for the T signal is $1.5 \mu s$. To prevent additional triggers to appear during the digitization, the OR of the CFDs is used to block the global enable signal until the readout process is complete. This is done in NIM logic external to the chip-board logic.

3.1.5. Interface to other devices

The PW can be operated in conjunction with Gretina or Digital Gamma-sphere. To be able to record particles in coincidence with γ rays, a trigger signal derived from the γ -ray array is needed. For a given event the digitized particle information is held for a selectable auto-reset period of up to $\sim 100 \mu s$. If the external signal arrives within this period then the information is read out, otherwise the system auto-resets and waits for the next particle event.

The time needed to process an event with a typical pixel-hit multiplicity of 9 can be estimated as follows. The ADC's digitize in parallel for the different chips. The digitization of the hits within an 8-channel chip is done serially. The worst case scenario is that all 8 channels fire, then it will take $8 \times 4 \mu s/\text{hit}$, i.e., in total $32 \mu s$ to digitize. The readout time is $(0.6 \mu s/\text{word}) \times (5 \text{ words}/\text{hit}) \times (\text{multiplicity } 9)$, i.e., $27 \mu s$. Adding the digitization time gives an average processing time of $59 \mu s$. The auto-reset waiting period is not added to this unless it exceeds the processing time of $59 \mu s$, in which case only the extra time should be added in. Note that for higher particle-multiplicity

events only the readout time is increased.

3.1.6. System control logic (XLM and VMUSB modules)

The data acquisition flow is controlled by the XLM (cf. Sec. 3.1.4). Upon initiation the XLM module loads the chip-data parameters. It offers additional capabilities, for example, scaled down particle-singles events can be inserted in the data stream. In turn, these singles allow monitoring the elastic scattering in many pixels with the same angle $\theta_{lab,TLF}$, a feature that is necessary to calculate cross sections. As discussed above, signal processing starts at the time of the CFD trigger. In the case of a particle- γ coincidence the time is determined with respect to an RF enabled γ -ray pulse which is used as a common stop. The time T is then the difference between the RF and the plastic times. In addition, the XLM communicates and passes the data to the acquisition computer via a VMUSB module that also resides in the VME crate. The latter module accepts time-stamp signals.

3.2. Software control of the system

3.2.1. Gate-width and delay adjustment

An optimal set of gate-width and gate-delay parameters was initially established from measurements with ^{252}Cf and ^{232}U sources. These give acceptable PID for α and β^- particles, as well as for α particles and light and heavy fission fragments. Because of the large dynamic range of the delay and gate values, the different ranges that are available in the XLM GUI had to be calibrated to avoid settings near the ends of the ranges where nonlinearities were found.

3.2.2. Gain selection for the chip boards

The XLM GUI offers eight settings for the gain output the chips; the gain can be changed by factors of 1 to 200. This is done by changing an attenuating resistor in the charge integrator. Changing the gain setting also drastically changes the digital offset for each A , B , and C channel and consequently the gain-matching calibrations, which is crucial for the integrity of the data (no cutting-off of low energies). It is advisable that a few settings be calibrated with a source and the information be stored prior to an in-beam experiment.

3.2.3. Online monitoring and off-line analysis

A version of the Michigan-State-University analysis package SpecTcl is used for on line display of acquired data. It supports displaying (A, B) , (A, C) , (B, C) maps and A , B , C , and T spectra with adequate channel resolution.

An offline sorting code written in C++ is available. It has options for creating the aforementioned histograms, which are written in ROOT format [20]. The options are: (a) raw data, (b) gain matched maps, (c) maps of the largest pulse height, (d) maps with the face-neighboring pixel pulse height added to the largest pulse height, (e) maps and spectra needed for determining the positioning algorithms, (f) maps of the sub-pixel hit pattern needed for providing the (x, y) coordinates within each hit pixel, and (g) output prescanned and fully characterized event data.

4. Summary

A new phoswich-type detector for counting charged particles and low- Z heavy-ions in inverse-kinematic reactions with beam energies $\lesssim 7$ MeV/u is described in detail. It is designed to provide light charged particle PSD and individual Z resolution for species with $Z \leq 7$ with high efficiency. Its small size permits it to be used in the cavities of 4π γ -ray arrays, such as Gretina and Gammasphere. It is based on four 8×8 multianode PMTs. It has a state-of-the-art compact electronics readout system based on an array of ASIC chips with triple-gating (charge integration) and timing capability. It can provide anode-subpixel position resolution of $\lesssim 1$ mm² ($\Delta\theta_{Lab} \lesssim 1.3^\circ$), suggested by measurements with a single-energy α source (Sec. 2.6). This translates to $\Delta\theta_{Lab,TLF} \simeq 1^\circ$ and $\Delta\Theta_{CoM,PLF} \lesssim 2^\circ$ resolutions in in-beam experiments. The new detector is intended to be mainly used for RIB experiments with reaccelerated beams, in particular nucleon transfer and Coulomb excitation.

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