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PLASTIC SCINTILLATOR DETECTORS FOR THE STUDY *
OF TRANSFER AND BREAKUP REACTIONS AT
INTERMEDIATE ENERGIES

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PLASTIC SCINTILLATOR DETECTORS FOR THE STUDY
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The detection of light particles associated with projectile like fragments can be used to separate transfer and breakup reactions provided the detectors cover a large solid angle. Three detection systems are described: (i) a 4π detector in the shape of a cube, 20 cm on a side, (ii) a X-Y position sensitive ΔE -E detector having an area of $20 \times 20 \text{ cm}^2$, and (iii) a multi-element detector consisting of eight position sensitive strips. The latter two detectors are of the phoswich type having the thin element of NE102 ($\tau=2.5 \text{ ns}$) and the thick element of NE115 ($\tau=225 \text{ ns}$). The performance characteristics of the three detectors are described.

I INTRODUCTION

The study of heavy-ion reactions becomes increasingly complicated at higher bombarding energies. At energies above 10 MeV/nucleon, the assumption of a two-body final state is no longer valid. A heavy ion in the exit channel may result from different, competing reaction pathways. A ^{12}C ion produced, e.g., in the reaction $^{20}\text{Ne} + ^{197}\text{Au}$ could originate via the following processes:

- i) transfer of ^8Be to the target: $^{197}\text{Au}(^{20}\text{Ne}, ^{12}\text{C})^{205}\text{Bi}^*$
- ii) inelastic scattering followed by the decay of the ejectile:
 $^{197}\text{Au}(^{20}\text{Ne}, ^{20}\text{Ne}^*); ^{20}\text{Ne}^* \rightarrow ^{12}\text{C} + 2\alpha$
- iii) transfer of one alpha particle to the target followed by decay of the ejectile: $^{197}\text{Au}(^{20}\text{Ne}, ^{16}\text{O}^*); ^{16}\text{O}^* \rightarrow ^{12}\text{C} + \alpha$
- iv) direct fragmentation: $^{20}\text{Ne} \rightarrow ^{12}\text{C} + ^8\text{Be}$

Reaction pathway i) is easily distinguished from ii)-iv) provided a 4π device enables rejection of all ^{12}C nuclei associated with light charged particles. A measurement of the energy, position, multiplicity and type of the light particles in coincidence with the heavy ion could, in principle, distinguish among reaction types ii) through iv).

Our first approach was to build a 4π array of plastic scintillators, which had the capability to detect charged particles with maximum efficiency and solid angle - the Plastic Box. It permits the above mentioned identification of reaction mechanism i), i.e., it separates transfer and breakup reactions. Later, the Plastic Box was upgraded by replacing individual elements of it by more elaborate detectors that provide more information on reactions ii) and iii). These detectors are referred to as Phoswich One and Two.

II THE PLASTIC BOX - THE POOR MAN'S γ -DETECTOR

II.1 Design

The Plastic Box consists of six walls of plastic scintillator arranged in a 20 cm cube around the target (Fig. 1). Each of the walls is made up of two parallel scintillator sheets (NE102) of 1 mm thickness. The plastic sheets are coupled individually via adiabatic light guides to RCA 8850 and 8575 photomultiplier tubes. The scintillators are wrapped with 6 microns of

Fig. 1. Schematic diagram of the Plastic Box .

aluminized mylar. Although this is a negligible thickness for light particles, the mylar prevents the detection of heavy residues or fission fragments. The purpose of the double layered wall with an inner (A) and an outer (B) element is to distinguish neutral particles hitting the Plastic Box from charged particles. Because of the close geometry the two layers provide, at best, only a crude particle identification (see Fig. 2). For obvious reasons, several walls must have openings. The extent of the slot in wall number 1 allows a maximum angle of 21° for the trigger telescope. Part of the solid angle lost due to this slot was regained by using another plastic scintillator wall behind the telescope. With all detectors in place, the total solid angle subtended by this arrangement was approximately 97% of the full 4π .

II.2 Operation

Fig. 2 shows a two dimensional plot of the light collected with layer A versus that in layer B for an actual experiment. In tests where light particles were well-collimated, protons and alphas were easily resolved. Here this separation is considerably degraded. This is due both to the averaging over many angles of incidence as well as the position dependence of the light collection. Fig. 2 also shows the portion of neutral particles seen with the plastic scintillators: due to the small absolute efficiency of the 1 mm NE102 for neutrons and gamma rays, the amount of neutrals seen in either one of the two layers is the same. The counts on the vertical line in Figure 2, representing those particles that caused a signal in layer B but not in A (i.e. neutrals) give a measure of the contribution of neutrons and gamma rays. In each event, the above described

features enable the unambiguous determination of the presence or absence of a charged particle in coincidence with a projectile-like fragment. For the reaction $^{20}\text{Ne} + ^{197}\text{Au}$ at 341 MeV, those yields are presented in Figure 3, where the quantity S stands for number of walls which have fired. This number is, insofar as multiple hits of one and the same wall are ignored, a direct measure of the number of light charged particles emitted in coincidence with the observed ejectile of charge Z . A detailed discussion of the operation of the Plastic Box and the results for ^{20}Ne on ^{197}Au at 220 and 341 MeV incident energy can be found in Refs. 1 and 2.

Fig. 2. A two-dimensional singles spectrum of the light output from the inner (A) and outer (B) paddles of the wall. Events appearing on the vertical axis are due to neutral particles.

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Fig. 3. The relative yield of ejectiles having none, one, or more than one scintillator wall in coincidence for an ejectile of charge Z , at a bombarding energy of 341 MeV.

III PHOSWICH ONE - ADDING PARTICLE IDENTIFICATION AND POSITION SENSITIVITY

III.1 Design

a) The Phoswich

The goal for Phoswich One was to obtain particle identification and position sensitivity and to do this in a size that could

replace one of the Plastic Box elements. Fig. 4 shows a sketch of the Phoswich One detector. Particle identification was achieved employing the phoswich technique (Ref. 3). Previous phoswich detectors typically had CaF_2 (which has a long decay time) as the first element ΔE counter. However, production limitations and cost restrict the size of the inorganic crystal and, therefore, the area of the whole detector. To get around these limitations we used a combination of NE102 (decay time

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Fig. 4. A sketch of the entire Phoswich One detector, including light guides, phototubes and bases.

$\tau=2.5$ ns) and a new plastic material NE115 which has a long decay time ($\tau=225$ ns). In contrast to other detectors (Refs. 3,4) the fast plastic scintillator is the first element of the phoswich (0.5 mm thickness). Since the light output of NE102 is higher than that of NE115, a reduction of thickness for the ΔE element is possible and, most important, good timing properties are obtained even for particles that do not penetrate into the second element. The first layer stops protons with $E < 6$ MeV and alpha particles with $E < 22$ MeV, and still gives a reasonable signal for 40 MeV protons. The second layer (4.5 mm thickness) of NE115 stops protons up to 20 MeV and alpha particles up to 90 MeV. The two layers were glued together with optical cement only at the edges to avoid a dead layer over the entire detector. The light is read out via twisted lightguides at each of the four edges of quadratic layers and fed into RCA 8575 phototubes. A typical signal from the phototubes is illustrated in Fig. 5. The sharp peak is from the ΔE plastic and the tail from the NE115 backing. The combined signal is analyzed by applying a short and a long gate, respectively, as shown in Fig. 5. Results for the particle identification will be shown in the next section on Phoswich Two. A more detailed description of Phoswich One is found in Ref. 6.

b) Position Sensitivity

To achieve position sensitivity, we made use of the natural light loss occurring at reflection from the scintillator surface due to surface irregularities (Fig. 6). We observed that, for a sufficiently thin sheet of scintillator the number of reflections that the light has to undergo to travel to the edge of the sheet is large enough to result in a dependence of the collected light

Fig. 5. Anode signals for reaction products from the reaction of 60 MeV alpha particles with Au nuclei. The gate signals used for the two QDC's were $T_1 = 30$ ns and $T_2 = 600$ ns.

on the distance of the light source to the photomultiplier. This behavior is shown in Fig. 7 together with Monte-Carlo simulations of light reflection from a partly irregular surface. Comparing the signals seen with the four phototubes allows the determination of the position where the particle hits the detector in both the X and Y directions. Fig. 8 shows the result of a test in which the detector was irradiated with scattered alpha-particles of 60 MeV beam energy. The figure

Fig. 6. Schematic illustration of light transmission by internal reflection in an ideal thin scintillator. The irregular surface of the real scintillator causes light loss for some of the reflections because the critical angle for internal reflection is exceeded.

Fig. 7. The light collected (in units of photoelectrons) at one end of a thin strip 20 cm long and 2 cm wide. Results for two thicknesses, 1 mm and 5 mm are given as a function of source distance along the strip. Solid lines guide the eye to the experimental data points. The dashed lines are results of a calculation described in the text.

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Fig. 8. A scatter plot showing the results obtained for alpha particles passing through the 16 holes of a mask. Holes 9-16 are beyond the grazing angle.

displays the image of a mask with 16 holes installed in front of the detector. Position and energy resolutions at 60 MeV were determined to be about 10 mm (FWHM) and 5-6% (FWHM), respectively. More details about reconstruction of position and energy will be presented in the next section.

IV PHOSWICH TWO - ADDING MULTIPLE HIT REGISTRATION

IV.1 Design

Although Phoswich One has several desirable properties, it still lacks the capability of multiple-hit registration. Therefore we gave up the continuous position information in one of the dimensions by segmenting the 20 by 20 cm² plane into 8

separate strips (Fig. 9). A strip has one phototube at each end, which allows continuous position determination along the strip. This design has the following major advantages: the detector can be operated at substantially higher integral count rates (which is of importance at forward angles where elastic scattering dominates), and it allows multiple hit registration.

IV.2 Operation

The strips of Phoswich Two have been tested using an 87 MeV alpha beam from the 88-Inch cyclotron. The beam current was reduced sufficiently so that the direct beam could be used to bombard the strips. Moving the horizontally positioned strip through the beam determined the position response. For each position the 87 MeV alpha beam was degraded in energy with aluminum foils of different thickness, providing alpha energies of

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Fig. 9. A sketch of the segmented Phoswich Two detector.

87, 79, 70, 60, 49, 35.5 and 14.5 MeV. Fig. 10 shows the spectrum of these energies measured with a strip. The figure does not yield the intrinsic energy/ resolution of the the phoswich detector directly since, for all but the highest energy, the energy spread in the degrader foils has to be taken into account. After correction for energy straggling in the degrader foils (Ref. 5) the energy resolution was determined to be 2.2, 2.4, 2.7, 3.1, 3.7, 5.8 and 32.8 % (FWHM) for the various alpha energies. The lowest energy alpha particles (14.5 MeV) were stopped in the thin ΔE layer, which results in a poorer resolution due to the stronger light attenuation in the layer. As shown in Fig. 11, the energy resolution is independent of position. The position was reconstructed according to equation (2) below. The position resolution is energy dependent and - after correction for beam spread due to multiple scattering in the degrader foils - is 0.4, 0.6, 0.8, 1.0, 1.3, 1.6 and 4.2 cm for

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Fig. 10. Energy spectrum of alpha particles. The various alpha energies were generated with the help of aluminum degrader foils of different thickness.

the different alpha energies.

If N stands for the number of light quanta produced by the ionizing particle, the light output I measured by the phototubes at the left and right edges of the scintillator can be described empirically by

$$I_{\text{left}} = N \cdot \exp(-ax + bx^2) \quad (1a)$$

$$I_{\text{right}} = N \cdot \exp(+ax + bx^2) \quad (1b)$$

where x is the position on the strip defined as

$$x := (I_{\text{left}} - I_{\text{right}}) / (I_{\text{left}} + I_{\text{right}}) \quad (2)$$

Therefore, the energy $E \sim N^{0.7}$ is given by the relation

$$E \sim (\sqrt{I_{\text{left}} \cdot I_{\text{right}} / \exp(2bx^2)})^{0.7} \quad (3)$$

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Fig. 11. Position spectrum of an 87 MeV alpha beam hitting a strip at different positions.

Finally, a test was performed by scattering alpha particles from a carbon target with the middle of the strip located at 43° . The result of this test is illustrated by a plot of the energy loss in the first layer versus the total energy deposited in the scintillators. Two bands are clearly defined (Fig. 12) and represent alpha particles and hydrogen isotopes. The lower band contains mainly protons, but it shows also a separated group of deuterons and tritons. A projection of alpha particles on the energy axis is given in Fig. 13. It indicates the resolution of the ground state and the first excited state of the ^{12}C target.

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Fig. 12 ΔE -versus- E_{total} plot of the reaction of 87 MeV alpha particles with ^{12}C . The plot is generated by gating on a narrow region of the position spectrum of one strip of Phoswich One.

Fig. 13. Projection of the alpha particles of Fig. 12 on the energy axis.

Given the thickness of the ΔE layer, the spectrum is cut at about 22 MeV for alphas. The good timing properties of plastic scintillator, however, should enable the separation of alphas and protons stopped in the first layer from other particles stopped there by time of flight. A time resolution of 580 ps (FWHM) was determined with a source and timing the two phototubes versus each other.

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