LIGHT PARTICLE DETECTION BY BGO SCINTILLATORS WITH PHOTODIODE READOUT

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The application of a BGO crystal coupled to a photodiode for detection of light charged particles in the energy range of 5-170 MeV has been investigated. Energy resolution, light output and scintillation efficiency have been deduced from the data.

1. Introduction

The detection of light charged particles of some ten to some hundred MeV is usually achieved by semiconductors of appropriate thickness (Si(Li) or Ge(Li) detectors), or by energy resolution is of minor importance, by scintillators (plastic, Na(Tl) etc.) with photomultiplier readout. The geometrical dimensions of the crystal in the first case or the length of the phototube with the voltage divider in the second often cause problems to the mechanical mounting in standard scattering chambers.

A promising, space saving alternative to conventional counters is now offered by BGO crystals \( \text{Bi}_4\text{(GeO}_2\text{)}_5 \) connected to large area silicon photodiodes with sufficient rise time and sensitivity in the appropriate spectral region (400-500 nm), which have recently become commercially available at reasonable prices. Because of the relatively long maximum emission wavelength of 480 nm, BGO is better suited for use with red sensitive Si photodiode than many other scintillation materials. The suitability of BGO crystals in gamma-spectroscopy at low and high energies [1,2] as well as to applications in high energy physics calorimetry [3] has already been proved in recent experiments. In order to test the applicability for detection of light charged particles from medium energy nuclear reactions in the range of some ten to some hundred MeV we performed an experiment at the Jülich isochronous cyclotron JÜLIC with the 170 MeV \( \alpha \)-particle beam.

Due to the high density of BGO (\( \rho = 7.13 \text{ g/cm}^3 \)) the \( 1 \times 1 \times 1 \text{ cm}^3 \) crystals used are able to stop protons of about 69 MeV and \( \alpha \)-particles of 275 MeV.


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2. Experimental details and results

The BGO detector was delivered by Harshaw Company and optically coupled to a Hamamatsu R7122-64 silicon photodiode with an active area of \( 1 \times 1 \text{ cm}^2 \). A photograph of this device is shown in fig. 1. In our experiment we used crystals which were sprayed with titanium dioxide reflector paint, but they could just as well be covered by aluminized mylar foils which would cause a thinner dead layer in front of the crystal.

In fig. 2 a sketch of the experimental setup with the electronics is given. Due to the small dimensions of the assembly the crystal could be mounted in a standard housing for Si surface-barrier detectors (see fig. 1), together with a 1000 \( \mu \text{m} \) Si counter (\( \Delta E \)) and a 3 mm diameter tantalum aperture. The collected charge of the high capacitive photodiode (\( \sim 100 \text{ pF} \)) was amplified by an Ortec 142B preamplifier which was connected to an Ortec 451 spectroscopy amplifier with a shaping time of 2 \( \mu \text{s} \). The diode gave the best signal to noise ratio when reverse-biased at 13 V.

In addition, a conventional plastic scintillator telescope was mounted in the scattering chamber to allow the detection of kinematical coincidences between \( \alpha \)-particles and recoil protons scattered from a 6 \( \mu \text{m} \) Mylar target. For off-line analysis the signals were recorded on tape every event.

To give a first impression of the applicability of this detector, fig. 3 shows the \( \Delta E-E_{\text{MeV}} \) scatter plot which demonstrates the excellent particle discrimination between \( p, d, t \). \( He \) and \( \alpha \)-particles. A peculiarity of this device is that the punch-through particles, which directly hit the depletion layer of the photodiode, give a very high \( E_{\text{MeV}} \) signal and therefore do not disturb the lower mass particle spectra.

To determine the energy resolution of the BGO detector the kinematical coincidence between the recoil protons and \( \alpha \)-particles was used. Fig. 4 shows the ratio of the uncorrected (upper part) and the coincident (lower part)
proton spectra, which were measured at $\theta_{lab} = 45^\circ$ with a Mylar target. The derived full width half-maximum energy resolution of this elastic proton peak at $E_{lab} = 32$ MeV, after correction for kinematical broadening, is 1.5 MeV, which is comparable to that of a NaI(Tl) photomultiplier detector under similar conditions and acceptable for most applications in this energy region.

While the maximum detectable particle energy of this detector is limited by the size of the crystal, the low energy cut-off is given by the noise level in the photodiode–preamplifier circuit. Due to the high intrinsic noise of the high capacitive photodiode and the low light output of BGO [10–12% relative pulse height to NaI(Tl)], these minimum energies turned out to be approximately 4 MeV for protons and 8 MeV for $\alpha$-particles. This low energy threshold may be reduced significantly by cooling the device, which lowers the noise level in the photodiode and raises the light yield of the scintillator [4].

One disadvantage of the BGO-photodiode assembly

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**Fig. 1.** BGO crystals (1 cm$^3$) mounted on a 1 cm$^2$ sensitive area photodiode and sprayed with TiO$_2$ as light reflector paint.

**Fig. 2.** Sketch of the experimental setup. In the coincidence mode the elastic scattered $\alpha$-particles were measured with the Si-plastic telescope at $\theta_{lab} = 14^\circ$. 
3. Scintillation response

It is well known that the differential light output, $dL/dx$ of organic and inorganic scintillators is a non-linear, particle dependent function of the differential ionization energy loss, $dE/dx$. This nonlinear response has been attributed by Birk's [6] to the quenching of primary excitation by the high density of excited molecules, or, in the case of activated inorganic scintillators, by the depletion of available activator sites [7].

To determine the scintillation response of BGO, the light output for the various particles as a function of the incident energy must be known. This calibration of the Si-BGO telescope was achieved by using the $\Delta E - E_{\text{miss}}$ correlations of all the measured data points. Therefore the surface-barrier detector was calibrated during the experiment by detecting the $\alpha$-particles of a mixed alpha source. In addition a pulse generator calibration was performed to establish the adc offset. By using this accurate $\Delta E$ calibration and the well known thickness of the surface barrier detector one can deduce the incident particle energy from the $\Delta E$ signal with the aid of energy-loss tables. This was done by fitting every particle-branch in the $\Delta E - E_{\text{miss}}$ plot with a proper $E_{\text{miss}}$ parametrization. Several known discrete peaks in the different particle spectra have additionally been used to check the result of the fitting procedure. The error of the $E_{\text{miss}}$ calibration has been estimated to be less than 4% up to the maximum particle energies.

While photomultipliers suffer from saturation effects at higher light intensities, the great advantage of photodiodes are the high linearity with the range of linearly achievable reaching 6–8 orders of magnitude. A direct measure of the light output accumulated by the photodiode is therefore provided by the $E_{\text{miss}}$ calibration curves. Due to the small dimensions of the crystal and the good matching to the photodiode, the light losses are small and the influence of the position variation of the light creation is negligible.

In fig. 5 the light output $L$, in arbitrary units, is shown as a function of the deposited energy $E$ in the crystal. The dashed lines are extrapolated from the maximum particle energies in the crystal to higher energies.

Differentiation of $dE/dx$ with respect to ion energy gives the relative scintillator efficiency $dL/dE$. We have deduced $dL/dE$ by numerical differentiation of the smooth empirical calibration curves shown in fig. 5. The result in the case of protons and $\alpha$-particles is plotted in fig. 6 versus the differential energy loss $dE/dx$. It can be seen that $dL/dE$ is not constant, except at high energies ($E_0 \gtrsim 30$ MeV). In analogy to measurements with plastic and NaI(Tl) scintillators [8,9] the variation of $dL/dE$ with energy is similar for different ions, but the magnitude depends on the particle charge $Z$. The data exhibit the well known saturation effect of scintillators, i.e. $dL/dE$ decreases rapidly with increasing ionization density. As pointed out by Birk's [6], there is a different behaviour in the dependence of $dL/dE$ on $dE/dx$ for organic and inorganic...
compact devices would be a detector-stack or -array to extend the dynamical range of the detector.

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References