Nuclear Instruments and Methods in Physics Research 225 (1984) 330–334
North-Holland, Amsterdam

THE RESPONSE OF BGO SCINTILLATION DETECTORS TO LIGHT CHARGED PARTICLES

E.A. BAKKUM, C.P.M. van ENGELEN and R. KAMERMANS

Fysisch Laboratorium, Rijksuniversiteit Utrecht, P.O. Box 80.000, 3508 TA Utrecht, The Netherlands

T.A. TEELING and L.J.M. TIMMERMAN

Harshaw Chemie B.V., P.O. Box 19, 3454 ZG De Meern, The Netherlands

Received 8 March 1984

Measurements of the response of BGO crystals to protons in the energy range from 6 to 13 MeV and to alpha particles in the range from 6 to 19 MeV are discussed. Results were obtained with a photomultiplier tube and a photodiode readout. A comparison is made with the response of a NaI(Tl) crystal to 13 MeV protons.

1. Introduction

In recent years there is an increasing interest in nuclear reactions between heavy ions at high incident energies. Experiments indicate that, at least above 10 MeV/nucleon, processes in which highly energetic light particles ($10 \leq E \leq 100$ MeV) are emitted contribute significantly to the total reaction cross section [1,2]. A sensitive way to study the underlying reaction mechanisms is provided by the detection of the energetic light particles in coincidence with other reaction products. This requires the use of several multiple detector systems (telescopes). The telescopes should preferably be of a limited size, since correlation experiments normally have strong geometrical constraints like the minimum relative angle to be measured and the size of the scattering chamber. In most of these experiments ΔE–E telescopes consisting of a combination of a thin surface barrier Si detector and a NaI(Tl) scintillation detector have been used [1–3]. This is mainly due to the fact that commercially available Si detectors are not thick enough to serve as a stop detector for the light particles at these energies, whereas Ge detectors have to be cooled to liquid nitrogen temperature, which seriously complicates the experimental setup.

A new scintillation material, which has many advantages compared to NaI(Tl), is bismuth germanate (or simply BGO) [4–6]. The main attraction of BGO is its high stopping power due to the high atomic number of bismuth. In addition, it is mechanically and chemically rugged and non-hygroscopic. Moreover it is a pure scintillator, which means that BGO is free of problems associated with a non-uniform dopant distribution. A drawback is its lower light output as compared to NaI(Tl) (10–15% for ^{137}Cs 662 keV gamma rays [6]). This results in an energy resolution which is worse than for NaI(Tl) (a factor 1.5 for 662 keV gamma rays [6]). However, at higher energies the difference in energy resolution becomes smaller [7]. At the moment there is no information with respect to the response (resolution, linearity etc.) of BGO to light ions.

In this paper data on the response of BGO crystals to protons in the energy range from 6 to 13 MeV and to alpha particles in the range from 6 to 19 MeV are reported. Measurements were performed with a photomultiplier and a photodiode readout. A photodiode is much smaller than a photomultiplier tube, thus allowing a considerable reduction of the size of the detector. In addition a photodiode has a better short and long term stability and is linear in light conversion over many orders of magnitude of intensity variation [8]. Since the photodiode has no internal amplification like the photomultiplier, the integrated charge is independent of the applied bias voltage circumventing the calibration of each individual experiment. A disadvantage is the poor signal to noise ratio with respect to the photomultiplier tube [8]. For comparison also the response to 13 MeV protons of a NaI(Tl) crystal with a photomultiplier readout was measured.

2. Experimental technique

Beams of 6–13 MeV protons and 8–20 MeV alpha particles were produced with the Utrecht 7 MV EN tandem Van de Graaff accelerator. The ions were elastically scattered from a 60 μg/cm^2 Au target. The ejectiles were deflected by an Enge split-pole spectrograph

0167-5087/84/$03.00

to the BGO detectors, which were placed in its focal plane. The spectrograph was placed at a scattering angle of 20°. The use of the magnetic spectrograph allowed scanning over the crystal surface by changing the magnetic field and effectively reduced the gamma ray yield. It proved to be not necessary to magnetically shield the photomultiplier with mu-metal from the fringing field of the spectrograph. The BGO detectors were provided by Harshaw Chemie BV, Holland. One consisted of a cylindrical BGO crystal with a diameter of 3.8 cm and a length of 2.5 cm mounted in optical contact with the photosensitive surface of an EMI 9856 photomultiplier tube. The other BGO crystal ($1.0 \times 1.0 \times 1.0$ cm^3) was mounted on a Hamamatsu 1723 photodiode. Since inhomogeneities in the thickness of the entrance layer of the detectors will significantly influence the energy resolution, the 6.3 μm Havar entrance foils were not coated with reflection material. Calculations show that, due to energy loss in the entrance foil, the energy deposited in the crystals ranges from 6 to 13 MeV for protons and from 6 to 19 MeV for alpha particles (see sect. 3.1). In all measurements the working voltage of the photomultiplier and the photodiode were 970 V and −30 V respectively. The photomultiplier signal was processed by an Ortec 113 preamplifier. In order to avoid noise due to cables an adapter was used for direct attachment of the photodiode to an Ortec 121 preamplifier. The preamplifier was matched to the large diode capacitance by a modification of the feedback capacitor (2.2 pF) and the decoupling capacitor (2.7 nF). The signals were amplified with standard Ortec 472 spectroscopy amplifiers (shaping time constant 0.5 μs for PM, 6 μs for PD) and stored on magnetic tape by a PDP-11/34 computer. Count rates were kept at about 500 Hz, however, it was found that the response of the detectors did not deteriorate for count rates up to 50 kHz. In order to compare the light output (fluorescence radiation) for protons and alpha particles, the pulse height of 13 MeV protons and 19 MeV alpha particles were measured in a single run.

In a separate measurement the response of a NaI(Tl) crystal, mounted on a Hamamatsu R750 photomultiplier tube, to 13 MeV protons was determined. The working voltage was 765 V and the electronical setup was identical to the setup used for the BGO crystal with a photomultiplier readout.

3. Results and discussion

3.1. Pulse height versus energy

In figs. 1 and 2 the variation of the mean pulse height with the energy for protons and alpha particles is shown for the BGO crystals with photomultiplier and photodiode readout, respectively. The energies of the light particles are corrected for losses in the target and in the entrance foil of the detectors. In the calculations of the energy losses the stopping powers tabulated by Andersen and Ziegler [9] were used. The corrections introduce an error in the energies of less than 3%. Kinematical effects in the target were negligible. The pulse heights at the various energies could be determined to within 1%. The pulse height for low energy alpha particles could not be determined accurately with the photodiode readout due to the small signal to noise ratio, as will be discussed later. It is clear from the figures that the BGO crystals have a linear response of pulse height to energy for protons in the entire region investigated, deviations from linearity are less than 3%. However, extrapolation of these lines yields a negative intercept with the vertical axis. The response curve of the crystals to alpha particles is slightly convex. In

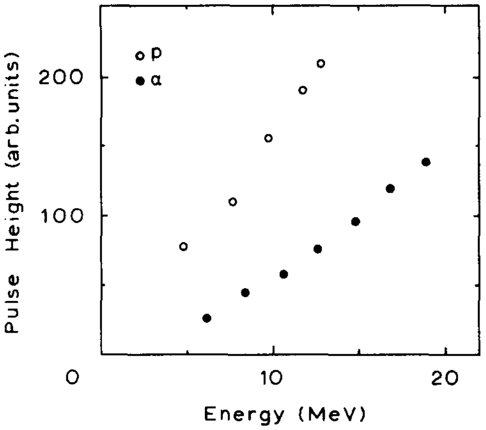

Fig. 1. Pulse heights resulting from the fluorescence radiation of BGO as a function of particle energy (corrected for energy losses in the target and the entrance foil). The light output was detected with a photomultiplier.

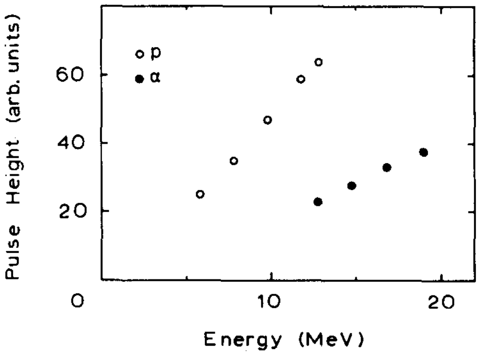

Fig. 2. Pulse heights resulting from the fluorescence radiation of BGO as a function of particle energy (corrected for energy losses in the target and the entrance foil). The light output was detected with a photodiode.

addition, the light output of the crystals is considerably less for alpha particles than for protons of the same energy. Thus the pulse height is not proportional to the energy deposited in the crystal by the particles. The deviations have also been found for other inorganic [10,11] and organic [10] scintillators. It is commonly attributed to a dependence of the scintillation efficiency (the slope of the pulse height versus energy curve) on the ionization density along the path of the particle in the crystal. For differential energy losses dE/dx above a certain value the scintillation efficiency starts to decrease. This brings on a convex behaviour of the pulse height versus energy curve for low energies, which becomes more pronounced for heavier particles. On the basis of stopping powers [9] and the data shown in figs. 1 and 2 it is estimated that for BGO values of dE/dx above 40 keV/(mg/cm^2) give rise to a nonlinear behaviour.

The pulse height of the NaI(Tl) crystal for 13 MeV protons was also measured. For a comparison with the BGO crystal data a good reference is provided by the pulse height of gamma rays, since it is fairly proportional to the energy deposited in the crystal [11]. The ratio of the proton pulse height to the pulse height of 662 keV gamma rays of a ^{137}Cs source was a factor 1.3 larger for NaI(Tl) than for BGO. The difference is probably caused by the smaller proton stopping power of NaI(Tl). This results in a decrease of the scintillation efficiency of NaI(Tl) at values of dE/dx above 100–200 keV/(mg/cm^2), depending on the Tl concentration [12]. Since these values are higher than for BGO, the ionization density effect is less pronounced.

It should be noticed that for very energetic light particles ($E \gtrsim 50$ MeV/nucleon) the loss of particles due to nuclear inelastic interactions in the crystal is considerable [13]. This results in a low-energy tail in the particle spectrum. Such a tail was not observed in the present experiments, since for the energies considered the ranges in the crystals and the total reaction cross sections were small. Calculations proceeding by a simple step integration method [13] show that the interaction loss is less than 1% for 6–13 MeV protons and 6–19 MeV alpha particles.

3.2. Resolution versus energy

The energy resolution of BGO as a function of the particle energy is shown in fig. 3 for the photomultiplier readout system. It is well known that for low energies the resolution is approximately inversely proportional to the square root of the mean number of photons produced per scintillation [13]. Therefore the data in fig. 3 were fitted with the curves fwhm(protons) = (17.6 ± 0.4)%/$\sqrt{E}$ [MeV] and fwhm(alpha particles) = (32.2 ± 1.1)%/$\sqrt{E}$ [MeV] (solid curves). A good fit is obtained for the proton data, but deviations are observed for the alpha particles. In addition the resolution is worse for alpha particles than for protons. These effects are caused by the dependence of the number of photons on the ionization density in the crystal, as discussed in the preceding section.

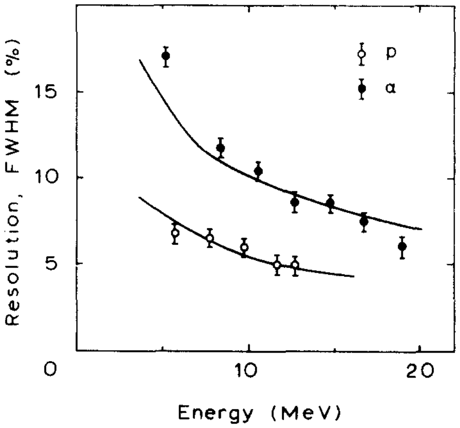

Fig. 3. The energy dependence of the resolution of the BGO crystal with a photomultiplier readout for protons and alpha particles. The solid curves are fits to the data under the assumption of a $1/\sqrt{E}$ dependence.

The resolution of the BGO crystal with a photomultiplier readout shown in fig. 3 is slightly worse for protons than for gamma rays of the same energy [5,7]. This is, at least partly, due to the lower light output for protons. The pulse height per MeV for gamma rays from ^{137}Cs and ^{60}Co sources, placed in front of the detector, was found to be a factor 1.6 larger than for 13 MeV protons.

The resolution of the NaI(Tl) detector was 2% for 13 MeV protons, which is a factor 2.5 better than the resolution of the BGO detector. This is in agreement with the results given in ref. [6], which show that the light output of BGO is 10–15% compared to NaI(Tl).

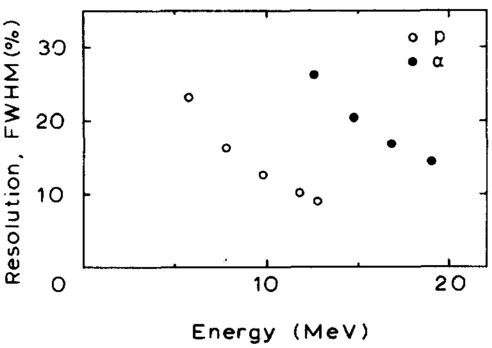

Fig. 4. The energy dependence of the resolution of the BGO crystal with a photodiode readout for protons and alpha particles.

In fig. 4 the energy resolution of BGO as a function of the particle energy is shown for the photodiode readout. The resolution in channels is constant for all particles and energies considered in the present experiments (5.9 ± 0.5 in the units of fig. 2). It is equal to the electronic resolution and thus determined by the signal to noise ratio. The noise level is equivalent to 1.2 MeV for protons, which is consistent with results for cosmic ray muons [8]. It is clear from figs. 3 and 4 that the energy resolution is considerably worse with a photodiode than with a photomultiplier readout. However, a comparable performance is expected at particle energies above 50 MeV.

3.3. Pulse height versus position

In order to investigate the position dependence of the energy signal due to inhomogeneities in the entrance foil or in the crystal itself, the surface of the BGO detectors was scanned with 13 MeV protons and 20 MeV alpha particles. The trajectories of the elastically scattered particles could be varied with the magnetic field of the spectrograph. The focal plane position of the light particles was calculated in order to determine the pulse height as a function of the place of incidence. The results for the BGO crystal with the photomultiplier readout are shown in fig. 5, similar results were obtained with the photodiode readout. The centre of the entrance window is arbitrarily chosen in the middle of the horizontal scale. The proton measurements were limited to the central region, but the alpha particle measurements were extended to the edges of the crystal, because changes in the pulse height will be more pronounced for alpha particles due to their relatively large stopping power. The pulse height is fairly constant in the central region, however, near the edges a somewhat increased light output is observed. This is possibly caused by an enhanced yield due to better light reflection conditions. The measurements described in sections 3.1 and 3.2 were performed with light particles incident on the central region of the detector entrance window.

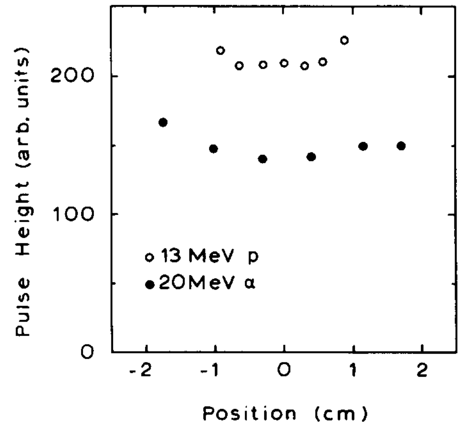

Fig. 5. The pulse height, obtained with a photomultiplier, of 13 MeV protons and 20 MeV alpha particles as a function of the position of incidence of the entrance window. The centre of the entrance window is chosen as the origin of the horizontal scale.

4. Concluding remarks

The present experiments show that BGO scintillation crystals are versatile for the detection of energetic light particles with multiple detector systems. This is especially true for experimental configurations, in which the geometrical contraints are more stringent than the requirement of a high energy resolution. At particle energies above 50 MeV the resolution will be less affected by the relatively low light output of BGO, and resolutions comparable to those of NaI(Tl) are expected. Since the light output of BGO, like other scintillation materials, is not proportional to the particle energy deposited in the crystal energy calibration measurements are necessary.

The size of the detector can be reduced by using a photodiode instead of a photomultiplier readout system. For low energies this results in a significant deterioration of the resolution, but at energies above 50 MeV competitive resolutions can be expected.

This work was performed as part of the research program of the 'Stichting voor Fundamenteel Onderzoek der Materie' (FOM) with financial support from the 'Nederlandse Organisatie voor Zuiver-Wetenschappelijk Onderzoek' (ZWO).

References

[1] T.C. Awes, G. Poggi, C.K. Gelbke, B.B. Back, B.G. Glagola, H. Breuer and V.E. Viola, Jr, Phys. Rev. C24 (1981) 89.
[2] T.C. Awes, S. Saini, G. Poggi, C.K. Gelbke, D. Cha, R. Legrain and G.D. Westfall, Phys. Rev. C25 (1982) 2361.
[3] R.L. Auble, J.B. Ball, F.E. Bertrand, C.B. Fulmer, D.C. Hensley, I.Y. Lee, R.L. Robinson, P.H. Stelson, D.L. Hendrie, H.D. Holmgren, J.D. Silk and H. Breuer, Phys. Rev. Lett. 49 (1982) 441.
[4] O.H. Nestor and C.Y. Huang, IEEE Trans. Nucl. Sci. NS-22 (1975) 172.
[5] A.E. Evans, Jr., IEEE Trans. Nucl. Sci. NS-27 (1980) 172.
[6] M.R. Farukhi, Proc. BGO Workshop, Princeton (1982) 21.
[7] D.M. Drake, L.R. Nilsson and J. Faucett, Nucl. Instr. and Meth. 188 (1981) 313.
[8] G. Blanar, H. Dietl, J. Dobbins, G. Eigen, E. Lorenz, F. Pauss, W. Pimpl, H. Vogel and P. Weissbach, Internal Report, Max Planck Institute, Munich.
[9] H.H. Andersen and J.F. Ziegler, The stopping powers and ranges of ions in matter, vol. 3 (Pergamon, New York, 1980).

[10] C.J. Taylor, W.K. Jentschke, M.E. Remley, F.S. Eby and P.G. Kruger, Phys. Rev. 84 (1951) 1034.
[11] R. Gwin and R.B. Murray, Phys. Rev. 131 (1963) 501.
[12] F.S. Eby and W.K. Jentschke, Phys. Rev. 96 (1954) 911.
[13] D.F. Measday and R. Richard-Serre, Nucl. Instr. and Meth. 76 (1969) 45.
[14] J.B.A. England, Techniques in nuclear structure physics, Part 1 (Macmillan, London, 1974).