université paris sud
INSTITUT DE PHYSIQUE NUCLEAIRE
B.P. N° 1   91406 - ORSAY   TEL. 941.51.10
laboratoire associé à l'IN2P3

FR8002825

poor quality

PERFORMANCE OF A HIGH PURITY GERMANIUM MULTI-DETECTOR TELESCOPE FOR LONG RANGE PARTICLES

G. RIEPE, D. PROTIĆ, C. ŠUKOŠD

Institut für Kernphysik der Kernforschungsanlage
Jülich GmbH D-5170 Jülich, West Germany

J.P. DIDELEZ, N. FRASCARIA, E. GERLIC
E. HOURANI*, M. MORLET

Institut de Physique Nucléaire
B.P. N° 1, F-91406 Orsay, France

IPNO-PhN-80-18

Performance of a High Purity Germanium Multi-Detector Telescope for Long Range Particles

G. Riepe, D. Protić, C. Sükösd

Institut für Kernphysik der Kernforschungsanlage Jülich GmbH
D-5170 Jülich, West Germany

J.P. Didelez, N. Frascaria, E. Gerlic, E. Hourani*, M. Morlet

Institut de Physique Nucléaire
B.P. No. 1, F-91406 Orsay, France

Abstract

A telescope of stacked high purity germanium detectors designed for long range charged particles was tested using medium energy protons. Particle identification and the rejection of the low energy tail could be accomplished on-line allowing the measurement of complex spectra. The efficiency of the detector stack for protons was measured up to 156 MeV incoming energy. The various factors affecting the energy resolution are discussed and their estimated contributions are compared with the experimental results

*Permanent address: Lebanese University, Faculty of Science, Hadat-Beyrouth, Lebanon

Introduction

The detection of long range particles by semiconductor detectors is limited by three factors: 1. the detector thickness which must be larger than the range, 2. the detector diameter which must be large enough to take care of the increasing radial spread due to multiple scattering, 3. the efficiency which drops gradually with increasing range due to nuclear reactions. These latter effects cause significant low energy tailing of the peaks distorting the spectrum. For example, 8 cm of germanium are necessary to stop 200 MeV protons, 25% of which undergo a nuclear reaction before stopping while as much as 10% are scattered out of a detector with 3 cm diameter[1]. Since the maximum detector dimension, which can be realized between its two contacts is about 20 mm, it seems reasonable to meet the above listed requirements by stacking several planar detectors with thin enough dead layers on both sides. The use of a side-entry type detector[2] can only be suggested if the high contribution from multiple scattering, resulting in a pronounced low-energy tailing of the peaks, does not impede the evaluation of the spectra.

High-purity germanium (HPGe) detectors with both contacts made by ion-implantation recently developed in Jülich[3] are particularly suitable for this purpose: they have very thin dead layers ($\sim$ 0.2 μm) and are reasonably thick ($\sim$ 15 mm) with sensitive areas as large as 14 cm^2. Stacking of detectors has the additional advantage that the amount of energy lost by a particle in each slice of the telescope is available, and this information cannot only be used for particle identification but also for low energy tail rejection[1].

In order to check the performance of such a detector telescope, 6 HPGe detectors with a total thickness of 66 mm were mounted inside a special cryostat[4]. Several experiments were performed using medium energy protons from the Orsay synchrocyclotron to check the obtainable energy resolution, the particle identification (PID), the low energy tail rejection (LETR), the efficiency as a function of incident energy, and the ability to reconstruct complex spectra after PID and LETR.

The High Purity Germanium Multi-Detector Telescope

The detector stack consisted of 6 HPGe detectors with a total thickness of 66 mm. Each detector had both contacts made by ion-implantation (phosphorous and boron) and was fabricated at KFA Jülich[3]. The thickness of the resulting dead layers was between 0.2 and 0.3 μm as measured with an ^{241}Am alpha source. The operating bias of all detectors was several hundred volts higher than needed for total depletion. The sensitive areas were from 450 to 900 mm^2, and the thicknesses from 2.5 to 14.5 mm. Each detector was mounted in a separate holder which could be fixed to the optical bench-like cold finger of the cryostat, similar to the set-up shown in figure 1. The 2.5 mm thick detector was mounted as the first one, the Si detector shown had been omitted. Since the detector holder used had been designed for a different purpose it was not ideally suited for this stack arrangement. As a consequence the distances between adjacent detectors were so large that the total length of the stack amounted to 153 mm as compared to 66 mm of germanium. This situation certainly increases the number of particles scattered out before they are stopped, and therefore not contributing to the full-energy peak.

The bore of the tantalum collimator was 6 mm, its thickness being 27 mm. The first detector was 14 mm apart from it.

The entrance window of the cryostat was made of 6 μm thick HAVAR foil (Hamilton Watch Co.) and had a diameter of 25 mm.

The detector stack was kept at room temperature until right before use, not only for ease in handling during storage and transport but also to reduce the condensation of residual gases on the detectors. This effect can be noticed even at high vacuum, depends on the cooling time and causes the dead layers to grow.

Experimental Arrangement

A germanium multi-detector telescope has already been used to detect high energy particles[1)], but the detection was limited to monoenergetic beams by triggering the telescope on the desired particles.

In order to test the above described telescope in a realistic experimental situation it was exposed to the reaction products of 170 MeV protons hitting a CD_2 target, and data from each detector were recorded. This target is very suitable for this purpose, since the $^{12}C(p,p')$ reaction provides well separated peaks (ground state and the first excited states at 4.4, 7.5 and 9 MeV), and the D(p,p') reaction provides another proton peak mostly at much lower energy (depending on the scattering angle). In addition, the presence of deuterium in the target produces a large flux of deuterons either by scattering or by pick-up reactions. Particles of mass three and four are more scarce but also present.

The energy spread of the incident proton beam was of the order of 600 keV. The target had a thickness of 10 mg/cm^2. The telescope was placed outside a scattering chamber at an angle of 24^0 having a distance of 60 cm from the target. The exit window (Al) of the scattering chamber had a thickness of 0.2 mm, and the entrance window of the cryostat was 20 mm apart from it.

For the particle identification and for the determination of the total particle energy very precise calibrations are necessary. A precision pulser (ORTEC 448) which had been calibrated with the 2.6145 MeV γ-line of ^{208}Tl for each detector was used for this purpose. Pulses corresponding to up to 170 MeV were accumulated in 10 MeV steps. If charge one and charge two particles have to be recorded simultaneously very wide dynamics is needed in each linear chain, since charge two particles deposit all their energy in the first two detectors (till 110 MeV in the first detector for alpha particles for example) while 170 MeV protons leave only about 4 MeV in the first detector. The gain of each linear chain has been set for optimum proton detection which necessarily results in some cut-offs in the spectra of heavier particles.

The analog signals from the five linear chains were fed into linear gates which were opened only when a coincidence occured between successive detectors. The logic signals produced by TSCA units using the bipolar outputs of the linear amplifiers were fed to a multipurpose coincidence unit "CAL1" developed at Orsay[5]. This unit allows selecting any kind of coincidence between the five inputs and produces a five bit label related to the number of HPGe detectors necessary to stop the detected particles. The five ADCs and the CALI were interfaced to a HP computer. This way each event was determined by 6 parameters, and was recorded on tape in list mode.

The particle identification (PID) was achieved using the conventional relation

$$\frac{\Delta x}{\alpha} = (E + \Delta E)^{1.76} - E^{1.76} \qquad (1)$$

which gives a figure proportional to the ΔE detector thickness Δx. The parameter α only depends on the mass and charge of the particle. For particles penetrating the first N detectors we took for ΔE the sum of energy losses: ΔE_1------ΔE_{N-1}, and for E the energy lost in detector N: ΔE_N, since this partition gives the best separation between different particles[1]. A PID value independent of the number of detectors involved, namely $\frac{1}{\alpha}$, was obtained by dividing the result of (1) by the thickness of the N - 1 first detectors. A large fraction of the recorded data could be treated on-line by the HP computer which generated a two-dimensional display of PID versus total energy as shown in figure 2). The separation between protons, deuterons and tritons is clearly visible. It is remarkable that the PID signal indeed is rather independent of the number of detectors involved and of the total energy of the particle. Counts lying between the particle bands are either due to pile-up or particles undergoing nuclear reactions in the germanium or escaping by scattering. Regions of the two-dimensional display corresponding to a given number of detectors involved are clearly separated by exponential lines. They correspond to accidental coincidences between a particle recorded in the N-1 detectors and a small pulse in detector N, resulting from γ-background for example. In this case relation (1) becomes close to $\Delta E^{1.76}$. The intensity of those lines is a clear indication of too high a counting rate for a given experimental situation. Finally, holes showing up in the particle bands of the PID display - as clearly seen for example in the middle fo the deuteron band - are due to insufficient dynamics for those particles for which one ADC saturates.

Setting a PID window on the proton band (causing LETR at the same time) we obtained the spectrum shown in figure 3). The peaks from the ground state and the excited states of ^{12}C are clearly separated with an energy resolution of 650 keV (fwhm) of which the largest contribution was due to the beam energy spread. Low energy tailing is almost completely suppressed. Some high energy tailing due to pile-up is showing up, being caused by the intense γ-background associated with high energy protons.

There is little evidence of dips resulting from dead layers or thresholds when going from a N-1 detector event to a N one. The dip showing up around 80 MeV in the continuous part of the proton spectrum is due to insufficient dynamics of ADC 2 rather than to threshold or dead layer effects. (The effects from dead layers are negligible as compared to those from electronic thresholds.)

All other types of particles up to ^{4}He which were not stopped in the first detector could be identified simultaneously, but large holes in their spectra due to limited dynamic range are apparent.

Efficiency and Energy Resolution of the Telescope

In order to determine the efficiency and the energy resolution of the telescope as a function of the proton incident energy the following experiment was performed. The primary proton beam was focused onto a CH_2 target, and the particles scattered at a given angle were deflected and momentum analyzed by the Orsay magnetic spectrometer "Montpellier".

The telescope was placed behind the magnet on the optical axis. A 6 mm diameter collimator defined a pencil beam entering the telescope. Its energy width $\Delta E/E$ given by the dispersion properties of the system was estimated to be 2.2×10^{-3}. The mean energy could be easily varied by changing the angular position and the field of the deflecting magnet according to the two body proton-proton kinematics. Using this method data were taken from 95 MeV to 156 MeV. These measurements therefore comprise the energy range of protons from those which stop in the first two detectors to higher energy ones which reach the last detector. (In this particular set-up the total thickness of 5 HPGe detectors was only 53 mm).

The efficiency was measured as the ratio of the number of events in the peak to the number of counts in the first two detectors if their signals were equal to energy losses ΔE_1 and ΔE_2 corresponding to the sum energy E.

The detector areas being very large compared to the diameter of the collimator it is anticipated that the loss by multiple scattering is negligible in the first two detectors. On the other hand, the loss by nuclear reaction occuring in the first two detectors can be calculated from the known total reaction cross section which is fairly constant in this energy range[6].

This method of measuring the efficiencies as a function of proton energy gave more consistent results than a comparison of the number of counts in the peak and its associated tail, because the spectrum just begins at an energy which a proton needs to penetrate the first detector.

However, there might be systematic errors in the absolute values. Therefore the whole efficiency curve was normalized to the calculated efficiency for particles just escaping the first two detectors.

Figure 4) shows the experimental points together with the calculated efficiency curve taking into account only nuclear reaction losses according to reference 7). The difference between experimental points and the calculated curve can be explained by multiple scattering losses which, due to the geometry of this telescope, increase fairly fast with the path of the stopped particles.

Figures for the resolution ΔE(fwhm) obtained for various proton energies are given in table I. It is interesting to note that the relative resolution $\Delta E/E$ is the same within ±3% for all energies, namely $(2.52 \pm 0.08) \times 10^{-3}$.

These figures for the peak half-width are made up of contributions from several sources: beam, window effects, detector system, electronics and low-energy γ-background, which will be considered in detail.

The energy spread of the beam was estimated according to Monte Carlo calculations concerning the particle trajectories in the beam transport system to be proportional to the energy and amounting to 330 keV at 150 MeV, for a collimator of 6 mm diameter.

This value does not include contributions due to energy loss straggling in the exit window of the magnet (0.1 mm Mylar), the entrance window of the cryostat (6 μm Havar) and the air gap in between. These three contributions together, however, amount to only 19 keV[8].

The detector system and the electronics contribute to the peak broadening by the following effects: electron-hole pair statistic (Fano factor of 0.05), 9 dead layers of the HPGe detectors (each about 0.3 μm), electronic noise of 5 linear chains, calibration errors and the finite resolution of the ADCs. The sum (quadratic addition) of these contributions of which the single values are listed up in table II amounts to 91 keV.

The contribution from electronic noise was determined from the pulser half-width, unfortunately, however, after the beam had been turned off, so that these figures do not comprise effects from low-energy γ-background. The calibration accuracy of the linear chains was estimated to be ±0.25%. In case of an ideal calibration the contributions from fluctuations of deposited energy in the individual detectors (due to their thickness and angular scattering) should disappear entirely when summing their signals. The above mentioned error, however, results in a contribution of 37 keV to the broadening of the sum peak if the experimental peak half-width of the individual detectors are taken into account.

When summing up (quadratic addition) all these estimated contributions (as listed up in table II) one obtaines 343 keV, a figure which is definitely smaller than the experimental peak half-width. Assuming, however, a slight uncertainty (only + 12%) in the estimated figure for the beam contribution this discrepancy disappears. That this contribution being proportional to energy is by far the most important, is furthermore supported by the surprising fact that also the measured energy resolution was within ± 3% proportional to the proton energy. All other contributions are expected to depend only slightly on energy. For this reason this experimental set-up was not ideally suited for testing the energy resolution of the detector system.

It should be mentioned that at the same experimental area the authors of ref. 1) obtained a comparable energy resolution (300 keV) with a single coaxial Ge(Li) detector exposed to protons of the same energy.

Conclusion

A telescope consisting of stacked HPGe detectors connected to an on-line computer was used as a long rang particle detection system. It was possible to reproduce a complex spectrum of protons after particle identification and low-energy tail rejection. The efficiency of this system remained above 70% untill 160 MeV. A more favourable detector geometry should result in a less severe decrease at higher energies.

The energy resolution of this detector system including electronics could not be determined exactly because of the complexity inherent to such a set-up. The estimated contributions (table II) to the peak broadening for protons of 160 MeV give a lowest value of about 90 keV. Without particular attention to the low energy γ-background an upper limit of 190 keV can be deduced from the experimental results.

The authors wish to express their acknowledgments to Prof. Mayer-Böricke for his continuous interest and encouragement. They are much indebted to the crew of the Jülich detector laboratory. They are especially grateful to A. Willis who wrote the data acquisition program, to F. Reide for his help in the electronic set-up and to the whole Orsay Synchrocyclotron crew.

References

1. R. Eisberg, M. Makino, R. Cole, C.N. Waddell, M. Baker, J.J. Jarmer, D.M. Lee and P. Thompson, Nucl. Instr. and Meth. 146 (1977) 487.

2. D. Dorcioman, R. Bertini, M. Hage-Ali, P. Siffert and L. Stab, Nucl. Instr. and Meth. 101 (1972) 91.

3. G. Riepe and D. Protić, Nucl. Instr. and Meth. 165 (1979) 31.

4. J.P. Didelez, G. Riepe, D. Protić, N. Frascaria, E. Gerlic, E. Hourani, M. Morlet and C. Sükösd, Annual Report of Institut für Kernpysik, KFA Jülich, Jül-Spez-36 (1978) 168.

5. J. Pouthas, Nucl. Instr. and Meth. 135 (1976) 187.

6. M.Q. Makino, C.N. Waddell and R.M. Eisberg, Nucl. Instr. and Meth. 60 (1968) 109.

7. D.F. Measday and C. Richard-Serre, Nucl. Instr. and Meth. 76 (1969) 45.

8. N. Kraft, N. Mangelson and G. Rogers, U.C.R.L. Report 11602 (1964).

Figure Captions

Fig. 1) Detector arrangement inside the cryostat. In the tests described here, only 6 (or 5) detectors were mounted to stop 170 (or 156) MeV protons. The Si-detector was left out.

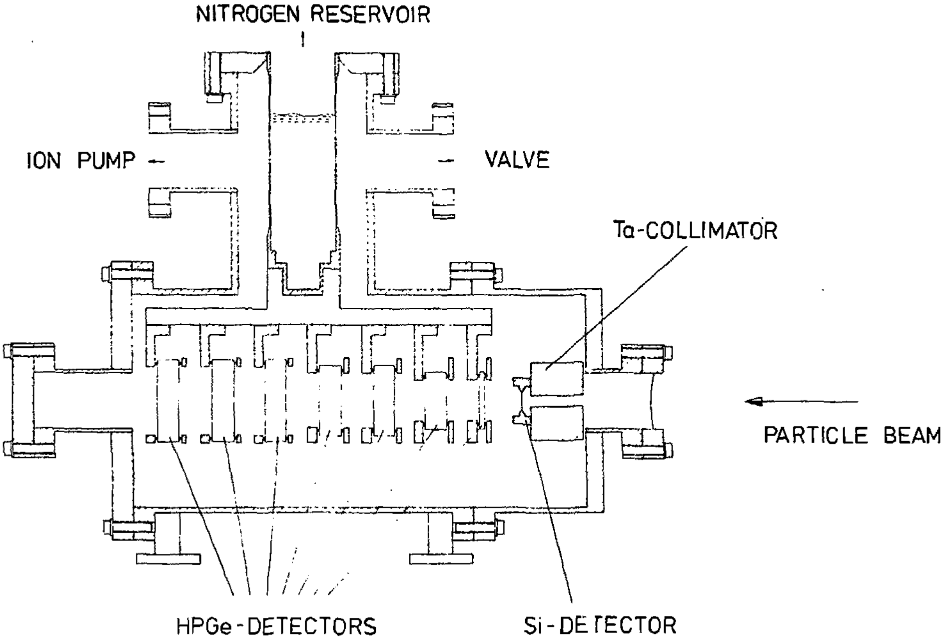
Fig. 2) Display of the PID signal versus the total energy ($E + \Delta E$).

Fig. 3) Spectrum of 170 MeV protons scattered on a CD_2 target at $\Theta_{LAB} = 24^{0}$.

Fig. 4) Telescope efficiency as a function of proton energy. Full curve: nuclear reaction contribution only (ref. 7). Dashed curve: experimental points.

Table I Resolution and efficiency figures obtained as a function of proton energy.

Table II Estimated contributions (in keV) to the peak broadening for protons of 150 MeV, stopped in detector No. 5.



NITROGEN RESERVOIR
ION PUMP
VALVE
Ta-COLLIMATOR
PARTICLE BEAM
HPGe-DETECTORS
Si-DETECTOR

Fig. 1

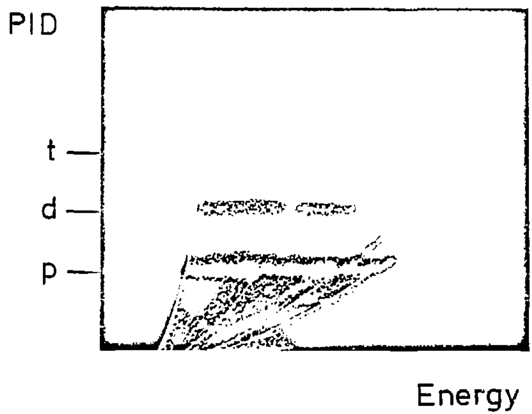
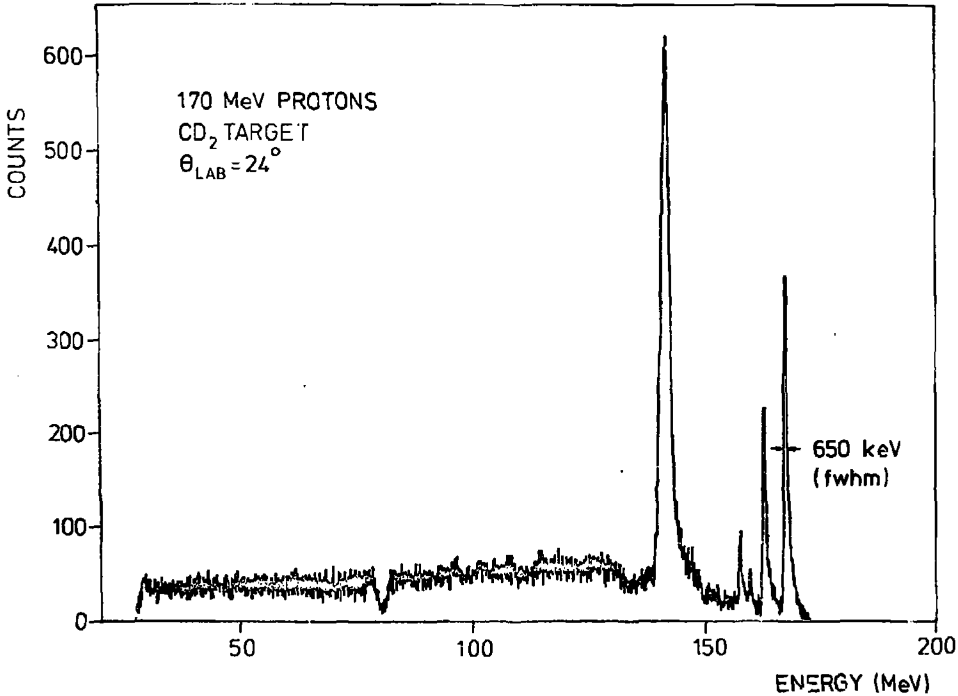


Fig. 2



170 MeV PROTONS
CD2 TARGET
θLAB = 24°
COUNTS
600
500
400
300
200
100
0
650 keV
(fwhm)
50
100
150
200
ENERGY (MeV)

Fig. 3

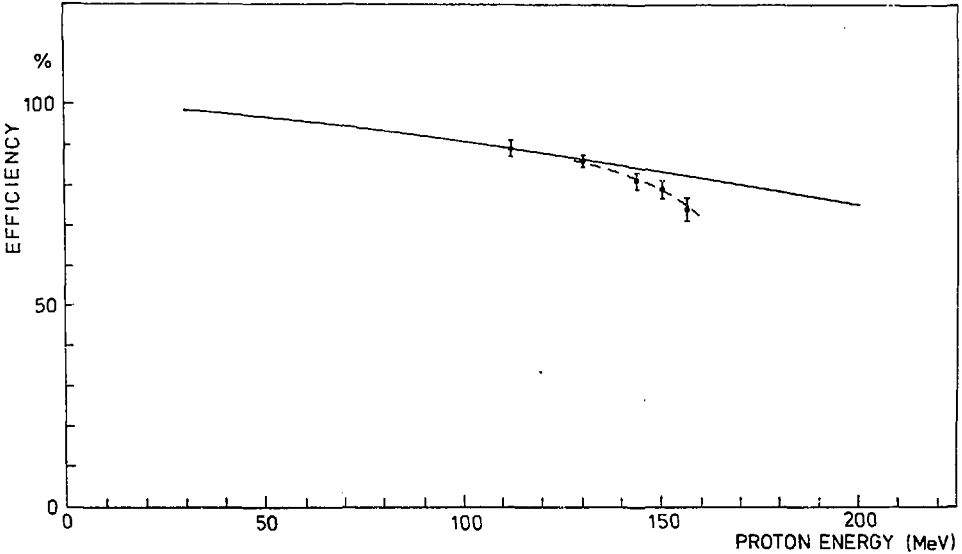


Fig. 4

Energy (MeV)	Range (mm)	Stopped in Detector No.	ΔE(fwhm) (keV)	$\frac{\Delta E}{E}$ x10^3	Efficiency (%)
95.6	21	3	240±20	2.51	91.53*
113.2	28	4	300±20	2.65	89±2
130.6	37	4	320±20	2.45	86±1.5
144	43	5	370±20	2.57	81±2
150.4	46	5	380±20	2.53	79±2
156.5	50	5	380±20	2.43	74±3
162.4	54	>5	-	-	-

* from ref. 7)

Table I

Resolution and efficiency figures obtained as a function of proton energy.

Beam		330
Windows		
Mylar window	17	
air gap	7.5	
Havar foil	5.3	19.3
Detector system and electronics		
statistics	11	
9 dead layers	< 5	
electronic noise	70	
calibration errors	37	
ADC resolution	43	91

Table II

Estimated contributions (in keV) to the peak broadening for protons of 150 MeV, stopped in detector No. 5.