Measurement of 15 MeV γ-rays with the Ge cluster detectors of EUROBALL

B. Million[a], A. Bracco[a,*], F. Camera[a], S. Brambilla[a], A. Gadea[b,1], D. Giugni[a],
B. Herskind[c], M. Kmiecik[d], R. Isocrate[e], S. Leoni[a], A. Maj[d], F. Prelz[a], O. Wieland[a]

[a]*Dipartimento di Fisica, Universitá di Milano, and INFN sez. Milano, via Celoria 16, 20133 Milano, Italy*
[b]*INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[c]*The Niels Bohr Institute, Copenhagen, Denmark*
[d]*The Henryk Niewodniczański Institute of Nuclear Physics, 31-342 Kraków, Poland*
[e]*INFN, sezione di Padova, Via Marzolo, Padova, Italy*

Abstract

A measurement of the response to 15.1 MeV γ-rays has been made for the Ge cluster detectors in the EUROBALL array. Each cluster detector consists of seven germanium capsules surrounded by a single anticompton shield of BGO. The reaction $D(^{11}B,\gamma)^{12}C$ + n at E_{beam} = 19.1 MeV has been employed. The "adding-back" of signals simultaneously present in the capsules composing each cluster detector has been made on an event by event basis. The intensity in full-energy peak increases by a factor of three as compared to that of the spectrum obtained by summing the individual spectra of the 7 capsules. The pulse height to energy conversion is found to be very linear from few hundreds keV to 15 MeV. The efficiency is discussed relative to that of large volume BaF_2 scintillators. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

The study of high-energy γ-rays in the interval 5–20 MeV has been one of the central points in a large number of experiments addressing both nuclear structure and reaction mechanism problems. The main difficulties connected to such measurements are related to the fact that in many cases the physical processes of interest have very small production cross section and that the efficient detection of the full-energy peak requires large volume detectors.

Until now most of the experiments involving the detection of γ-rays with E_γ = 5–20 MeV have been made employing large volume inorganic scintillators detectors such as NaI(Tl), BGO or BaF_2 with which rather efficient detector arrays have been constructed (see e.g. Ref. [1]). In particular, in the last decade the BaF_2 material has been largely employed for the cases in which a good neutron-γ discrimination is necessary. The drawback of these scintillator detectors is that the energy resolution cannot be better than 5–6% at 15 MeV. In contrast,

---

*Corresponding author. Tel.: + 39-2239-2252; fax: + 39-2239-2487.

E-mail address: bracco@mi.infn.it (A. Bracco).

[1] Present address: IFIC, Edificio Institutos de Paterna, apartado 2085, 46071 Valencia, Spain.

Ge detectors are largely employed for γ-ray spectroscopy up to 2–3 MeV because they are characterized by an energy resolution which is more than one order of magnitude better. Although the gain stability of Ge detectors is orders of magnitude better than for scintillators, they are not in general used for detection of high-energy γ-rays because of their low efficiency connected to their rather small volumes [2]. Larger efficiencies and intermediate value of the energy resolution can be obtained by using, in a non-standard way, the HpGe detectors of the Ge array with the surrounding BGO scintillator anti-Compton shield that was originally designed to improve the peak/total ratio. In particular, the response to high-energy γ-rays has been measured in the situation in which the signal from the HpGe detector is added to that of the BGO scintillators and resolution of the order of 1% was obtained at 15 MeV (see Refs. [3,4]).

More recently, composite detectors of rather large volume made of germanium have been developed and placed in large detector arrays for γ spectroscopy. Among them the cluster germanium detectors [5–7] of the EUROBALL array have the largest volume. Some of these cluster detectors have been previously used in different smaller setups to study low-lying collective modes of various types involving the detection of γ-rays up to 6–7 MeV (see e.g. Ref. [8] and references therein). However, because of their large volume these detectors are expected to be also suitable for γ-ray spectroscopy at even higher energy.

With this purpose in mind we have measured the response of these cluster detectors in the EUROBALL set up for γ-ray energy up to 15.1 MeV γ-rays. In a previous work the response of a single-cluster detector for γ-rays with energies up to 10 MeV has been measured using an Al source and standard electronic modules for Ge γ-spectroscopy which are commercially available [5]. In the present case not only have we used γ-rays of higher energy but we have also investigated the response of these detectors when they are placed in the complete array and using the VXI electronics developed for the EUROBALL system. The results discussed in the following sections concern mainly the linearity of the pulse-height to energy conversion, the features of single and "add back" spectra,

the resolution and the efficiency of these composite germanium detectors and the comparison with large volume BaF_2 detectors.

2. The cluster germanium detectors

The EUROBALL set up comprises 15 detectors of the cluster type. Each cluster detector consists of 7 HpGe-encapsulated crystals. Each crystal has an hexagonal shape with an external diameter of 65 mm and a depth of 78 mm. The detection efficiency at 1.332 MeV is on average $\approx 60\%$ (relative to a $3'' \times 3''$ NaI(Tl) detector for 1.33 MeV γ-rays). The 7 crystals are mounted together in a honey comb geometry in a common cryostat and are surrounded by a BGO anti-Compton shield, as schematically shown in Fig. 1. The composite detector corresponds to a single-germanium detector with a volume of nearly 2000 cm^3. The pre-amplifier outputs of each crystal is fed to a VXI card which contains the electronics to perform both time and energy measurements. Concerning the energy part it is important to mention that the gain of the amplifier is fixed and that the converting time is 6 μs. The gain is such that the dynamical range of the ADC (analogue to digital converter) corresponds to 4 MeV at full scale. In addition, a second
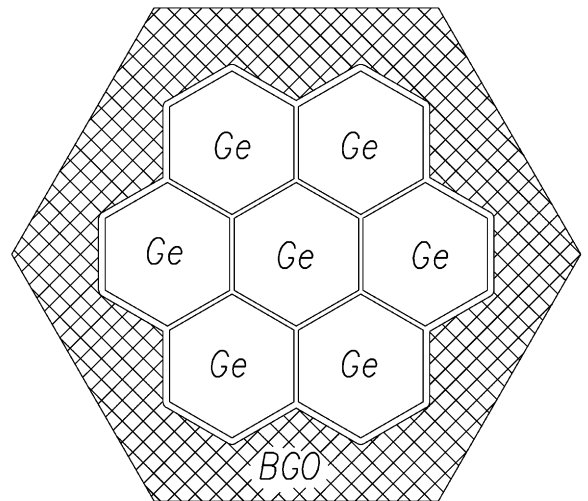

Fig. 1. Schematic illustration of the geometry of the front view of one cluster detector. The seven germanium capsules are surrounded by a single BGO anti-Compton shield.

output of the amplifier is sent to another ADC. This parallel output is attenuated to give a dynamical range corresponding to approximately 20 MeV. The discussion of the results presented below concerns this 20 MeV electronic line. More details on the detectors themselves and on the electronics and acquisition system can be found in Refs. [5–7,9].

3. The measurement

The reaction $^{11}B + D \rightarrow {}^{12}C + \gamma + n$ at the laboratory bombarding energy of 19.1 MeV was used to populate the resonant state at 15.11 MeV in the ^{12}C nucleus. This state decays directly to the ground state by emitting a single γ-ray with energy of 15.1 MeV (which is of magnetic dipole type [10,11]). The target used was made of $C_{32}D_{66}$ material with a thickness of 490 $\mu g/cm^2$ deposited on a 0.1 mm tantalum backing. Both the recoiling nuclei and the beam were stopped in the target backing. The beam intensity was kept at values of 1–2 nA during the 24 hours in which the measurement was made.

During the measurement the eight large volume BaF_2 detectors of the HECTOR array were placed in the front 1 π of the EUROBALL set up instead of the 30 single-tapered detectors of the standard configuration. A comparison of the results concerning these scintillators and the Ge cluster detectors is presented and discussed in Section 4. The energy spectra were measured as singles in order to avoid rejecting events which deposited the whole of the 15.1 MeV γ-ray energy in one single crystal. No time information could therefore be obtained with this reaction as no time reference from the accelerator was used. The anticompton shields, each surrounding seven germanium capsules, were used in the standard way so that all events in the germanium cluster having also a signal in the corresponding BGO detector shield were rejected. The data were collected in a list mode on DLT tapes using the standard EUROBALL acquisition system.

In Fig. 2 two measured energy spectra, compressed to display the entire dynamical range, are shown. The binning of the data is in both cases 9 keV per channel and the logarithmic scale has
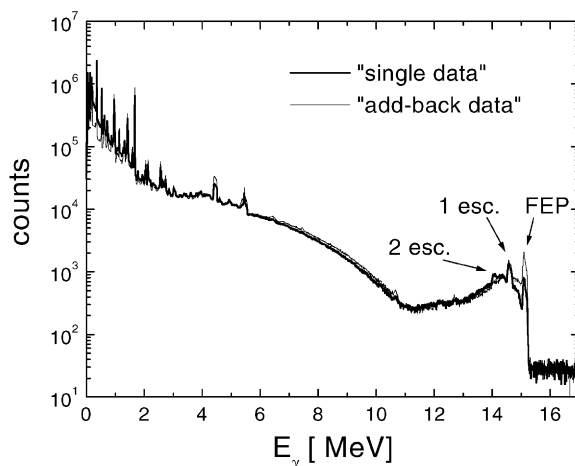
Fig. 2. γ-ray spectrum measured with the Ge cluster detectors (with rejection of events with signals in BGO shields) using the reaction $D(^{11}B,\gamma)^{12}C + n$ at $E_{beam} = 19.1$ MeV. The "single" spectrum is shown with the thick line while the "add-back" spectrum is shown with the thin line. The 15.1 MeV full energy peak (FEP) and the associated first (1 esc.) and second (2 esc.) escape peaks are indicated with the arrows.

been used. One spectrum, denoted by "single", was obtained by adding the energy spectra of the individual capsules while the other, denoted by "add-back", was obtained by adding the spectra of the cluster detectors, where for each cluster detector the adding mode technique among signals of the seven capsules has been applied. A more detailed description of the procedure employed to obtain these spectra and of the results is given in the following.

3.1. Calibration and linearity

When adding the signals of germanium detectors it is very important, even if one focuses on high-energy γ-rays, to have a very precise energy calibration both at low and high energy in order to have a good energy resolution in the add-back spectrum, as discussed in more details in Section 3.2.

The energy calibration of each crystal detector was made using several radioactive sources (^{152}Eu, ^{137}Cs, ^{133}Ba, ^{60}Co, ^{88}Y and ^{56}Co) emitting known γ-rays ranging from 122 keV to 3.56 MeV. For the $(^{11}B, \gamma)$ reaction one had to take into account that the emission occurs from a nucleus recoiling with a velocity equal to 5% of the light velocity

(the rather high value of $\beta = v/c$ is due to the inverse kinematics of the reaction). The corresponding correction for Doppler shift was therefore applied.

In particular, two different procedures were used for applying the Doppler shift correction. When the capsules are considered as individual detectors the value of the polar angle of each capsule is used. In the case in which each cluster detector is considered as an individual detector, the add back case, the Doppler correction is applied considering the polar angle of the capsule which has the maximum deposited energy. The validity of this approach is based on the assumption that the capsule with the largest signal corresponds to the first interaction of

a γ-ray entering the cluster detector. This fact is supported by simulations, made with the computer code GEANT [12], which show that for γ-rays with energy larger than 0.5 MeV the first interaction gives the largest energy deposition in a Ge detector.

The gain stability could be measured with reasonable statistics up to 5.3 MeV. The gain was found to be constant with time up to 5 MeV with typical deviations of the order of 1 per mil in the worst case and less than 0.5 per mil on average.

In Fig. 3 the γ-ray energy versus the measured pulse height (in channel number) is shown for several values of the γ-ray energy up to 15.1 MeV. The points in this figure correspond to measurements
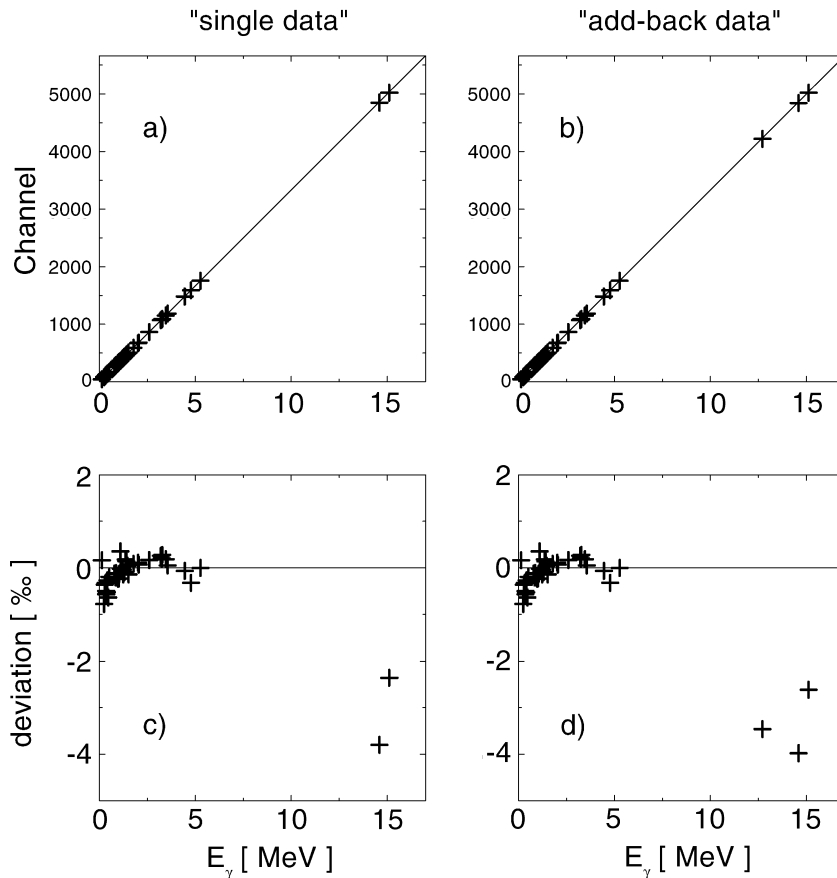

Fig. 3. The γ-ray energy into pulse height conversion (20 MeV-ADC channel) is shown in the case of "single" data (left column) and "add-back" data (right column). The top panels (a) and (b) show the channel to energy correspondence. The straight lines are obtained using the radioactive source data only (see text). The deviation of the measured points from the straight lines are shown (in per mil) in the bottom panels: panel (c) shows the deviations for the "single" data and panel (d) for the "add-back" data. The values of the errors are smaller than the symbol sizes.

with radioactive sources up to γ-ray energy of 3.6 MeV and to the measurement with the D(^{11}B, γ)^{12}C + n reaction (cf. Fig. 2) for the higher energies. The left column corresponds to the so-called "single" data, while the right column corresponds to the "add-back" data. In panels (a) and (b) the straight lines show the 3 keV/channel calibration. The deviations of the points measured with this reaction from the straight line obtained with the radioactive sources are displayed in the panels (c) and (d) of Fig. 3. The present results show that up to 4.4 MeV the deviations are very small (of the order of 0.05%) while the point at 15.1 MeV deviates percentually from the line by 0.24% (≈ 40 keV). By comparing panels (c) and (d), one sees that the add back procedure does not introduce any visible deviation.

A good linearity, extending from low energy up to high energy, is critical if one wants to employ the cluster detectors of the EUROBALL array for the measurement of high-energy γ-rays having only calibrations based on the standard radioactive

sources available. It should be noted that the earlier study for 10 MeV γ-rays reported in Ref. [5] cannot be used for this purpose mainly because the employed electronics is not the VXI-based standard of the EUROBALL array.

3.2. Distribution of hits in the cluster detectors

To make a good use of composite detectors one has to study the distribution of hits in the different elements of each cluster detector as a function of γ-ray energy. This distribution depends of course on the number of γ-rays emitted in the reaction and in this connection it is important to remind that in the present case we are dealing with a low multiplicity reaction. In particular, the 15.1 MeV is a one-step decay to the ground state so that some caution has to be taken when applying these conclusions in the study of reactions producing γ-rays in high multiplicity cascades.

In Fig. 4 the distribution of the number of folds (namely the number of capsules in one cluster
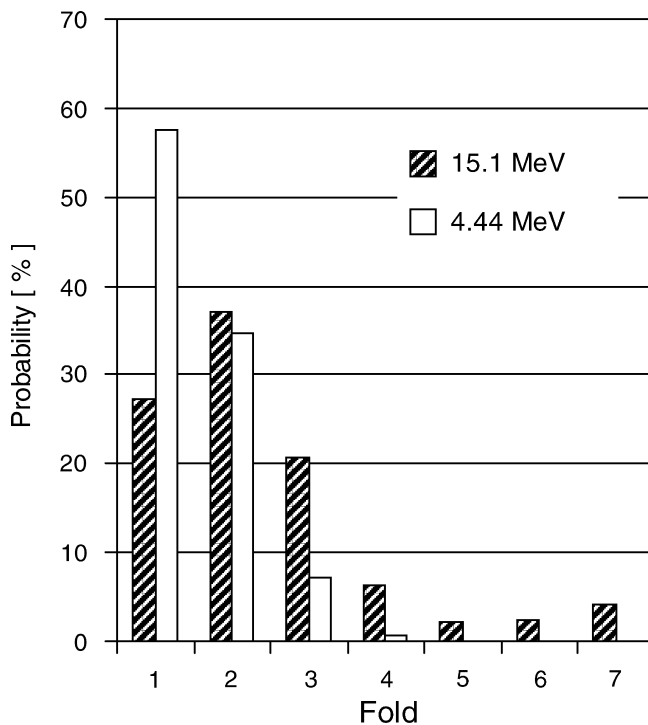

Fig. 4. Probability (in percent) of coincidence fold in the 7 HpGe capsules of the cluster detectors. The data concerning the transition at 4.44 MeV are shown with empty bars while those concerning the 15.1 MeV transitions are shown with the hatched bars.

giving coincident signals in one event) is shown for the cases of the 4.4 and 15.1 MeV ^{12}C-transitions. The present results are in good agreement with the value extrapolated from the existing measurement at 10 MeV [5] and indicate clearly that by adding the signals one expect to improve significantly the quality of the spectrum as discussed in the next section.

It is also interesting to see the energy spectrum measured in the single capsules for the subset of events which gives the full energy peak of 15.1 MeV and deposits that energy in two capsules or more. This spectrum is shown with the full-drawn line in Fig. 5. One can note that indeed, as discussed above, most counts concentrate in the very high (14–15 MeV) and low (0–1 MeV) energy regions, as a result of the fact that the main interaction mechanism is pair production. This shows that the events which deposited the whole of the 15.1 MeV γ-rays in two or more HpGe capsules of one cluster detector are characterized by a energy distribution corresponding to a large fraction ($\geq 93\%$) of the energy in one capsule and to a much smaller energy deposition in the surrounding capsules. This shows that even for high-energy γ-rays it is important to minimize the absorbing material between the active Ge crystals. This information can be very useful

also for future detector developments based on tracking techniques [13].

4. Energy spectra and efficiency

From the comparison of the "single" spectrum with the "add-back" spectrum shown in Fig. 2 one can see that the intensity in the full energy peak at 15.1 MeV is larger in the "add-back" spectrum and that the excess of counts becomes lower and lower as the γ-ray energy decreases. As expected, at γ-ray energy lower that 3–4 MeV one finds a sizable reduction of the background.

In order to see in detail the region of interest around 15 MeV, an expanded view of Fig. 2 is given in Fig. 6, where the data are shown in a linear scale. In this figure it is interesting to see the differences between the "single" and the "add-back" spectra. In the "add-back" spectrum, the second escape peak disappears while the ratio of the area between the full energy peak and the first escape peak improves by a factor of ≈ 3.

The ratio between the full energy and the first escape peaks was found to further improve by selecting the particular class of events in which the central capsule corresponds to the first interaction of the γ-ray in the cluster detector (maximum detected energy). This of course decreases the probability for the escape of Compton scattering γ-rays as they have a large probability to be detected in the 6 surrounding capsules (cf. Fig. 1). A gain of 40% is in fact obtained for the full energy peak over first escape peak ratio but the detection efficiency is then reduced by a factor of 4.

Concerning the energy resolution, it is difficult in this case to give a precise value which corresponds to the intrinsic resolution of the detector at 15.1 MeV. In fact, the reaction has a $v/c = 5\%$ and therefore the Doppler broadening is an overwhelming factor in the measured FWHM of the peak. In the present case the Doppler broadening has been estimated to be 73, 65 and 37 keV for the angles 130°, 137° and 157°, respectively. This point can be clearly seen in Fig. 7 where the "add-back" spectra in the region of 15 MeV are shown separately for the 3 rings of clusters at 130°, 137° and 157° (see Fig. 7). One can see that the spectrum measured at
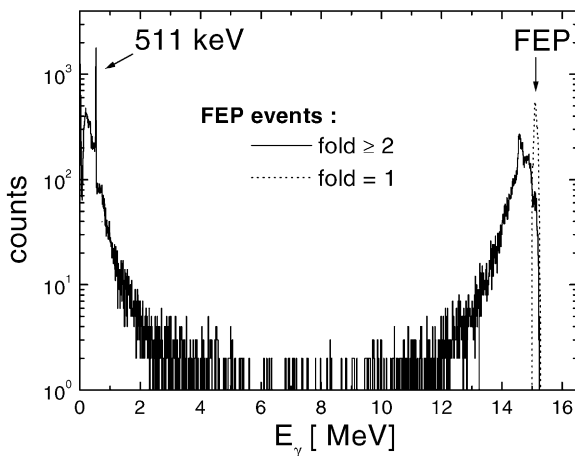
Fig. 5. γ-ray energy spectrum measured in the HpGe capsules for the subset of events corresponding to the full energy deposition of 15.1 MeV. The dashed line show the fold 1 case while the thick continuous line shows the fold ≥ 2 case.
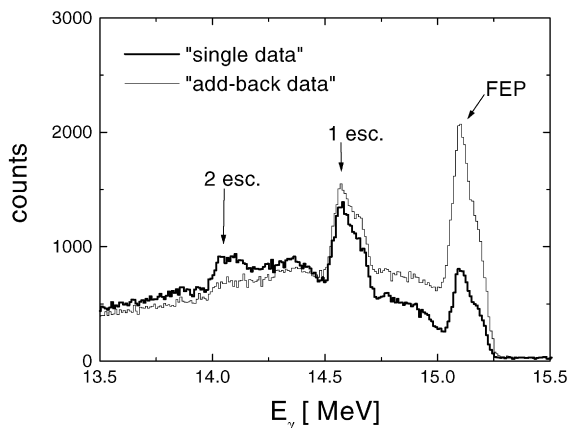
Fig. 6. Expanded view in linear scale of Fig. 1 in the high-energy interval. The γ-ray energy spectrum in the region around 15 MeV measured in "single" is shown with a thick line and in "add-back" with a thin line. The 15.1 MeV full energy peak and the associated first and second escape peaks are indicated with the arrows.

Fig. 7. The γ-ray energy spectrum in the region around 15 MeV obtained using the "add-back" technique and measured at the three different angles 130°, 137° and 157°. At 157°, where the Doppler broadening is smaller one can see a separate peak (indicated with the arrow) due to events in which the high-energy γ-rays piled up with X-rays.

157° is indeed much narrower. In addition, one can see that the 157° spectrum has a second smaller peak which appears at an energy of approximately 70 keV higher than the more intense one. A similar structure is present in the first escape peak. These satellite peaks have been interpreted as due to pile-up of X-rays produced at high rate in the heavy tantalum collimator (placed in front of all BGO shields) over the low rate 15 MeV γ-rays. In fact, as one can see from the total counts in the 15.1 MeV peak and by inspecting the total measured spectrum shown in Fig. 2, the rate of events at 15 MeV is very low as compared to the other much more copious events that can produce X-rays in the collimators. From the measurement at 157° one can infer that the intrinsic energy resolution is better than 60 keV (this value includes the calibration uncertainty discussed in Section 3.1). In contrast, the 4.44 MeV peak due to Coulomb excitation of ^{12}C nuclei in the target does not have any Doppler broadening and benefits from a much smaller calibration uncertainty. Its resolution is found to be 10 keV in good agreement with what was previously measured [5]. In Fig. 8 we compare the "add-back" spectrum measured at 15.1 MeV by one cluster with that measured at the same time by the one
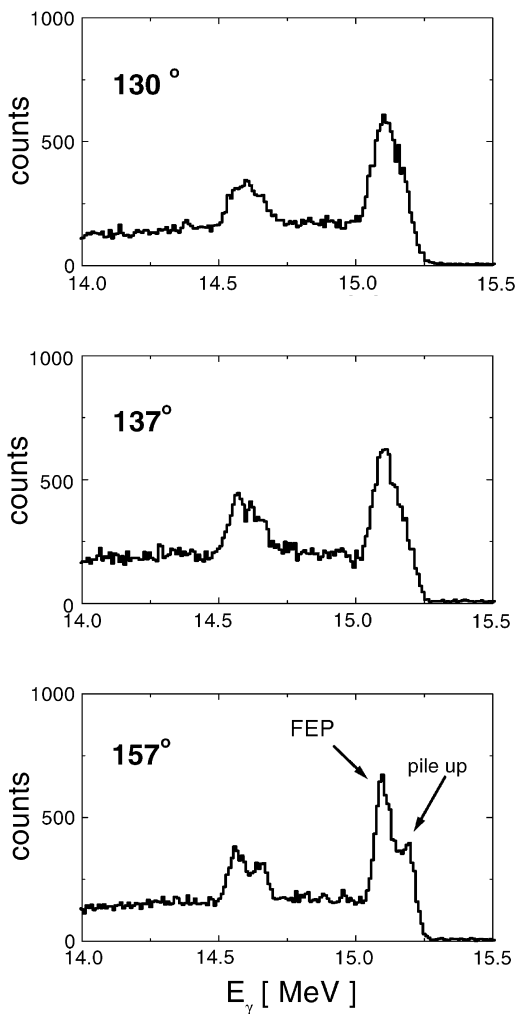
large volume BaF_2 detector. In this connection it is important to recall the dimensions and the distances of these detectors. The Ge cluster detectors ($\approx$ 130 mm in diameter and 78 mm in length) were placed at 440 mm from the target while the BaF_2 detectors (145 mm in diameter and 175 mm in length) were positioned at 300 mm from the target. The comparison made in Fig. 8 shows both the very
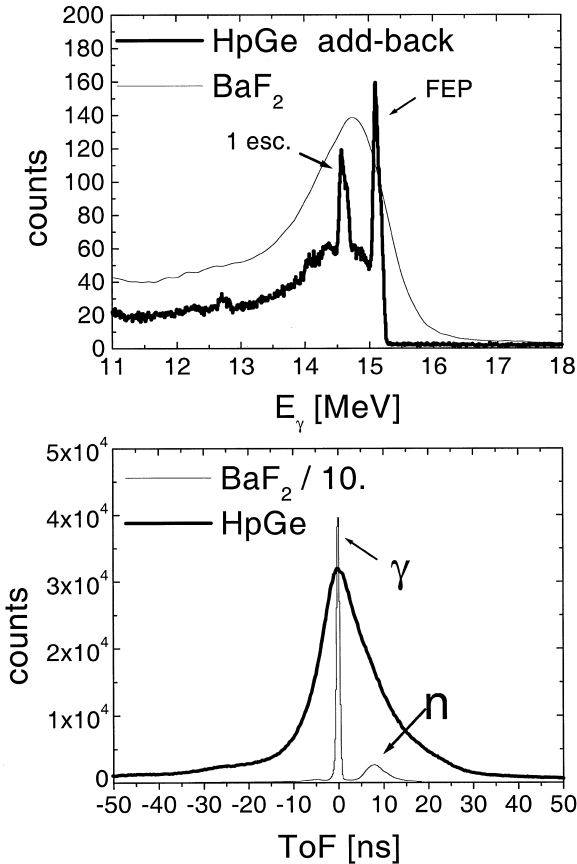
Fig. 8. (Top panel) The γ-ray energy spectrum in the region around 15 MeV obtained for the cluster detector using the "add-back" technique (thick line) is compared with the spectrum measured with a large volume BaF_2 detector (see text); (Bottom panel) Time spectrum measured for a large volume BaF_2 detector and for a Ge cluster detector relative to a signal measured with a small BaF_2 detector using the reaction $^{37}Cl + {}^{110}Pd$ at incident laboratory energy of 165 MeV. Again the thin line refers to the BaF_2 detector and the thick line to a Ge cluster detector.

good energy resolution that can be obtained using a Ge cluster detector and the relative efficiency of the two systems. After subtraction of background and escape peaks we have found that the efficiency of the full energy peak for one cluster detector is approximately 40% of that of a BaF_2 detector. However, this number can become smaller if one needs longer flight distances to make a good γ-neutron separation by time-of-flight technique.

In fact, the time resolution of germanium detectors is almost an order of magnitude worse than that of BaF_2 detectors, as one can see in Fig. 8, bottom panel. In the latter the time spectrum measured using the reaction $^{37}Cl + {}^{110}Pd$ at incident laboratory energy of 165 MeV is shown for one HpGe capsule and one BaF_2 detector. In both cases the time is measured relative to a coincident γ-ray detected in a small volume BaF_2 detector placed at 15 cm from the target.

5. Conclusion

The response of the Ge cluster detectors to 15.1 MeV γ-rays has been studied using the reaction $D(^{11}B, \gamma)^{12}C + n$ at $E_{beam} = 19.1$ MeV and the EUROBALL set up. We have focused on the add-back spectrum obtained for this composite detectors and discussed its differences with the single spectrum. In particular, the linearity of the pulse height to energy conversion and the hit distribution due to the interaction of one γ-ray has been investigated as a function of the γ-ray energy. These, together with the good resolution of each individual HpGe detector, are important factors affecting the energy resolution of the "add-back" spectrum.

The conversion between pulse height to γ-ray energy has been found to be very linear up to 15.1 MeV. This is a very useful information since it tells that one can use the low-energy transitions of the standard radioactive sources for calibration resulting in deviations of the order of 40 keV at 15.1 MeV. The "add-back" spectrum, obtained by summing the energies on the event by event basis was found to have a photopeak efficiency approximately three times better than that obtained by summing the individual spectra. Finally, a comparison of the detection efficiency of one cluster detector with that of one BaF_2 detector was made and a value of 0.4 was found.

Altogether one can say that experiments requiring the detection of γ-rays in the 10–20 MeV interval with good energy resolution, can benefit from the use of these germanium detectors although some caution has in general to be taken if one needs to reject neutrons by time-of-flight.

References

[1] A. Maj, J.J. Gaardhøje, A. Atac, S. Mitarai, J. Nyberg, A. Virtanen, A. Bracco, F. Camera, B. Million, M. Pignanelli, Nucl. Phys. A 571 (1994) 185.

[2] F.E. Cecil, F.J. Wilkinson III, R.A. Ristinen, R. Rieppo, Nucl. Instr. and Meth. A 234 (1985) 479.

[3] A. Bruce, J.J. Gaardhøje, B. Herskind, R. Chapman, J.C. Lisle, F. Khazaie, P.J. Twin, J.N. Mo, Phys. Lett. B 215 (1988) 237.

[4] F. Camera, A. Bracco, M. Mattiuzzi, G. Lo Bianco, M. Pignanelli, J.J. Gaardhøje, I.G. Bearden, Z. Zelazny, A. Maj, Nucl. Instr. and Meth. A 351 (1994) 401.

[5] M. Wilhelm, J. Eberth, G. Pascovici, E. Radermacher, H.G. Thomas, P. von Brentano, H. Prade, R.M. Lieder, Nucl. Instr. and Meth. A 381 (1996) 462.

[6] J. Eberth, P. von Brentano, W. Teichert, H.G. Thomas, A.V.D. Werth, R.M. Lieder, H. Jäger, H. Kämmerling, D. Kutchin, K.H. Maier, M. Berst, D. Gutknecht, R. Henck, Prog. Part. Nucl. Phys. 28 (1992) 495.

[7] J. Eberth et al., Prog. Part. Nucl. Phys. 38 (1997) 29.

[8] R.-D. Herzberg, A. Zilges, Phys. Lett. B 390 (1997) 49.

[9] J. Simpson, APH N.S., Heavy Ion Phys. 6 (1997) 253.

[10] R.H. Howell, F.S. Dietrich, F. Petrovich, Phys. Rev. C21 (1980) 1158.

[11] D. Berghoffer, M.D. Hasinoff, R. Helmer, S.T. Lim, D.F. Measday, K. Ebisawa, Nucl. Phys. A 263 (1976) 109.

[12] GEANT Refence Manual, CERN/DD/ee/84-1 1986.

[13] Slide report on the Meeting of the Working Group of TMR project of Development of γ-ray Tracking Detectors for 4π γ-ray Arrays, Padova, June 7–8, 1999 (TMR-DS-02, TMR-PS-02, TMR-DD-02, TMR-EL-02).