

Technical Note

Resolution, efficiency and stability of HPGe detector operating in a magnetic field at various gamma-ray energies

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Abstract

The use of High Purity Germanium detectors (HPGe) has been planned in some future experiments of hadronic physics. The crystals will be located close to large spectrometers where the magnetic fringing field will not be negligible and their performances might change. Moreover high precision is required in these experiments. The contribution of magnetic field presence and long term measurements is unique. In this paper the results of systematic measurements of the resolution, stability and efficiency of a crystal operating inside a magnetic field of 0.8 T, using radioactive sources in the energy range from 0.08 to 1.33 MeV, are reported. The measurements have been repeated during several months in order to test if any permanent damage occurred. The resolution at 1.117 and 1.332 MeV gamma-rays from a ⁶⁰Co source has been measured at different magnetic fields in the range of 0–0.8 T and the results are compared with the previous data.

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1. Introduction

The spectroscopy of gamma-rays, emitted in the de-excitation of a nucleus or in nuclear reactions is one of the best tools to obtain experimental information on nuclear structure. The full understanding of the nuclear processes requires observations with instruments having an excellent energy resolution together with a reasonable efficiency. The most powerful detector for gamma-ray measurements up to a few MeV is the large volume High Purity Germanium

crystal (HPGe). In the last few years a rapid progress in nuclear structure studies has been made thanks to the high quality data obtained with gamma-ray spectroscopy experiments using large arrays as EUROBALL [1,2] and GAMMASPHERE [3], based on HPGe detectors. In order to reduce the Doppler broadening in measuring gamma-ray emission in flight, VEGA [4] and EXOGAM [5] used segmented geometry. The segmentation technique has been further developed in MINIBALL [6,7] and AGATA [8].

Recently, the use of Ge crystal systems has been proposed also for the hypernuclear physics [9,10]. The main advantage of this technique, with respect to the traditional methods employing magnetic spectrometers, is

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the possibility to measure with good precision the energy of the gamma-rays coming from nuclear cascades, transitions and decays. HPGe detectors are planned to be installed in present (FINUDA at DAΦNE) [11] and future (PANDA at FAIR [12], E13 at J-PARC [13]) hypernuclei experiments. In PANDA due to the technique for the strangeness production, based on the antiproton–nucleus interaction [14,15], not only double hypernuclei, but also doubly strange atoms [16,17] can be explored. HPGe detectors can provide the sufficient precision for measuring levels, shifts and widths of the doubly strange systems [18]. A common feature of these large apparatuses is the presence of large spectrometers with intense magnetic fields: it implies the needs of locating the gamma-ray detectors in areas where the fringing field is not negligible. Moreover, the data acquisition lasts in general several weeks or months. Due to the magnetic field effects on the charge carrier trajectories the performances of the Ge crystals could be modified as well as the electronic circuits affected. In previous measurements at GSI [19] the resolution at 1.332 MeV of a set of some crystals operating in the range between 0 and 1.6 T was investigated. A correlation between the rise time and the measured pulse-height of the signal was found. In the present work we explore the effects of a 0.8 T magnetic field on a Ge crystal at different gamma-rays energies, in the range from 88 keV to 1.332 MeV. The variation of the energy resolution and efficiency within and outside the field has been investigated. Also, the left–right asymmetry of the gamma-ray peaks has been measured in order to evaluate the level of the ‘tailing effects’ in presence and absence of magnetic field. Repeated measurements have been performed for long time (several months) in order to check whether the changes become permanent or some recovery of the properties occurs in absence of magnetic field. In this

way the stability of the detector during several months of operational time has been tested. Finally, a set of measurements of the detector resolution has been performed at different values from 0 to 0.8 T, using a ^{60}Co source, in order to evaluate the dependence on the magnetic field.

2. Experimental setup and measurements

The apparatus used to measure the performances of the HPGe detector operating inside a magnetic field was located in the Optics Laboratory of Politecnico di Torino. It consisted of a magnet, a germanium crystal, six radioactive sources and an acquisition system based on a multi-channel analyzer.

The magnet was a VARIAN dipole type V7310 with a 30 cm coil diameter and with a distance between the poles of 13 cm. The total free volume between them allowed to place the detector in a vertical position, with the magnetic field perpendicular to the detector axis, as shown in Fig. 1(left). The maximum value of the field was 0.8 T and the uniformity was within 3% up to 8 cm from the central point of the coil axis. The map of the magnetic field, measured with an Hall probe of 0.001 T precision, is reported in Table 1. The positioning of the probe was made with an accuracy of 1 mm.

The germanium detector is a closed-ended coaxial crystal manufactured by the EURISYS MEASURES and consists of a high-purity, n-type, non-segmented, germanium cylindrical crystal with a diameter of 70.3 mm and a length 70.5 mm within its vacuum aluminum capsule. The detector has an energy resolution of 2.4 keV at 1.332 MeV (gamma ray from a ^{60}Co) and a relative efficiency of 70% guaranteed in 1991. In the “inside position” the crystal



Fig. 1. Experimental set-up. The system made by HPGe and frame for the source is positioned between the two poles of the magnet for the inside runs (left) and far from them for the outside runs (right): the crystal (smaller cylinder) is cooled by liquid N_2 from the upper down and the source is underlying.

was located at the center of the magnet, while the preamplifier laid close to the boundary, where the field was only 70–80% of the value in the center.

A set of six sources (^{60}Co , ^{57}Co , ^{22}Na , ^{133}Ba , ^{54}Mn and ^{137}Cs) were used to irradiate the crystal. The volume of each source was $\approx 2 \times 2 \times 1 \text{ mm}^3$. A support was rigidly mounted on the HPGe detector in order to place each source at a fixed distance of 20 cm from the end cup of the crystal, along its axis (see Fig. 1(right)). In this position each (pointlike) source illuminated the HPGe with a statistically suitable gamma-ray flux. From these sources, gamma-rays of 11 different energies, reported in Table 2, are emitted.

The read-out electronics consist of a power supply TENNELEC TC 950, an amplifier SILENA Mod. 7613 and a multichannel analyzer (MCA) ORTEC 926 with 8192 channels. The acquisition software ORTEC MAESTRO 5.12 Program was used. Throughout the experiment, the detector was biased at 3000 V. The built-in pre-amplifier pulses were fed through the amplifier to the

Table 1
Map of the magnetic field (in kG) inside the free volume between the magnet poles

$X \text{ (cm)} \backslash Z \text{ (cm)}$	−4	0	4
−2	8.00 ± 0.01	8.01 ± 0.01	8.01 ± 0.01
0	8.01 ± 0.01	8.01 ± 0.01	8.01 ± 0.01
2	8.00 ± 0.01	8.01 ± 0.01	8.01 ± 0.01
4	7.98 ± 0.01	8.01 ± 0.01	7.99 ± 0.01
6	7.94 ± 0.01	7.98 ± 0.01	7.97 ± 0.01
8	7.84 ± 0.01	7.91 ± 0.01	7.87 ± 0.01
10	7.63 ± 0.01	7.76 ± 0.01	7.67 ± 0.01
12	7.24 ± 0.01	7.43 ± 0.01	7.30 ± 0.01
14	6.56 ± 0.01	6.83 ± 0.01	6.62 ± 0.01

The Z -axis coincides with the dipole axis, while X is horizontal and perpendicular to the Z -axis. The origin of the reference system is in the center of the dipole.

Table 2
Measured widths (FWHM) vs. source energy (column 1)

Source energy (keV)	FWHM (keV)							
	Overall	Period 1	Period 2	Period 3	Overall	Period 1	Period 2	Period 3
^{133}Ba 80.997	1.599 ± 0.041	1.612	1.601	1.553	1.586 ± 0.082	1.530	1.605	1.698
^{57}Co 122.061	1.366 ± 0.065	1.391	1.332	1.357	1.478 ± 0.079	1.511	1.461	1.411
^{133}Ba 276.398	1.684 ± 0.068	1.682	1.646	1.805	1.711 ± 0.048	1.665	1.740	1.766
^{133}Ba 302.853	1.708 ± 0.058	1.668	1.718	1.800	1.747 ± 0.029	1.738	1.747	1.772
^{133}Ba 356.017	1.760 ± 0.056	1.776	1.772	1.677	1.807 ± 0.044	1.815	1.789	1.838
^{133}Ba 383.851	1.748 ± 0.101	1.743	1.733	1.806	1.817 ± 0.057	1.780	1.845	1.843
^{137}Cs 661.660	2.005 ± 0.080	1.969	1.996	2.095	2.162 ± 0.094	2.119	2.230	2.115
^{54}Mn 834.848	2.050 ± 0.106	2.073	2.033	2.07	2.238 ± 0.104	2.350	2.193	2.196
^{60}Co 1173.237	2.415 ± 0.097	2.391	2.410	2.465	2.690 ± 0.177	2.672	2.701	2.699
^{22}Na 1274.530	2.482 ± 0.118	2.533	2.456	2.511	2.767 ± 0.153	2.867	2.736	2.720
^{60}Co 1332.501	2.577 ± 0.069	2.528	2.592	2.631	2.910 ± 0.130	2.917	2.951	2.814

Averaged over all outside measurements (column 2) and over each period (columns 3, 4, 5) and over all inside measurements (column 6) and over each period (column 7, 8, 9). The errors in each period were close to the overall ones.

MCA, using a shaping time of $\tau = 6 \mu\text{s}$. The amplification was adjusted to 0.206 keV/channel.

Many repeated measurements with gamma-ray sources were performed with the HPGe detector during several months. Each measurement, called “run”, lasted 4 h: the position of the HPGe could be either inside the magnet (“inside run”) or at a distance of $\approx 1.5 \text{ m}$ far from the magnet (“outside run”). The value of the magnetic field in the outside runs was about 20 G, while during the inside runs it was monitored by an online probe, and its stability in time was within 0.4%. In every run there was either a radioactive source on the above-mentioned support or none (“background run”). In order to investigate systematically the magnetic field effects at every energy, we performed with each source the following “sequence”: one outside run and one inside run with the source, a background outside run and a background inside run. The complete series of sequences of all the six sources is called “cycle”. Inside and outside runs relative to the same source were performed in the same day when possible. Sometimes, due to various external constraints, they were performed in 2 days. The same procedure was followed for the background inside and outside runs, which were performed close in time to the corresponding source run. The difference in time between the measurements of a source and the corresponding background was at most 3 days. During 2006, five cycles were measured in the period January–March (Period 1), six cycles in April–June (Period 2), and six cycles in July–September (Period 3).

At the end of each period a set of short time measurements ($\approx 1 \text{ h}$ each one) of the ^{60}Co peak resolution was performed at different magnetic field values: 0, 0.1, 0.2, 0.3, 0.4, 0.6, 0.7 and 0.8 T. These measurements will be referred to as “variable magnetic field” measurements in the following. Other kinds of measurements, not reported in the present work, were performed as tests of the read-out electronics or of the DAQ system during these periods, for a total of more than 500 h of HPGe operating inside the magnetic field.

3. Analysis of the data

The information about how the magnetic field should possibly affect the performances of the HPGe detector at a fixed gamma-ray energy is contained in a sequence. The data of every sequence have been treated using the following procedure.

Net spectra from the inside and outside runs have been created by subtracting the corresponding background spectra. The environmental ^{40}K peak, present in all spectra, was used to check the relative energy position in both measurements. The maximum observed shift was at most one channel (0.206 keV). The channel containing the maximum number of counts in the peak was found. From the FWHM of the peak, the channels $C_{(-3)}$ and $C_{(+3)}$, corresponding to the boundaries of the interval $(-3\sigma, +3\sigma)$ around the maximum, were calculated. For each peak a linear background was fitted to the intervals $(C_{(-3)} - 2, C_{(-3)})$ and $(C_{(+3)}, C_{(+3)} + 2)$ and subtracted from the net spectrum. This correction did not change appreciably the spectra except at low energies. The results are called “corrected spectra” and an example is shown in Fig. 2. All the quantities used in the data analysis are obtained from these corrected spectra.

For each peak the analyzed quantities are the following: (1) the FWHM of the Gaussian curve, fitted to the peak, to evaluate the HPGe resolution (see Fig. 2 as an example), (2) the intensity of the corrected peak, to evaluate the intrinsic efficiency, (3) the full-width at $\frac{1}{10}$ of maximum (FWTM) and the skewness (μ_3) of the corrected spectra, to evaluate possible tailing effects. The intensity, the FWTM and skewness were calculated in the interval between $C_{(-3)}$ and $C_{(+3)}$.

In one cycle these quantities were measured for all the 11 gamma-ray energies of the six sources. In one period some cycles have been repeatedly measured in order to obtain a mean value and a standard deviation, the latter assumed as

experimental error. By comparing the mean values over the 3 periods, it was checked whether the change of the HPGe performances due to the magnetic field was a permanent or not.

4. Results and discussion

The collected data along all the periods allowed to get information about the magnetic field effects on the resolution, efficiency and tailing of the HPGe detector as a function of the gamma-rays energy. Moreover, by comparing these quantities obtained in different periods, the stability of such effects for long time measurements inside the magnet was tested. Finally, using the data of the ^{60}Co source at several magnetic field values between 0 and 0.8 T, the trend of the resolution for increasing magnetic field has been measured.

Before looking at these quantities, few words have to be spent to describe the results of the calibration procedure, due to the concerns about the possible electronic drifts. We recall that the High Voltage (HV) was fixed at 3000 V, the amplification set once at the beginning of the data taking in such a way that the DAQ system had a resolution of 0.206 keV per channel and the shaping time chosen equal to 6 μs , in order to maximize the energy resolution and minimize the ballistic deficit effects. The drift of the electronics was monitored each day by using the position of the ^{40}K peak (which moved at most of five channels during the total time) and tuning consequently the channel position. The channel dependence on the energy is shown in Fig. 3. The straight line fitted to the points shows a very high degree of correlation, and therefore we can conclude that no problems with Field Effect Transistors (FETs) were observed even for long duration operation of the detector inside the magnetic field.

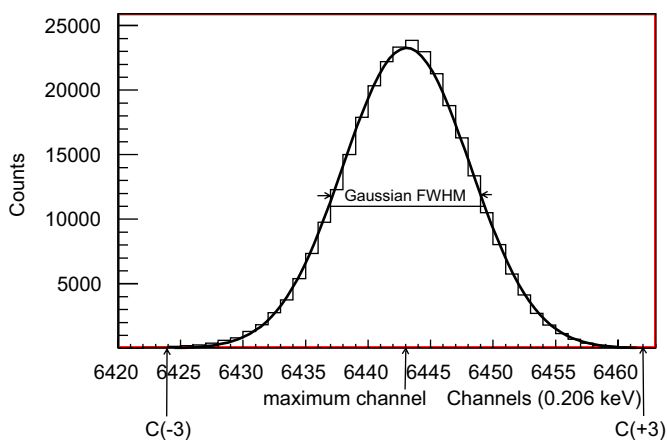


Fig. 2. Corrected spectrum of the 1332 keV peak (Period 1, cycle 3, inside run) and fitted Gaussian curve. The histogram FWHM (between arrows) and the Gaussian FWHM (solid line) are indicated together with the maximum of the peak and the boundaries $C_{(-3)}$ and $C_{(+3)}$ of the interval $(-3\sigma, +3\sigma)$ around the maximum.

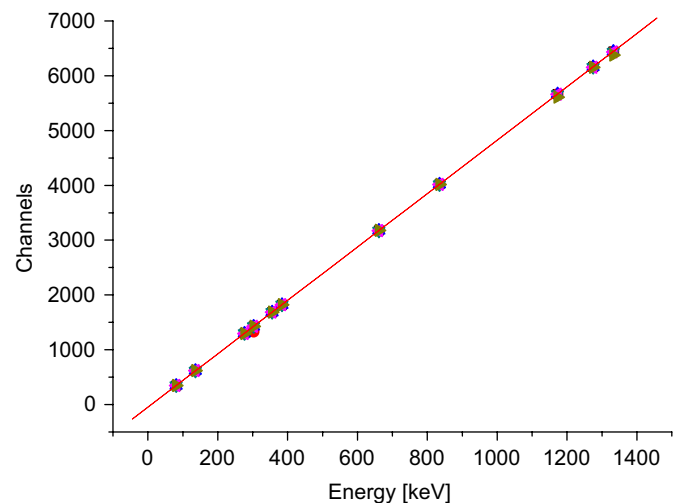


Fig. 3. Calibration of the HPGe detector: maximum peak channel vs. energy. The straight line $y = -47.153 + 4.87x$ is fitted to the points, with a correlation coefficient 0.9999.

4.1. Energy resolution

In order to evaluate the dependence of the HPGe energy resolution on the gamma-rays energy, the FWHM of the Gaussian curve, fitted to each corrected histogram of each gamma-ray peak, has been evaluated and averaged over the 17 values in the 3 periods. The results inside and outside the magnet are reported in Table 2 and in Fig. 4 as a function of the gamma-rays energy for inside and outside the magnet. The widths vary from ≈ 1.4 up to ≈ 2.6 keV for outside and ≈ 2.9 keV for inside data, respectively. The uncertainty (standard deviation) on the FWHM is less than 0.2 keV, indicating that the spread of the data is within the detector binning. The difference Δ FWHM of the peak width inside and outside the magnetic field varies with the gamma-ray energy, as shown in Fig. 5. It is negligible at few hundred keV and increases up to 0.4 keV at energies over 1 MeV.

A major concern about the use of the HPGe crystals inside a magnetic field is the possibility that the worsening of the performances be irreversible or even increasing with time. To check this possibility we took advantage of the long time during which the measurements were performed and we grouped them into 3 periods. The widths were averaged over the cycles of each period and the results are reported in Table 2 for all energies. The values of every period are fully compatible with the corresponding ones of the other periods (and with the overall average), within the uncertainties, for both outside and inside measurements. This proves that the FWHM variation, due to the magnetic field, is constant in time, and disappears totally when the detector operates outside the magnetic field.

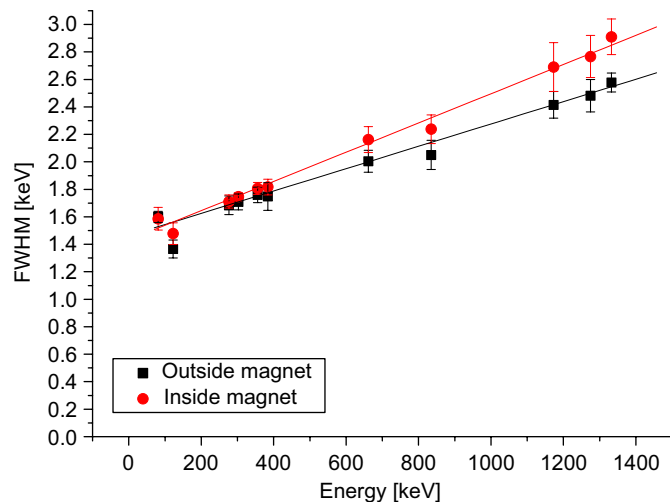


Fig. 4. FWHM, averaged over all data, vs. gamma-ray energy for inside and outside runs. As a first order approximation of the behavior, straight lines are fitted to the data, with the parameters: $\text{FWHM} = 1.426 + 0.00083 \cdot \text{Energy}$ (outside) and $\text{FWHM} = 1.415 + 0.0018 \cdot \text{Energy}$ (inside).

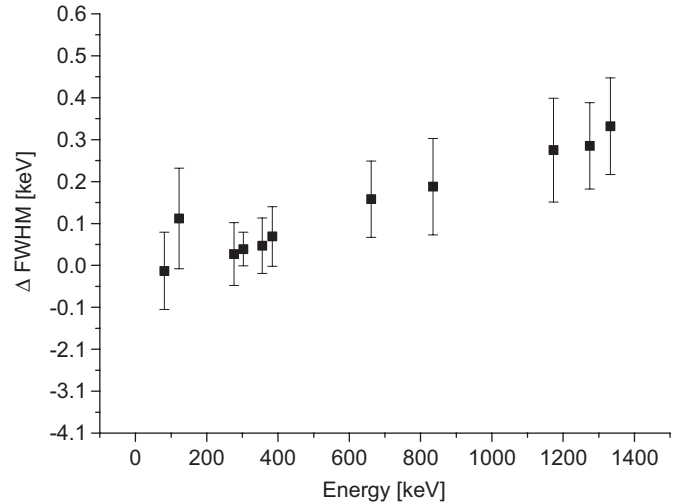


Fig. 5. Difference of FWHM between the values inside and outside magnet vs. gamma-ray energy.

4.2. Efficiency loss

Although the heaviest concerns about the efficiency of an HPGe are due to trapping phenomena and resultant lack of charge collection, it is also interesting to explore whether a “lack of counting” can occur due to the effects of a magnetic field on the charge carrier trajectories. This variation of the intrinsic efficiency of the crystal was checked using the contents of the corrected spectra. In each histogram the contents of the channels in the range $(-3\sigma, +3\sigma)$ across the maximum were summed and the sum of the 0.8 T histogram was divided by that one of 0 T. This ratio is equal to the ratio between the intrinsic efficiency inside and outside the magnet, because the same exposure time and geometry guarantee the same incident flux. The 17 ratios of each source have been averaged and are plotted in Fig. 6 as a function of the energy. They show a flat behavior with values equal to unit within the uncertainties, indicating that the intrinsic efficiency of the detector is not appreciably affected by the magnetic field over the whole energy range.

4.3. Tailing effects

The degree of asymmetry of the peaks, the so-called “tailing”, is one of the features characterizing the performance of the detector. A parameter commonly used to evaluate the severity of tailing is the ratio between the FWTM and the FWHM of the full-energy peak. Typically for a good quality detector this ratio should be less than 2. The ratios in the present case are reported in Fig. 7 as a function of the energy, where it can be seen that: (a) all the values lie close to the symmetry line (the ratio for a Gaussian) and are less than 2 within the errors and (b) the difference between the inside and outside measurements is very small, negligible within the errors. For sake of completeness the corresponding

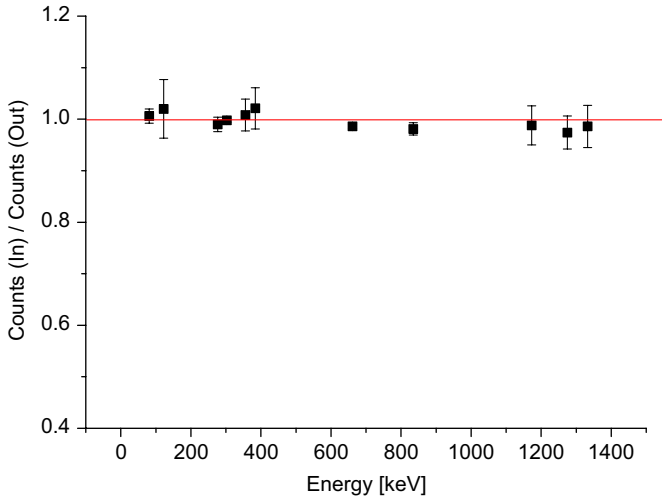


Fig. 6. Efficiency: the ratio of counts under inside and outside peaks vs. peaks energy. The straight line indicates no variation.

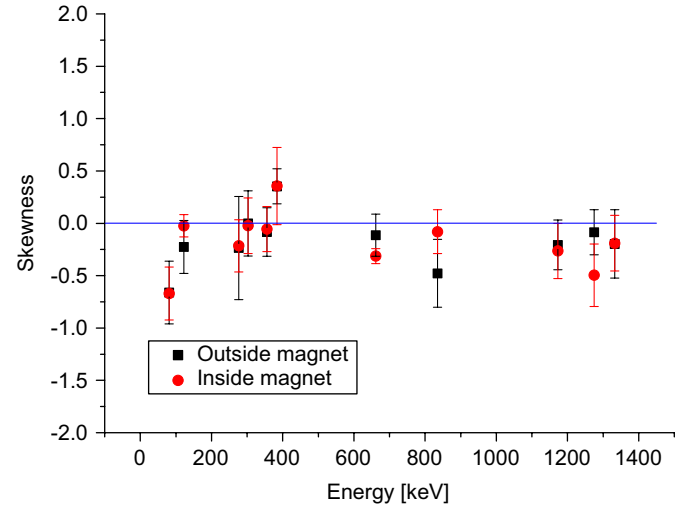


Fig. 8. Average skewness of inside and outside runs vs. gamma-ray energy.

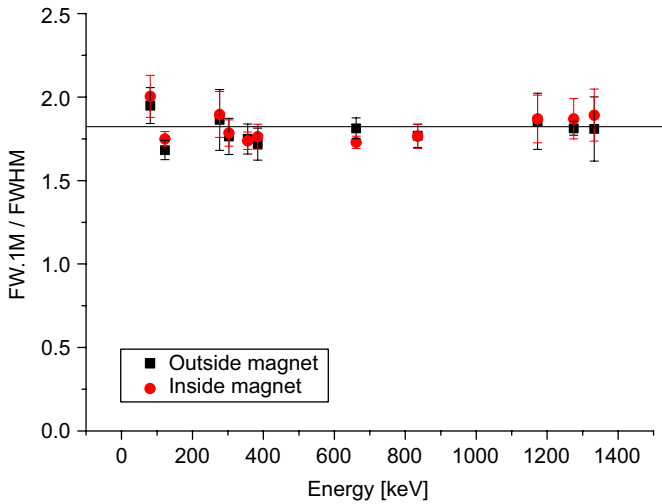


Fig. 7. Tailing: the ratio of the full width at $\frac{1}{10}$ of the gamma-ray height (FW0.1M) and at half (FWHM) is plotted vs. the peak energy. The straight line refers to the value expected from a pure Gaussian peak shape.

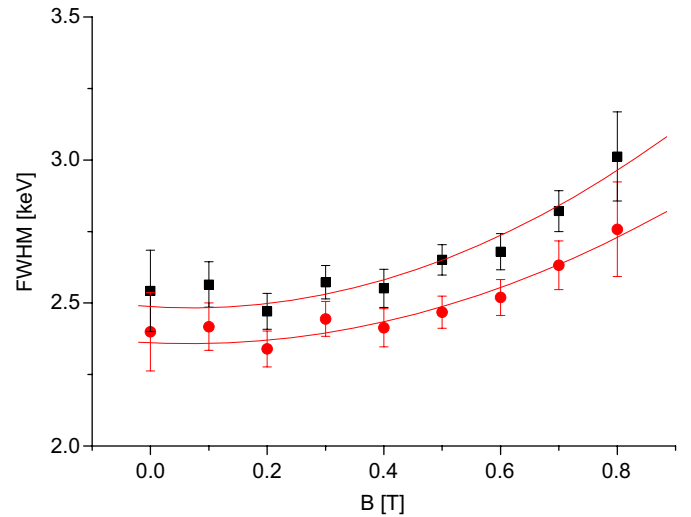


Fig. 9. FWHM at different magnetic field values B of the 1.173 MeV peak (full circles) and 1.332 MeV peak (full squares). To guide the eye the data have been fitted with a parabolic function.

skewness also has been evaluated in the same range (-3σ , $+3\sigma$), and again the values at 0 and 0.8 T, shown in Fig. 8, are close to each other and to the symmetry line. Both results confirm that a good quality detector, with minimal tailing, has been used and that the tailing is not affected by the magnetic field.

4.4. Variable magnetic field measurements

In a previous paper [19] we report on a study of the resolution for HPGc detectors in a magnetic field in the range 0–1.6 T. The FWHM at 1.332 MeV for EUROBALL cluster detectors [20] and VEGA detectors [21] was measured using a shorter shaping time constant (3 μ s) than in the present case. In this work, for sake of comparison, measurements were performed at different magnetic fields

below 0.8 T, using a ^{60}Co source. Resolutions (FWHM) at 1.173 and 1.332 MeV, averaged over all the periods, are presented in Fig. 9 as a function of the magnetic field. At both energies the width is increasing with the field and agree with a parabolic behavior, as indicated by the correlation coefficients. The curves look nearly parallel within the errors and the relative shift is about 6–7% for an energy gap of 0.16 MeV.

In order to make a qualitative comparison, the FWHM's at 1.332 MeV have been plotted also in Fig. 10 together with those ones of Ref. [19]. An overall agreement can be seen among the trends which look quite parabolic in all measurements. In general, we observe that the resolution of different HPGc detectors, EUROBALL and VEGA type, are consistent, within about 30%, with the measurements performed using our HPGc.

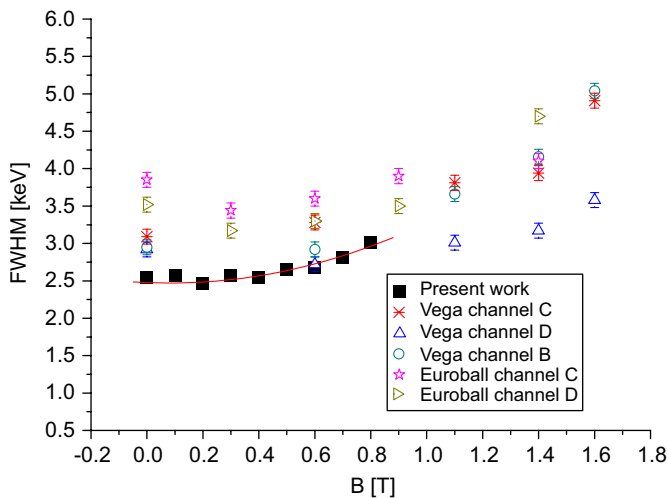


Fig. 10. Resolution (FWHM) of the HPGe detector at 1.332 MeV (full squares) as a function of magnetic field, compared with data from Ref. [19].

5. Conclusions

The performance of an HPGe detector operating in a magnetic field of 0.8 T has been systematically studied in view of the new perspectives for using such kind of crystals in future general purpose apparatuses, where they could be located in the fringing field region. The gamma-ray spectra of six sources have been measured for long time inside and outside the magnet, in the energy range from 0.088 up to 1.33 MeV. In this range a consistent amount of data is expected in hyperatomic and hypernuclear spectroscopy future experiments.

The result concerns the resolution of the detector, whose dependence on the energy has been found linear for both inside and outside magnet measurements as well as the difference between them. The absolute value of the worsening, when the HPGe operates at 0.8 T, is of the order 10% for energies around 1 MeV and becomes negligible at few keV. Also the intrinsic efficiency has been found not change appreciably inside the magnetic field and the same holds for the symmetry properties of the spectra. We can summarize that the quality of the crystal performances remains unchanged.

A second noteworthy result has been obtained thanks to the long time along which the measurements were performed. By comparing the data of different periods it

has been observed that the variations in the HPGe performance, when they exist, disappear as the field is off. Last, the resolution measurements in the range from 0 to 0.8 T allowed to determine the dependence upon the magnetic field in good agreement with previous data in literature.

In conclusion, the results obtained in the present work are strongly encouraging the use of Ge crystals at the future hadronic machines where magnetic spectrometers will be used together with high precision gamma-ray detectors.

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