MICHIGAN STATE
UNIVERSITY

National Superconducting Cyclotron Laboratory

THIRTY-TWO-FOLD SEGMENTED GERMANIUM DETECTORS TO IDENTIFY γ-RAYS FROM INTERMEDIATE-ENERGY EXOTIC BEAMS

W.F. MUELLER, T. GLASMACHER, D. GUTKNECHT, G. HACKMAN, P.G. HANSEN, Z. HU, K.L. MILLER, and P. QUIRIN

NSCL MSU

MSUCL-1155

MAY 2000

Thirty-two-fold segmented germanium detectors to identify γ rays from intermediate-energy exotic beams

W.F. Mueller, [a,1] T. Glasmacher, [a,b] D. Gutknecht, [c]
G. Hackman, [a,2] P.G. Hansen, [a,b] Z. Hu, [a] K.L. Miller, [a,b]
P. Quirin [c]

[a] *National Superconducting Cyclotron Labomtory, Michigan State University, East Lansing, MI 48824*

[b] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824*

[c] *Eurisys Mesures, 1 chemin de la Roseraie, F-67383 Lingolsheim, France*

Abstract

Thirty-two-fold segmented coaxial high-purity large-volume germanium detectors for use in intermediate-energy radioactive-ion-beam experiments have been developed and tested. This high degree of segmentation will allow a precise localization of the point of photon interaction in the detector, thus allowing accurate doppler reconstruction of the energy of a γ ray emitted in flight. In this article we report on the design of these detectors and their operational characteristics.

Key *words:* germanium detectors; segmentation; radioactive ion beams

1 Introduction

Studying the y-rays emitted from deexciting fast exotic beams is a field that has been quickly growing in recent years. Such experiments typically involve the production of a radioactive beam by fragmentation of a projectile with a

[1] Corresponding author. Tel.: +1 517 333 6428; fax: +1 517 353 5967; e-mail: mueller@nscl.msu.edu.

[2] Present address: Department of Physics and Astronomy, University of Kansas, Lawrence. KS 66045.

typical energy of 10-300 MeV/nucleon ($v/c \approx 0.15$–0.65). These exotic beams of nuclei can then subsequently be studied, for example, by their Coulomb excitation (1), nucleon knockout (2), or other reactions in a secondary target. In these experiments, both the direct study of the γ-ray deexcitation and the use of the γ rays as a tag for other effects play a role in the complete understanding of these rare isotopes. To detect the γ rays, the secondary target is typically surrounded by low-resolution photon counters such as NaI(Tl) detectors (see e.g. Refs. (3; 4)), the photon energy in the moving frame is reconstructed from the energy and angle measured in the laboratory frame on an event-by-event basis.

There are three primary factors that contribute to the total energy resolution (ΔE_γ) observed in the γ-ray detectors. The uncertainty in the source velocity due to the slowing down of the projectile in the target ($\Delta\beta$), the uncertainty in the emission angle of the γ ray due to the finite opening angle of the γ-ray detector ($\Delta\theta$), and the intrinsic energy resolution of the γ counter (ΔE_{intr}). These contribute to the total energy resolution in the following way:

$$\left(\frac{\Delta E_\gamma}{E_\gamma}\right)^2 = \left(\frac{\beta\sin\theta}{1-\beta\cos\theta}\right)^2 (\Delta\theta)^2 + \left(\frac{-\beta+\cos\theta}{(1-\beta^2)(1-\beta\cos\theta)}\right)^2 (\Delta\beta)^2 + \left(\frac{\Delta E_{intr}}{E_\gamma}\right)^2 . \quad (1)$$

The relative importance of each term is illustrated in Fig. 1(a) for an experiment with NaI detectors. For this figure, the intrinsic resolution of NaI(Tl) is assumed to depend on the γ-ray energy as $\Delta E_{intr}^{NaI} \sim k_{NaI}\sqrt{E_\gamma}$, where k_{NaI} is a proportionality constant. The parameters used to make this figure are chosen from a ^{40}S on ^{197}Au Coulomb excitation experiment reported in Ref. (4). While the finite opening angle of the detectors and the uncertainty in the source velocity in the target both contribute rather importantly to the total resolution, the most significant contribution comes from the intrinsic resolution of the NaI(Tl) detectors used in the experiment.

This intrinsic resolution of the photon detector can be improved by using germanium detectors rather than scintillator counters. Such detectors have been used by Anne *et al.* (5) in experiments with fast heavy-ion beams. The major limitations of germanium detectors, however, is their expense and detection efficiency. Thus the detectors are typically placed close to the secondary target, and thus present a large opening angle. Consequently, the gain in intrinsic energy resolution is lost due to the uncertainty in the Doppler-reconstructed energy created by the opening angle of the detector.

The recently developed electronic segmentation of germanium crystals (see Refs. (6; 7; 8; 9)) has created an opportunity where it is possible to localize the interaction of a γ ray within a detector, thereby dramatically reducing the effective opening angle of the detector (10; 11). This allows the detectors to be placed closer to the target for greater efficiency while minimizing the effect of the detector opening angle on the final energy resolution.

This improvement in energy resolution compared to NaI(Tl) detectors can be seen in Fig. 1(b). Contrary to NaI(Tl), the intrinsic γ-ray resolution of germanium is not strongly energy dependent, $\Delta E^{Ge}_{intr} \sim k_{Ge}$. The results in this figure are calculated assuming a 100 MeV/A ^{32}Mg beam impinging on a 200 mg/cm^2 target, and a germanium detector with 2.7 keV energy resolution at 1332 keV and 1.43° angular resolution (this is equivalent to a detector with 1 cm position resolution at 40 cm from the target). This represents a configuration that will be possible following the coupling of the two cyclotrons at the National Superconducting-Cyclotron Laboratory.

In this article, we report on the development of segmented germanium detectors that will be appropriate for in-beam γ-ray spectroscopy of fast exotic beams.

2 Design of the detectors

Typical experiments with fast radioactive beams have low γ-ray multiplicity events (typically $M_\gamma \leq 2$), but high velocities of the emitting nuclei (v/$c \approx$ 0.15-0.65). This is in contrast to recent discussions on the use of highly-segmented coaxial germanium detectors for use in a γ-ray energy tracking array (GRETA) in Refs (10; 11), where the concept of a device for detecting high-spin states in fusion-evaporation residues is described. Deexcitation of nuclei from fusion-evaporation reactions typically involves γ-ray multiplicities greater than ten, but at typical recoil velocities of v/$c \approx$ 0.02-0.06. As a consequence emphasis for γ-ray tracking devices is placed on identifying individual γ rays and the resolving power of the device must be optimized (12). For experiments with fragmentation beams, precisely identifying the first interaction point and thus the angle of emission (the azimuthal angle, θ, in particular) of the γ ray is of primary importance. Thus the design of the detectors reported here focus of achieving the most reliable point of first interaction.

In addition to GRETA (10; 11), other segmented Ge arrays such as MINIBALL (6; 7) and EXOGAM (13) are being designed primarily to study low-energy (<5 MeV/A) radioactive beams. In these arrays the individual coaxial germanium crystals in MINIBALL and EXOGAM are longitudinally six-fold and four-fold segmented, respectively. A different approach was used for the development of the detectors reported in this article (henceforth referred to as the MSU detectors). Rather than aligning the detectors with the axis-of-symmetry toward the source as is traditionally done, the detectors can be aligned with the axis-of-symmetry perpendicular to the source and parallel with the azimuthal spherical angle (θ). In this manner, the outer surface of the single-crystal detector can be segmented laterally (i.e. disk segments).

The MSU detectors utilize cylindrically-symmetric n-type coaxial germanium crystals. These crystals have an external diameter of 70 mm and length of 80 mm. The outer contacts of the detectors are electronically divided into eight 10 mm wide disks in the lateral direction, and four-fold radial segmentation for a total of 32 segments. A schematic diagram of this segmentation is presented in Fig. 2. Included in this figure is the scheme for labelling the segments. The radial segmentation is necessary because the outer disk rings of the detector will not be directly facing the target, consequently an interaction near the front of the disk and rear of the disk will correspond to different angles.

The central contact and each of the segments are operated with room-temperature field effect transistors (FET's) accessible outside the cryostat. While a slightly better energy resolution can be achieved with cryogenic FET's, cold FET's are not easily accessible should one become damaged and special consideration is necessary to handle the heat load of 33 of these devices. In addition, due to the high velocity in fast beam applications the resolving power is not critical (see Fig. 1(b)), and consequently the difference in resolution between room-temperature and cold FET's is less significant than for other applications. The signals from the FET's are connected to 33 independently-operating charge-sensitive preamplifiers. These preamplifiers are compactly designed and have 30 ns rise times at 0 pF (40 ns at 45 pF), 50 μs time constants, and a gain of 300 mV/MeV. The 33 preamps draw currents of 0.6 A at +12 V and 0.36 A of −12 V. For normal operation a bias between +4000 and +5000 Volts is applied to the central contact of the germanium crystal.

Because the detectors will be operated with the axis of symmetry perpendicular to the target-to-detector radius, it is inconvenient to have the required LN_2 cryostat mounted in the traditional fashion along the axis of symmetry of the detector. For the MSU detectors the cryostat is mounted at a 45° angle with respect to the detector axis of symmetry. The cryostat dewar has a 2.7 liter capacity and maintains the detector at liquid nitrogen temperatures for 28 hours while the detector is biased (33 hours unbiased). The detector's FET's are located close to the cryostat, while the preamplifiers are located at the base of the liquid nitrogen dewar. A photo showing the detector with the preamplifier housing removed is presented in Fig. 3.

3 Operating characteristics of the detectors

The full complement of detectors will be eighteen. The results presented here are based on measurements of seven detectors, and the charateristics of these detectors are quite similar.

The energy resolution of the MSU detectors were determined for the 1332-keV γ-ray from a ^{60}Co source located 25 cm from the germanium crystal. The strength of the source was such that it produced a rate of $\approx$1 kHz in the central contact preamplifier. The measurements are made with a 6 μs shaping time setting on the spectroscopic amplifier. The full width at half the maximum peak height (FWHM) energy resolutions measured for the central contacts of the detectors vary from 2.5 to 2.8 keV, and for all detectors the ratio of the full-width at tenth-maximum height by half-maximum height (FWTM/FWHM) is $<$2. The peak-to-total ratio (P/T) from the central contact was also measured. The ratio was determined by integrating the number of counts in the 1173 and 1332-keV peaks of ^{60}Co and dividing by the total number of counts in a room-background subtracted spectrum. To minimize scattering from surrounding material, the detector is mounted in an open aluminum frame where the detector is at least 15 cm from any surface. The P/T values for the MSU detectors are measured to be between 21.0% and 21.6%.

The energy resolution of the segments were determined by placing the ^{60}Co source close enough to the segment to produce a rate of 0.8-1 kHz from its corresponding preamplifier. The measured energy resolutions for the individual segments for a typical detector are displayed in Fig. 4. For disks B through H the average resolution is 2.5 keV (FWHM), while for the four segments of disk A the average is 3.3 keV (FWHM). The worse resolution for the A segments is likely due to the larger outer surface area compared to the other segments. This larger surface area results in an increased capacitance between the segment and the detector housing.

The detectors have measured efficiencies along the axis of symmetry relative to a 3 in diameter by 3 in long NaI detector 25 cm from a source between 72.2% and 76.1%. The photo-peak efficiency of the detectors as a function of energy differs depending on whether the source is along the detector's axis of symmetry or perpendicular to it. The efficiency as a function of energy for the two configurations is illustrated in Fig. 5. These data were taken from a representative detector with a ^{152}Eu source located 25 cm from the crystal of the germanium detector. For energies less than 1.4 MeV the larger detector surface available for photons incident perpendicular to the symmetry axis increases the detectors efficiency by greater than 15% compared to photons incident from the front. This increase is even more pronounced for lower energy γ rays.

A major concern for operating such a highly segmented germanium detector is the possibility of cross talk between the segments. To test this, a collimated 121-keV γ ray from a ^{57}Co source was directed at the center of the segment of interest. A full energy photopeak registered in the central segment is used as a trigger for a storage oscilloscope which is successively connected to neighboring segments. The number of pulses in the neighboring segments are then counted and normalized to the total number of photopeak events in the central segment. For all segments there were less than 30 events in neighboring segments per 1000 full-energy events in the primary segment.

The time resolution of the central contact of the segmented germanium detector was tested with respect to a CsF detector (6 ns risetime). The threshold on the constant fraction discriminator (CFD) processing the germanium signal was set to trigger only on energies greater than 100 keV, while the CsF CFD threshold was set just above the noise. The FWHM time resolution, measured with a ^{60}Co source, was found to range from 7.0 to 9.0 ns for the signal from the central contact. It should be noted that a better time resolution is achieved by restricting the sample to only full-energy events in the germanium detector; however, the value stated here is more reflective of a true experimental situation. A projection of representative time spectra illustrating the gated and ungated results are shown in Fig. 6.

The susceptibility of the segmented germanium detectors to ambient noise was also studied. It was found for all detectors tested that noise in the vicinity of the Ge crystal up to 85 dBC has no effect on the energy resolution of the central contact preamplifier. Microphonic effects are observed a volumes >85 dBC; however, the energy resolution is not observed to increase greater than 10% of the typical resolution for abient volumes less than 95 dBC.

4 Summary and future prospects

The design and first tests of the MSU 32-fold segmented germanium detectors have been reported. The energy resolution, P/T ratio, and timing characteristics from the central contact are typical for a detector of its size (75% relative efficiency). The orientation of the cryostat dewar allows the placement of the detectors with their axes of symmetry perpendicular to the target to detector radius and parallel to the azimuthal arc without interfering with other detectors at the same polar angle.

The outer contact of the MSU detectors are segmented into eight 10 mm long transverse segments and four longitudinal divisions to create a total of 32 outer segments from which unique energy signals can be collected. The energy resolution of most segments are comparable if not better than the resolution of the central contact with the exception of the four front segments (A1-A4). There is negligible cross talk between segments, which means that it will be possible to localize an event to within 10 mm transversally in the detector without resorting to pulse-processing techniques.

When the segments of a detector are as small as those of the MSU detector, it becomes highly unlikely that an incident γ ray will only trigger one segment, particularly if the γ ray is of high energy. Clearly this complicates the identification of the first interaction point. Several techniques for identifying the first point of interaction are currently under study. It is also clear that obtaining radial information for the point of a γ-ray interaction may also eventually play a role in improving the first interaction identification and localization.

The two cyclotrons at the NSCL are currently being coupled to allow higher energies and intensities of primary beams which will allow the creation of more intense radioactive beams near the drip lines. The construction of an array of segmented germanium detectors operated together with existing low-resolution high-efficiency scintillator photon counters will create very effective and versatile configurations for in-beam γ-ray measurements of fast exotic beams.

5 Acknowledgements

We thank Dr. David Radford for first suggesting the lateral segmentation. This work was supported by the U.S. National Science Foundation under contracts PHY-9724299, PHY-9528844, and PHY-9875122.

References

[1] T. Glasmacher *et al.*, Ann. Rev. Nucl. Part. Sci. **48** (1998) 1.
[2] A. Navin *et al.*, Phys. Rev. Lett. **81** (1998) 5089.
[3] T. Motobayashi *et al.*, Phys. Lett. B **346** (1995) 9.
[4] H. Scheit *et al.*, Phys. Rev. Lett. **77** (1996) 3967.
[5] R. Anne *et al.*, Z. Phys. A **352** (1995) 397.
[6] D. Habs *et al.*, Prog. Part. Nucl. Phys. **38** (1997) 111.
[7] J. Eberth *et al.*, Prog. Part. Nucl. Phys. **38** (1997) 29.
[8] I.Y. Lee *et al.*, Prog. Part. Nucl. Phys. **38** (1997) 65.
[9] S.L. Shepherd *et al.*, Nucl. Instr. and Meth. A **434** (1999) 434.
[10] M.A. Deleplanque *et al.*, Nucl. Instr. and Meth. A **430** (1999) 292.
[11] G.J. Schmid *et al.*, Nucl. Instr. and Meth. A **430** (1999) 69.
[12] C.W. Beausang and J. Simpson, J. Phys. G **22** (1996) 527.
[13] F. Azaiez *et al.*, Nucl. Phys. **A654** (1999) 1003c.

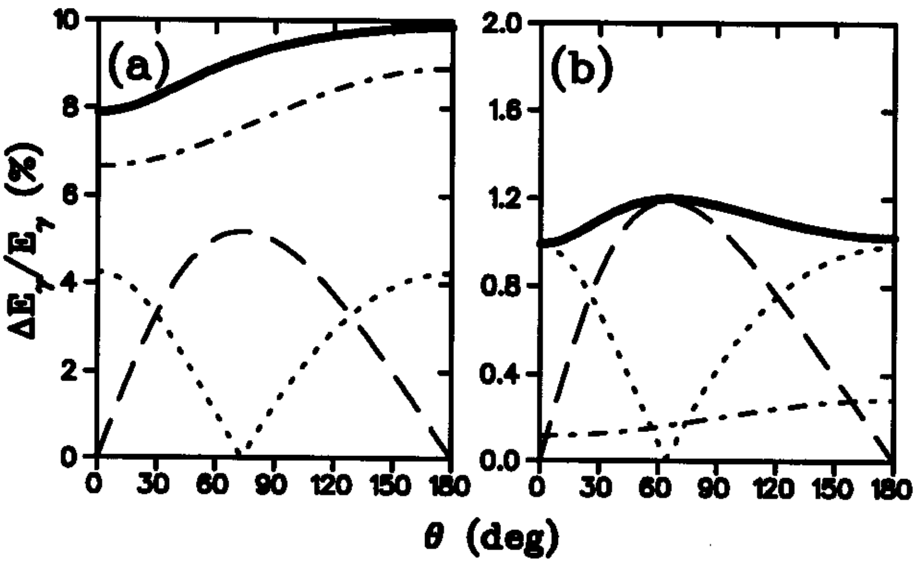

Fig. 1. Calculated contributions to the total energy resolution as a function of scattering angle for (a) NaI(Tl) and (b) Ge detectors. The dashed lines are the contribution to the energy resolution from the detector opening angle ($\Delta\theta$), the dotted lines are the contribution from the uncertainty in the beam velocity ($\Delta\beta$), and the dash-dotted lines are the assumed resolutions for each dectector, $\Delta E_{intr}^{NaI} = k_{NaI}\sqrt{E_\gamma}$ and $\Delta E_{intr}^{Ge} = k_{Ge}$ respectively. The solid line is the quadrature sum of these three contributions. The values used for $\Delta\theta$, $\Delta\beta$, and k in panel (a) are 10°, 10%, and 0.08 respectively and an incident beam energy of 40 MeV/A; while for panel (b) these values are 1.43°, 0.8%, and 0.002 for a beam energy of 100 MeV/A.

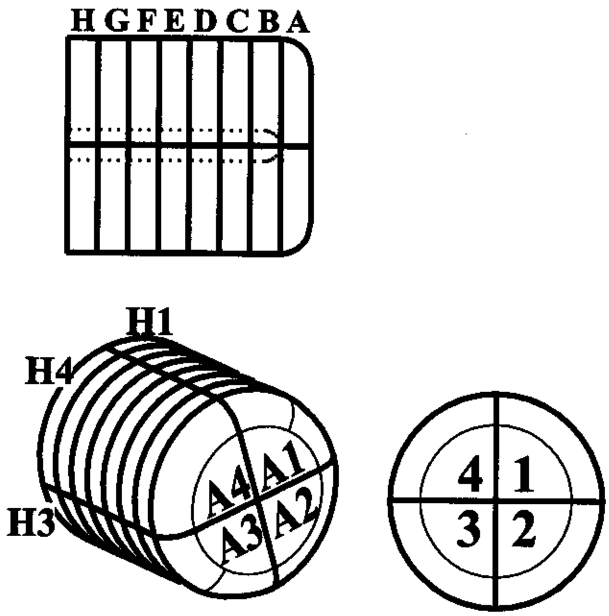

Fig. 2. Schematic diagrams of the segmented germanium crystal. The letters label the lateral disk divisions, and the numbers label the radial quadrant. The dotted line in the top schematic, shows the dimension of the inner core.

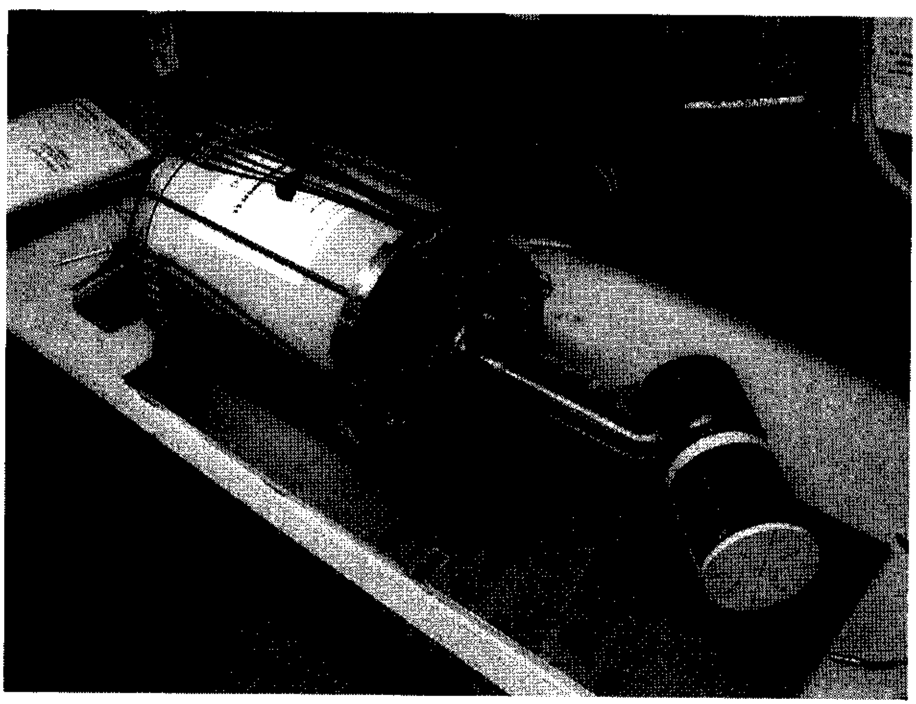

Fig. 3. Photograph of an MSU 32-fold segmented germanium detector. The preamplifier housing has been removed to allow viewing of a portion of the preamplifiers.

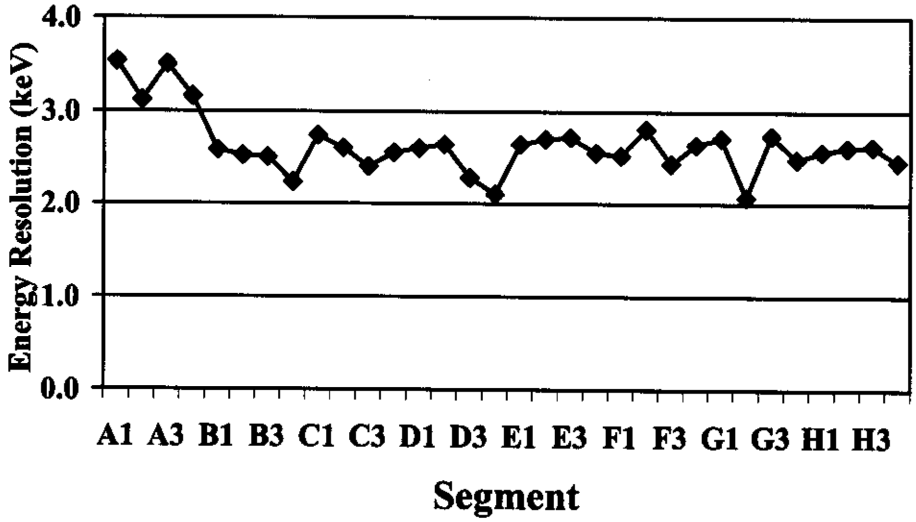

Fig. 4. The energy resolution (FWHM) at 1332 keV for the individual segments of the first delivered segmented detector. The segment labels are defined in Fig. 2.

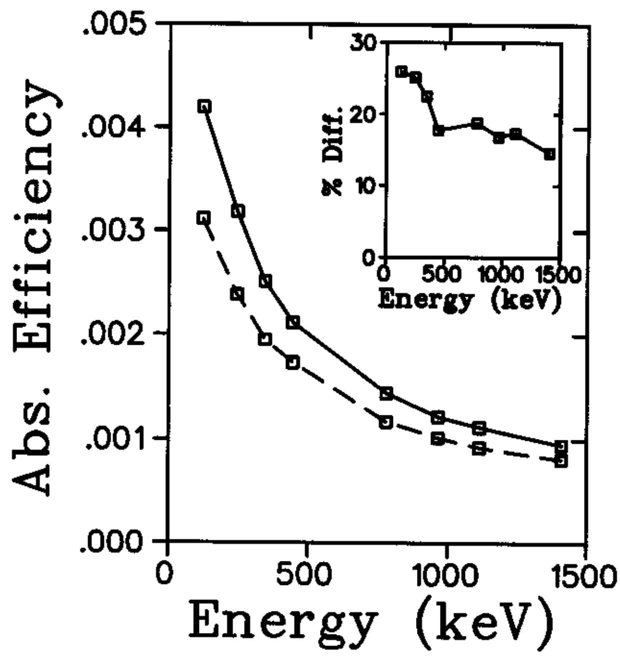

Fig. 5. Absolute photopeak efficiency for one detector as a function of energy when the source is 25 cm from the detector crystal along the axis of symmetry (dashed line) and perpendicular to the symmetry axis (solid line). The inset figure shows the relative difference between these two curves.

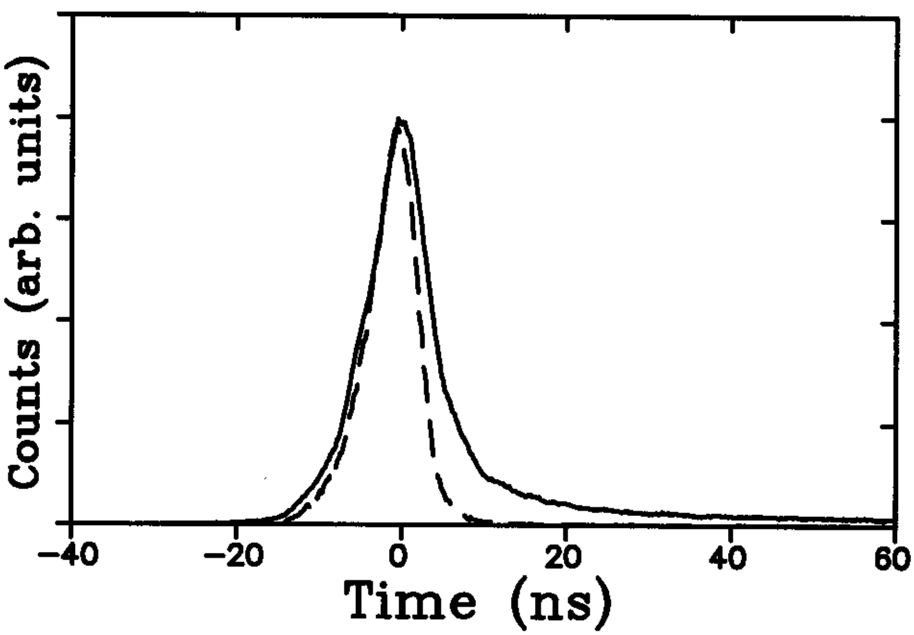

Fig. 6. Representative time spectra between a CsF counter and MSU germanium detector. The solid line represents an ungated spectrum, while the dotted line results from a energy gate on the 1332.5 keV line of ^{60}Co. The two spectra are normalized to the maximum of the prompt peak. Time $t = 0$ is set to be at the centroid of the prompt peak. The FWHM of the prompt peak is 8.8 ns in the ungated spectrum and 6.6 ns in the gated.