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TEST AND PERFORMANCE OF A BGO COMPTON-SUPPRESSION SHIELD FOR GAMMASPHERE

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Bismuth germanate (BGO) Compton-suppression shields have been constructed to surround the Ge detectors of the GAMMASPHERE array. A shield consists of six hexagonal tapered BGO elements, each coupled to two 1-inch x 1-inch photomultiplier tubes. In addition, a cylindrical BGO detector is placed behind the Ge detector to intercept the forward scattered gamma rays. One hundred ten such shields are planned for the GAMMASPHERE array. Procedures for measuring the performance of these shields have been developed. Large (70%) Ge detectors when used with these shields give a peak-to-total ratio of better than 0.60. To date more than 85 shield have been tested and approved for use in GAMMASPHERE.

1. Introduction

The Ge detector, with its high energy resolution, is a powerful tool for gamma-ray spectroscopy, but it suffers from a low peak-to-total ratio (defined as the ratio of counts in the photopeak to the total counts in the spectrum). For example, 1-MeV gamma rays deposit their full energy in a 7.0 cm x 7.0 cm Ge crystal only ~25% of the time. The majority of the gamma rays deposits only a portion of their energy in the crystal thus generating a Compton tail in the spectrum. This large tail makes the identification of weak lower energy gamma rays difficult. The Compton background can be reduced [1] by placing a Compton-suppression shield around the Ge detector. The reduction in the Compton events is achieved by requiring an anticoincidence between the Ge signal and the shield signal. In the past, NaI(Tl) crystals (density = 3.67 g/cm^3) have been used to build Compton-suppression shields. However, in recent years, shields made of higher-density (density = 7.13 g/cm^3) scintillator, bismuth germanate (BGO), have been manufactured. These shields can be made more compact because of the higher density of BGO crystals, and the higher stopping power of Bi (Z = 83). The reduction in size is extremely important in large arrays. The use of 1-in x 1-in photomultiplier tubes, instead of the conventional 2-in x 6-in photomultiplier tubes, has further reduced the size of the Compton-suppression shields for the GAMMASPHERE array.

For nuclear science research, a large array of 110 Compton suppressed Ge detectors known as GAMMASPHERE [2,3] is under construction in the USA. The Ge crystals are approximately 7.0 cm x 7.5 cm with efficiencies on the order of ~75%. Each Ge detector is surrounded by a BGO Compton-suppression detector system which consists of one tapered hexagonal BGO side shield and one slotted BGO back plug. Three types of shields with tapered hexagonal geometry are required. These types are referred to as B, C and D, and the array consists of 60, 30 and 20 of these units, respectively. The thickness of the BGO crystals has been chosen for optimum performance based on Monte Carlo calculations. When placed in the array, the inside faces of the BGO side shields will define a sphere with a 8.45" radius, and a nominal gap of 0.04" between sides of neighboring shields. Each shield is divided into six optically separate sections, each with its own pair of 1" x 1" photomultiplier tubes. The backplug has a cylindrical shape with the same diameter as the Ge can except for a slot to accommodate the off-axis tube which contains the cold finger and electrical cables connecting the Ge crystal to the preamplifier. The entire Ge-BGO assembly is shown in figure 1. The manufacturing of the BGO detectors are being done by two companies; Solon/Bicron [4] (B and D-type detectors) and Crismatec [5] (C-type and backplug detectors).

In GAMMASPHERE, the main function of the BGO detectors will be to veto the Compton events which scatter out of the Ge detector, thus reducing the overall background in the data. However, the entire array of detectors, both BGO and Ge, can also be used to measure the total energy and multiplicity of gamma rays emitted in a nuclear reaction. For the shield to be an effective Compton-suppression device, an important quantity is the low-energy threshold above which Compton-scattered gamma rays suppress events in the Ge detector. The effectiveness of the BGO as a calorimeter and spectrometer depends on the detector resolution (FWHM), light-output uniformity of the crystal, linearity in energy, and time resolution. At Argonne, we have devised testing procedures to determine all these parameters and have so far tested 85 shields. (Testing is now also being conducted by Prof. D. Fossan's group at Stony Brook). Fifty six of them are already at Lawrence Berkeley Laboratory and 36 are being used in experiments in the early implementation phase of GAMMASPHERE. In the present article we describe the design and testing of the BGO detectors, as stand-alone detectors or as Compton-suppression shields. The performance of an early prototype detector has been reported in ref. [6].

2. Experimental Methods and Results

As mentioned above, the BGO side shields define a close packed sphere with minimal clearance between detectors when mounted in GAMMASPHERE. Thus, it is critical that each detector conform to tight mechanical tolerances. The BGO crystals are housed in Al cans which are only .020" thick. The can itself cannot deviate more than 0.010" from its nominal envelope (+0/-0.010"). Furthermore, it is critical that the detector body be perpendicular with respect to its mounting flange. In order to measure the physical dimensions of individual modules, we have taken a two fold strategy. The first ten detectors of each type were measured using a coordinate measuring machine (CMM) at Argonne National Laboratory. Such a computer controlled instrument accurately measures all mechanical aspects of the shield to insure that all required tolerances are met. Once we were certain that the manufacturing process was sound and consistent, the remaining B and D type detectors were checked with test molds, with periodic spot checks using the CMM. All C type detectors were CMM'd by the vendor and spot checked by the CMM at Argonne. The detectors are also inspected for light leaks along seams and phototube feed throughs.

In order to determine whether or not the detector meets its performance specifications, a number of energy and time measurements are made on each crystal. Since each side shield has six BGO crystals associated with it, we have designed a procedure to make individual measurements of all six crystals simultaneously. This greatly reduces the amount of time involved in testing the detector.

Before beginning measurements, the gains of all phototubes on the detector are gain matched identically by adjusting the high voltage of each individual tube. This is accomplished by placing a ^{137}Cs source in the center of the Ge well 3.5" from the front face. The high voltage for each tube is roughly set such that its output as viewed on an oscilloscope is 150 mv for the 662 kev γ

ray. The final gain adjustment is made using a common shaping amplifier and MCA. In this arrangement, the individual tube biases are adjusted so that the centroid for the 662 keV transition is the same for all tubes.

2.1 Gain Calibration

Once the gains on each phototube have been adjusted, spectra are taken using a ^{22}Na source which has two γ rays associated with it at 511 keV and 1274 kev. These spectra are used for energy calibration.

2.2 Energy Resolution

There are two measurements using ^{137}Cs which are taken to determine whether or not the resolution specification for the BGO crystal is met. The first measurement is performed with a weak source (≤ 2 μCi) placed inside the center of the Ge well and located 3.5" from the front face. It is **imperative** that a weak source be used, since a stronger source can give a measured resolution which is 10-15% worse than optimal due to pileup and other count rate dependent effects. To analyze each spectrum, the 662 keV line is fit with a gaussian and the FWHM and centroids are recorded. For each detector, no single crystal can have a FWHM/Centroid greater than 22% and the average resolution determined from the six sectors must be <20%.

The second measurement is taken with a ^{137}Cs source placed at the focal point of the detector (target position in GAMMASPHERE) which is ~8.5 inches from the detector front face and centered with respect to the Ge well. Since the γ rays are incident on the front face and inner well of the detector, the resolution measured for this position is generally worse than when the source is placed inside the well. This is due mainly to lower light collection efficiency at the front face which is quantified in the uniformity test. As such, we have placed the upper limit for acceptable resolution at 23% for the source at the target position.

2.3 Detector Noise

The detector noise is checked for each BGO element by measuring the peak-to-valley ratio with a ^{241}Am (E_γ = 60 keV) source placed in the Ge well and shielded by a 0.25 mm Cu foil to absorb the Np L x-rays. For the crystal to meet specifications, the Peak/Valley must be >10 where "Peak" is defined as the peak height for the 60 keV γ ray and the valley is the average of the flat region between the single electron noise and the peak. All crystals have met this criteria and the majority far exceed it. Most measured values are between 25-35 for this ratio, and a typical Am spectrum is shown in Fig. 2. For GAMMASPHERE, these results show that the discriminator which provides pulses for anti-Compton coincidences can be safely set at 10-15 keV.

2.4 Pulse-Height Uniformity

In order to measure the pulse height uniformity of the BGO crystal, a collimated 10 μCi ^{137}Cs source is used and spectra are taken at 4 different positions along each BGO crystal. The cesium source is collimated by placing it between two 2" diameter x 1.5" length hevimet cylinders and the whole assembly is placed in a closed-end plastic tube. The measurements are taken by placing the collimated source into the Ge well and moving it along the length of the shield. Spectra are taken with the source placed at 0.5, 3.0, 5.0 and 7.0 inches from the front face, and spectra for a typical crystal are shown in

Fig. 3. The centroid of the 662 keV γ-ray is measured at each location and the deviation of the centroid from the average is defined as the uniformity at this position and must not exceed ±10%. A number of the hexagonal detectors have not met the uniformity specifications. The problem manifests itself in poor light collection in the lip region and is usually reflected in the measurement where the Cs source is placed at the target position with FWHM-values which are greater than 25%. In the worst cases, two separate peaks are seen in the target position spectra.

2.5 Response to Higher Energy Gamma Rays

The response of the detector elements to high energy gamma rays is determined by measuring the spectra of a 1.0 μCurie ^{228}Th source placed in the center of the well 3.5" from the front face. The peak width of the 2.6 MeV photopeak can also be used to assess the uniformity for light collection at high energies, as opposed to separately measuring the uniformity with a collimated source. Most crystals give resolutions between 9.5 and 12.5%. We find that the resolution for ^{228}Th tracks nicely with the centroid differences between the collimated Cs source spectra measured at 3 and 5 inches i.e. the larger the difference between the two Cs centroids the worse the measured Th resolution.

2.6 Timing Measurements

The time resolution of each element was measured with a ^{60}Co source. For the start signal, a 1 cm^2 x 1-cm BaF_2 crystal was used. A 0.3 microCurie ^{60}Co source was placed on top of the BaF_2 and the BaF_2 and photomultiplier assembly was inserted in the shield such that the source was located in the center of the shield. A leading-edge discriminator was used to extract the timing signal for the BGO element. The threshold on the discriminator was set at the single-electron level (~4.9 keV). Events were recorded in a two-dimensional matrix whose x-axis was the gamma ray energy deposited in the BGO crystal and the y-axis was the time difference between the BaF_2 and BGO signals. The time spectrum of one element of the BGO shield is shown in Fig. 4. The time resolution varies with the energy window and for higher energy gamma rays (1.0 to 1.5 MeV) ranged from 2.5 to 4.0 ns, which exceeds the specification of 5 ns. Good time resolution permits discrimination against neutron-induced events, which can lead to false suppression.

2.7 Testing of Backplugs

The geometry for the BGO backplug crystal is much more simplified relative to the crystals used in the side shield. As a result, the performance testing for these detectors is not as rigorous as those for the side shield. The tube bias for each backplug is matched in the same manner as those for the side shield and the spectrum is calibrated with a ^{22}Na source. Resolution checks are made with ^{137}Cs and ^{228}Th sources placed approximately 5" in front of the detector's front face. Timing and Peak/Valley measurements are also performed, however, no uniformity measurements are done due to the simplified geometry of the detector. The same applicable performance specifications quoted above for the side shield are applied to the backplug detectors.

2.8 Compton-suppression Performance

The above measurements serve to define the intrinsic quality of each BGO element, providing an indicator of performance when the BGO elements are used as Compton-shields or as stand-alone spectrometers. Examples of the latter include their use in add-back mode with BaF_2 detectors (which replace Ge detectors), or in measuring the sum-energy emitted in a given reaction. To explicitly test the effectiveness of the BGO shields for Compton suppression of the Ge detectors, measurements with a 75% Ge detector were conducted for each of the Type B, C and D hexagonal BGO detectors. The results of these measurements are given in Table 1. Results with and without the backplug electrically connected are also stated in the Table. The suppression performance of each type correlates with the BGO thickness. For example, they agree rather well with results from GEANT simulations (Sobotka et al.). The P/T values (0.58-0.61) are lower than the value of 0.68 reported [4] earlier with a prototype shield [6]. The original prototype shield was of the original honeycomb design, and was approximately twice as thick as the present individual shields. However, equally good performance may be achieved with the present design by electronically combining the signals of adjacent individual sectors, thereby yielding shields which have the same equivalent thickness as the original honeycomb design. This new mode of observation is referred to as electronic-honeycomb. (The decision to adopt the present GAMMASPHERE design of individual shields was motivated, in part, by the greater ease of fabricating detectors with flat outside surfaces.)

Table 1 also shows that the incremental gain in P/T ratio with the backplug in the individual shield appears to be lower than for the thicker honeycomb shield. This is due to a larger Compton background from reduced suppression with the thinner hexagonal shield. However, it can be computed from the measured P/T ratios that, in the electronic-honeycomb mode, the backplug will provide the same incremental gain as observed with the honeycomb shield. The expected improvement in P/T ratio of 0.62 to 0.68 with the backplug implies a ~40% increase in sensitivity for 4-fold Ge coincidence events. [Sensitivity is proportional to $(P/T)^n$, where n is the coincidence fold.]

3. Conclusions

The Compton-suppressed shield designed and built for GAMMASPHERE is very effective. Our earlier measurements [4] show that the backplug is extremely important for optimal removal of Compton scattered events. These shields have quite reasonable time and energy resolutions and, hence, can be used for measurements of total energy released in nuclear reactions.

Acknowledgements

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Table 1

Suppression Tests with Different Types of Detectors

Peak/Total Ratios with ^{60}Co

	Type B	Type C	Type D	Original Honeycomb
Unsuppressed			0.259	0.268
SUPPRESSED				
backplug on	0.577	0.601	0.612	0.678
backplug off	0.554	0.566	0.576	0.622
backplug on heavymet shield	0.570	0.589		0.622
backplug on in Al hemisphere	0.570			
GEANT simulation [8]				
Individual	0.61	0.62	0.63	
Elec. Honeycomb	0.71	0.74		

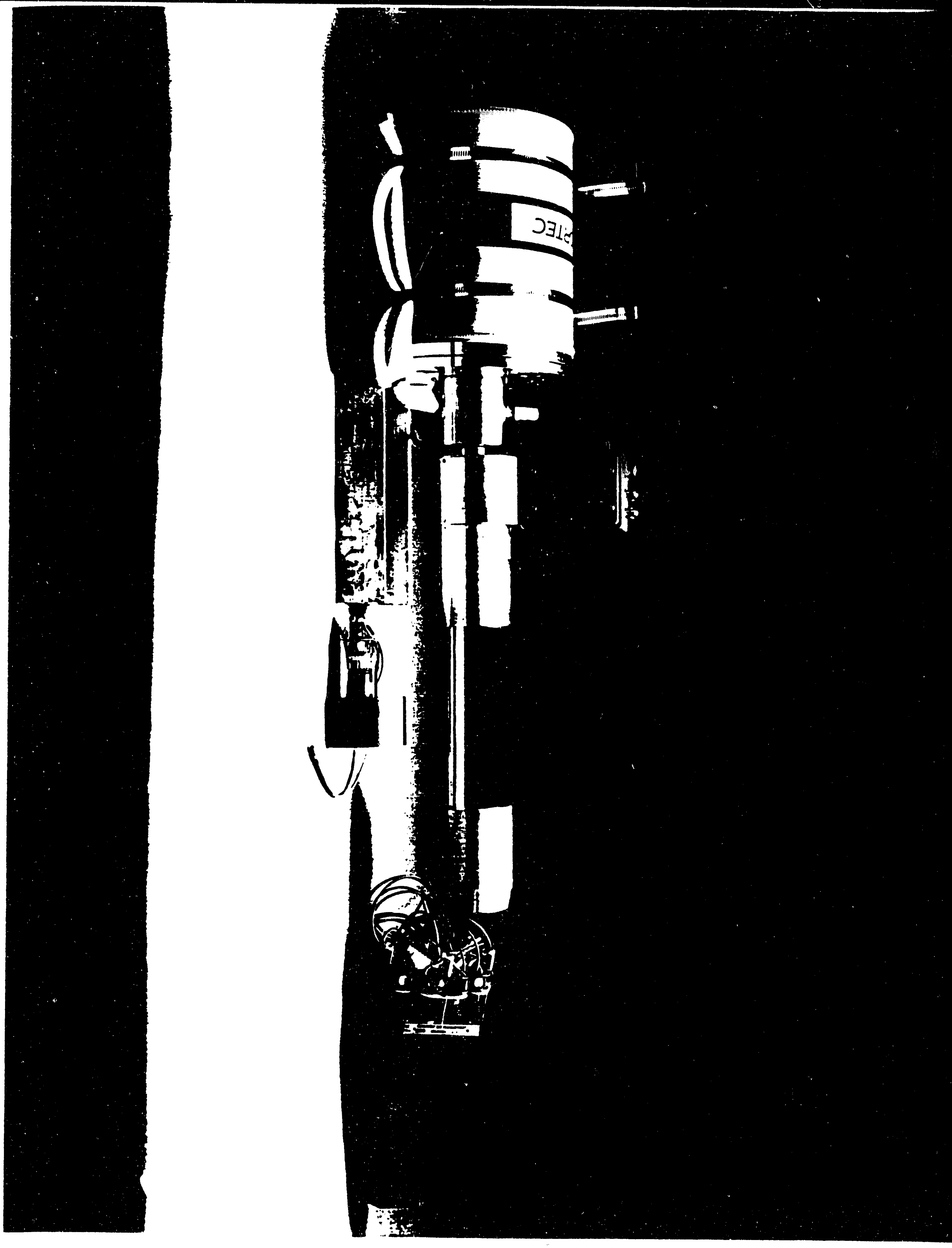
Figure Captions

Fig. 1. A photograph showing the Compton-suppression shield, the backplug and a 70% Ge detector.

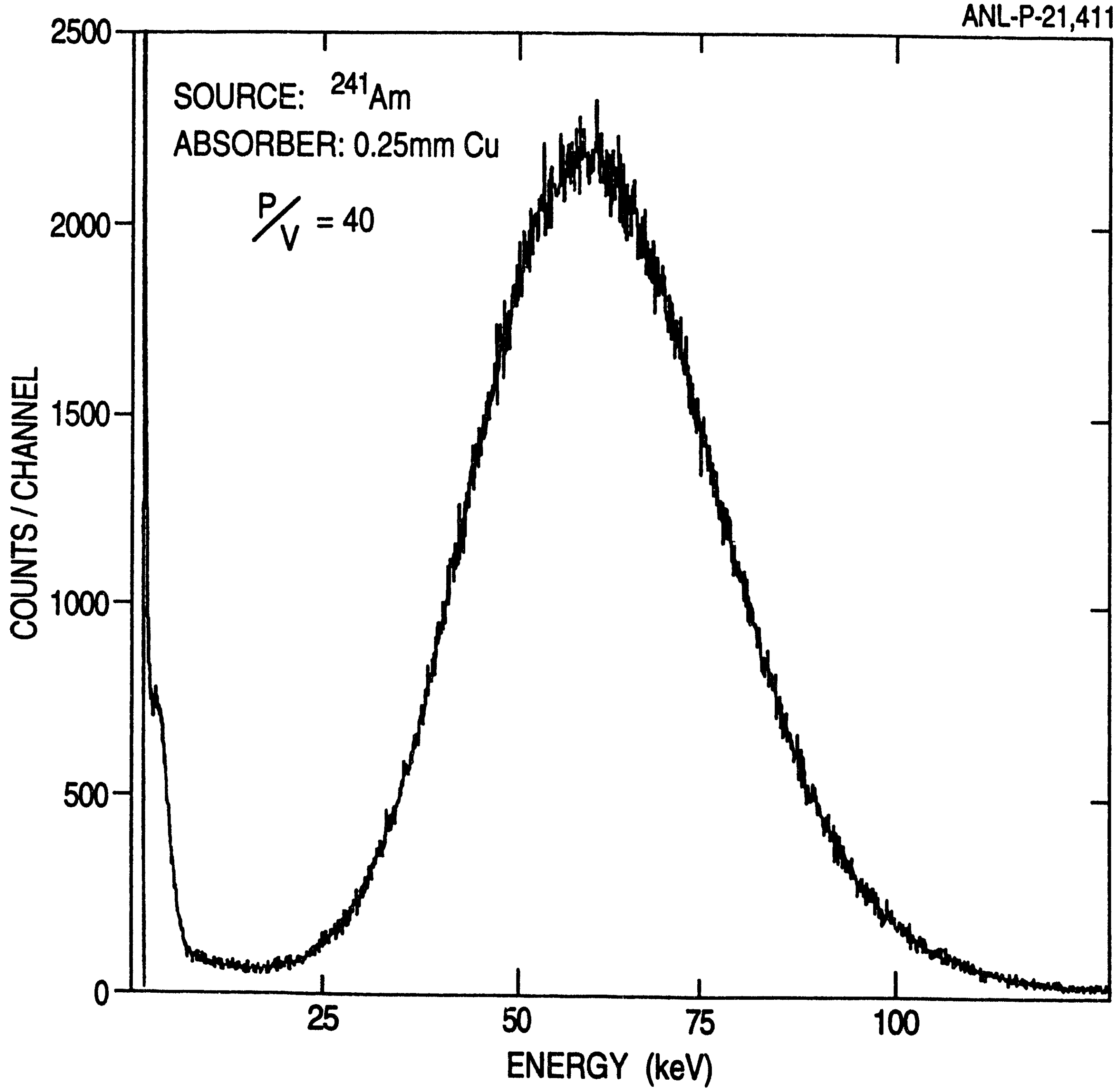
Fig. 2. A gamma ray spectrum of an ^{241}Am source (59.5 keV) measured with one element of the BGO Compton-suppression shield. Low energy γ rays and X rays were absorbed in a 0.25-mm thick Copper foil and the aluminum housing of the BGO scintillator.

Fig. 3. Gamma ray spectra of ^{137}Cs taken with one BGO element by placing the source at 0.5", 3.0", 5.0" and 7.0" from the detector narrow end.

Fig. 4. Time spectrum of one element of the BGO shield with respect to a small BaF_2 crystal. Threshold on the leading edge discriminator was ~5 keV. The spectrum in the figure was gated by 1.0 to 1.5 MeV gamma rays.



ANL-P-21,411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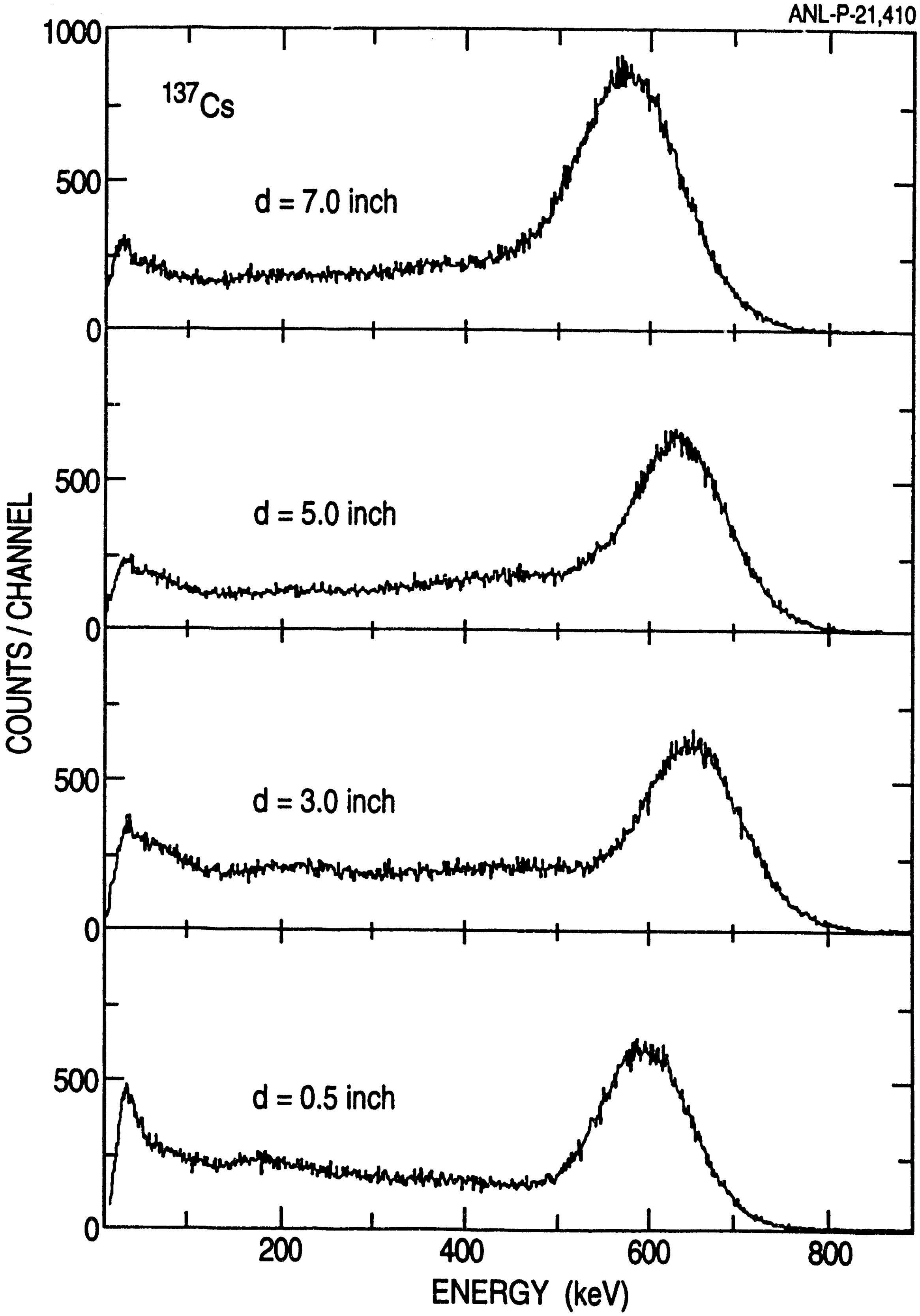
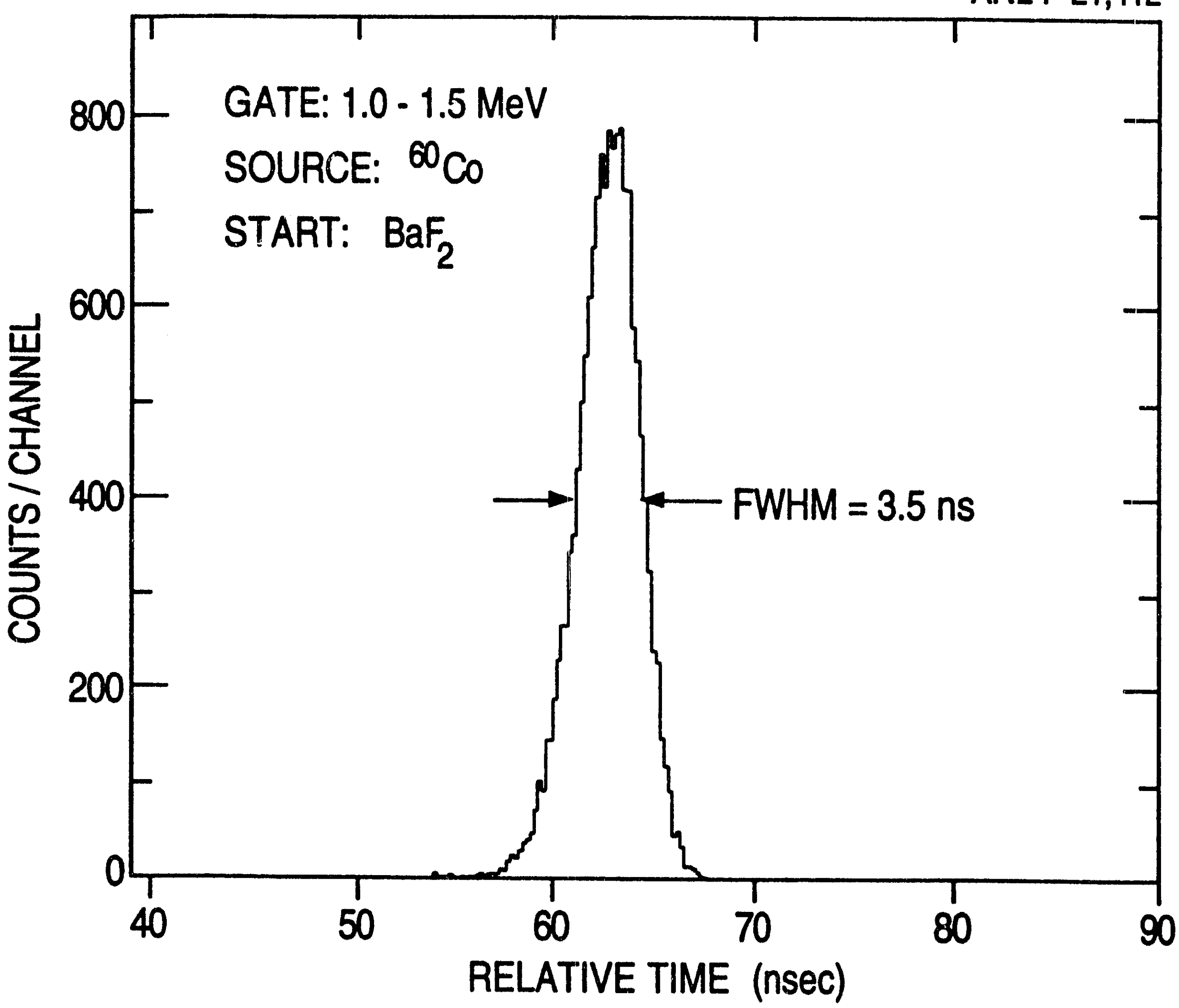
ABSORBER: 0.25mm Cu
P/V = 40
2500
2000
1500
1000
500
0
COUNTS / CHANNEL
25
50
75
100
ENERGY (keV)


ANL-P-21,410
137Cs
d = 7.0 inch
d = 5.0 inch
d = 3.0 inch
d = 0.5 inch
1000
500
0
COUNTS / CHANNEL
200
400
600
800
ENERGY (keV)

ANL-P-21,412


GATE: 1.0 - 1.5 MeV
SOURCE: 60Co
START: BaF2
FWHM = 3.5 ns
COUNTS / CHANNEL
RELATIVE TIME (nsec)
0
200
400
600
800
40
50
60
70
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