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BISMUTH GERMANATE'S ROLE IN THE NEW REVOLUTION IN GAMMA-RAY SPECTROSCOPY

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In this paper we do not wish to deal at great length with the technical details concerning the properties of BGO as an efficient γ-ray detector. Rather, we cover some of the considerations on how to effectively incorporate BGO into complex detection systems, discuss some of these new systems now in opration or under construction, and stress the new physics to be learned by utilizing these detector arrays.

To appreciate the present status of γ-ray spectroscopy, it seems appropriate to first review a bit of the history of the field and then to show some of the recent results based on data taken with coincidence arrays of germanium detectors and Compton-suppression spectrometers. At that point we will address the first impact that the use of bismuth germanate (BGO) detectors is having on our understanding of the properties of nuclei that have been excited into states of high energy (E) and very high angular momentum (I). BGO uses in this area are really in their infancy, but it is rather clear that the utilization of these detectors with their large stopping power for γ rays will play a major role in unraveling many of the mysteries of the nucleus in these extreme conditions.

In reviewing the significant achievements in nuclear physics during the past 3-4 decades, we recognize that they are closely related to the advancement of the technology of nuclear radiation detection. In nuclear structure physics, for example, the use of sodium iodide (NaI) for γ-ray detection firmly established the field of γ-ray spectroscopy, which subsequently led to a confirmation of the predictions by Bohr[1] of nuclear rotational motion. Thus was demonstrated the existence of non-spherical (deformed) nuclear shapes. With this detector technology, experimentalists were able to study strongly populated states in nuclei up to spins of about 8-10.

The advent of the high-resolution germanium (Ge) detector in the mid-Sixties and its use in γ-γ coincidence techniques greatly expanded our knowledge of nuclei and ultimately led just a decade ago to the discovery[2] of the "backbending" effect. This discontinuity in the rotational motion became the focus of many experimentalists and theorists. This effect is illustrated for ^{160}Yb in Fig. 1 where the moment of inertia ( ) vs. the rotational frequency (ω) of the nucleus is plotted. Note the contrasting behavior of a more typical rotational band for ^{174}Hf. The rotational alignment of quasiparticles in high-j orbitals was first proposed by Stephens and Simon[3] in 1972 as the explanation of this effect and in subsequent years it has provided the basis for a rich and detailed theory of nuclei at high spins. Thus, the importance of the interplay between the collective rotation mode and the single-particle mode of carrying angular momentum was established.

These experiments, usually employing a small number of Ge detectors, were applied to many nuclei through the mid-Seventies and led to a still better understanding of backbending and other interesting phenomena peculiar to nuclei excited to high spins. The next significant experimental advance in nuclear spectroscopy came through the use of a larger number

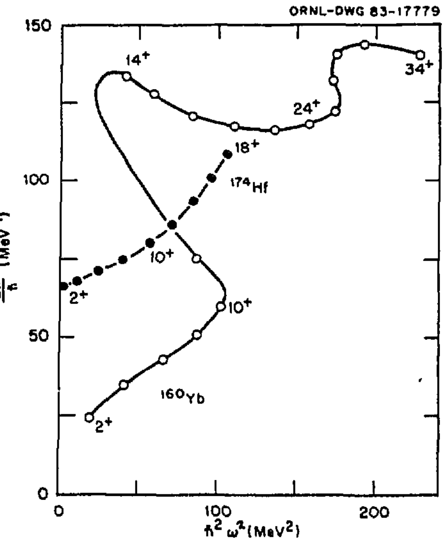

Fig. 1. Plot of moment of inertia vs. rotational frequency for ^{174}Hf and ^{160}Yb.

(5-7) of Ge detectors, together with multiplicity filters and/or total-energy sum spectrometers. This combination provides high coincidence efficiency and reasonable final reaction-channel selection, resulting in improved sensitivity for observing weaker γ-ray lines. The introduction of multiplicity and total-energy filters also benefited detailed studies of reaction mechanisms through the ability to make some selection of the imparted angular momentum and excitation energy to the final system. Out of this development, we have attained a reasonably good picture of states up to about spin 30 along or near the yrast line, a line defining states of the lowest excitation energy for a given angular momentum.

Another important advance in instrumentation for nuclear spectroscopy and reaction mechanisms came with the completion of the "spin spectrometer" at the Holifield Heavy-Ion Research Facility (HHIRF) and, more recently, the "crystal ball" at Heidelberg. The spin spectrometer[4-6] shown in Fig. 2 consists of 72 NaI detectors closely packed in a 4π arrangement. It is capable of recording, on an event-by-event basis, the pulse height and time-of-flight for each element that is triggered. From this information, it is possible to derive with good resolution the total γ-ray energy, E* (excitation energy for fused systems), the γ-ray multiplicity M_γ which is directly related to the transferred angular momentum I, and the direction of spin. As a consequence, nuclei can be selected with known excitation energy and given spin, so that their decay can be studied by means of discrete and/or γ-ray continuum spectroscopic techniques.

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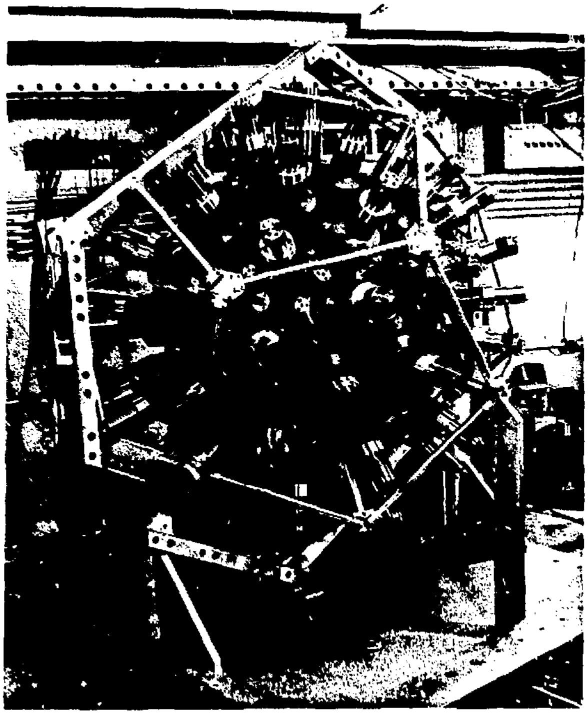

Fig. 2. The 72-NaI-detector spin spectrometer located at HHIRF.

The ability of the spin spectrometer to select nuclei formed at low excitation above the yrast line and very high spins has been employed in a very recent spectroscopy experiment in which six of the NaI elements were replaced with Ge detectors for a study[7] of the nucleus ^{160}Yb. The power of the spin spectrometer has also been demonstrated in recent energy-energy correlation measurements on the γ-ray continuum. This sea of γ rays emanating from the many collective bands running parallel to the yrast line contains valuable information on both the effective moment of inertia and the collective moments of inertia within these bands. These experiments reveal clear indications of both a spin and a temperature dependence on these moments of inertia. However, due to a lack of high resolution detectors with a large peak-to-total ratio, such experiments are now restricted to only light nuclei with small moments of inertia.

Among the major strides made during the past two or three years has been our improved understanding of high angular momentum phenomena at a microscopic level. This is true for both the experimental and theoretical approaches. We now recognize that refined γ-γ coincidence spectroscopy, coupled with measurements of electromagnetic properties (g-factors and lifetimes of states), can identify most quasiparticle alignment processes in addition to the first backbend, can show the gradual destruction of nuclear pair correlations, and can provide us with a map of the interplay between collective and single-particle degrees of freedom — a map that shows us the evolution of the nuclear shape with increasing angular momentum.

We have emphasized some exciting new accomplishments in high-spin research; but, at the same time, we are acutely aware of the limitations with the experimental apparatus commonly used when we seek to measure discrete γ rays emanating from states with spins above 30. Similar difficulties also exist for γ-ray continuum studies of states at 40-60 ħ. Certainly, these are spin regimes that contain the answers to truly fascinating questions. For example, will we see nuclear shapes that have evolved from prolate to triaxial at spins 20-30 move on to fully oblate distributions that demand a full single-particle description at spins 30-40 — and finally evolve once again into a collective assemblage or perhaps into a super-deformed system? Will we be able to carefully trace out the gradual pairing loss for protons and neutrons to the point at which there is a total pairing collapse? The answers to these and many other such intriguing questions are surely achievable if one is able to develop the proper γ-ray detection system.

For these γ-ray measurements demanding high resolution, the Ge detector is a necessity. However, it suffers from a poor peak-to-total ratio, with the result that weak γ-ray transitions often are not discernible above the background of Compton scattered events from either resolvable lines or from the higher energy γ-ray continuum. Whether it be for the spectroscopy studies of discrete γ-ray lines from states up to $I \approx 40$-50, for measurements in the γ-ray continuum covering $I \approx 30$-60, or for investigations of reaction meachanisms where it is necessary to gate on weak γ-ray lines, it is mandatory that we have a detection system that reduces the background problems resulting from Compton scattering. To accommodate these and other needs for research on high angular momentum behavior, we conclude that this detector system should have as a minimum the following capabilities: (1) It should have sufficient resolution to allow good selection of energy and spin. (2) At least some of the individual detector elements should provide for angular distribution and linear polarization measurements and, hence, should have good energy and angular resolution. (3) The spectroscopy detectors should have superior resolution and a high peak/Compton ratio. (4) The system must have good 2- and 3-fold coincidence counting efficiencies. (5) The device should permit good final reaction channel selection.

Such a device, which combines superior selectivity with excellent resolution and allows simultaneous study of discrete and quasi-continuum transitions, would tremendously facilitate our future investigations of many new aspects of high-spin behavior in nuclei. It is obvious that a central ingredient of this device is a grouping of Compton-suppression spectrometers.

To illustrate the power provided by Compton-suppression, we show in the top panel of Fig. 3 a standard (unsuppressed) γ-ray spectrum for ^{162}Yb formed in a compound-nucleus reaction and in the lower panel the spectrum resulting from a very modest Compton-suppression factor of about 3.5. It is apparent that, even with suppression factors of 3-4, many very weakly populated states can be studied. In this case NaI was used in the four Compton-suppression shields. However, if we are to achieve the goals for a detection system as discussed above, we must use a large number of detectors. These must involve from 40-70 units arranged in such a geometry as to yield good total energy and multiplicity information and must include a sufficient number of Compton-suppressed Ge detectors to yield the high resolution γ-γ coincidence information. Obviously we need a more dense material than NaI in order to get an adequate number of suppressed Ge detectors close to the target. This is where BGO enters the picture. BGO, i.e., $Bi_4(GeO_4)_3$, is an inert, crystalline

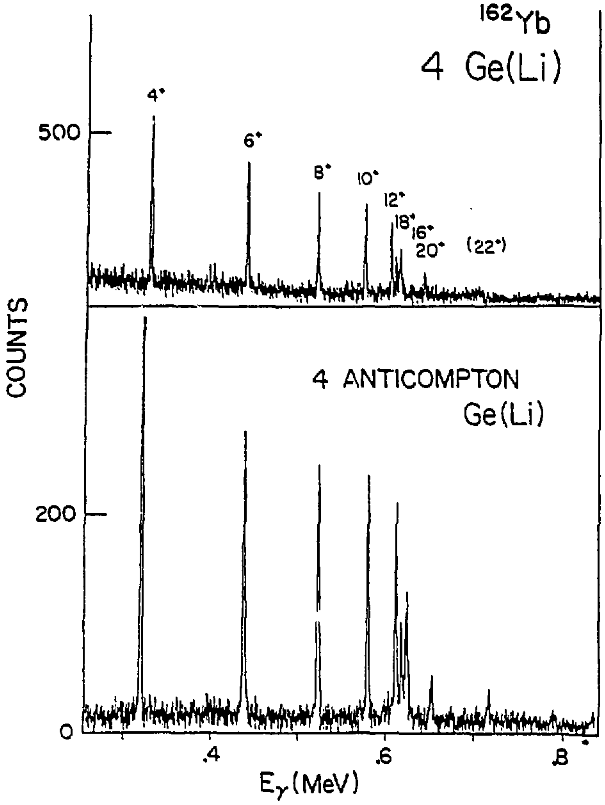

Fig. 3. Compton-suppressed (lower panel) and unsuppressed (upper panel) γ-ray spectra of ^{162}Yb following the reaction ^{149}Sm(^{16}O,3n).[8] Even with a suppression factor of 3-4 used here, the improvement in ability to measure weak γ-ray lines is dramatic.

nonhygroscopic scintillator with a decay constant of 0.3μs, emission wavelength of ~480nm, density of 7.13 g/cm^3 (compared with 3.67 for NaI), and light output of about 10-15% of that of NaI.

Let us deal now with a few aspects of Compton suppression that must be considered in the design of such a system. First of all, the Ge detectors must be at sufficient distance from the target so that Doppler broadening of the γ-ray lines does not become a severe problem. Figure 4 shows the Doppler broadening as a function of scattering angle for several target-detector separations. For a detector with 2 keV resolution at 1 MeV, it is apparent that a separation of 20 cm or greater is desirable. Even then, for a detector located at an angle of 25° with respect to the beam direction, there is about 3-keV broadening and when this is added in quadrature with the intrinsic resolution of the detector, the overall resolution has increased to 3.6 keV as opposed to, e.g., 4.6 keV for a 14 cm separation. Of course, the large separation comes at considerable cost in efficiency and thus affects the number of Compton-suppressed detectors needed to achieve acceptable coincidence counting rates. The importance of the Compton-rejection factor r is appreciated by viewing Fig. 5 where the improvement in the peak-to-total ratio for different coincidence folds (k = 1 corresponds to singles) is plotted as a function of the rejection factor. These values were calculated with the following expression

$$Q = (p/p_0)^k = \left[\frac{1}{p_0 + (1 - p_0)/r}\right]^k$$

where p is the peak-to-total ratio after suppression, p_0 is the peak-to-total before suppression (p_0=0.15 used in this case), r is the rejection factor and k is the coincidence fold. The improvement in the quality of data is nearly linear up to rejection factors of about 5-6 and after 10 the curves level off so that the added cost in achieving higher suppression may be questioned.

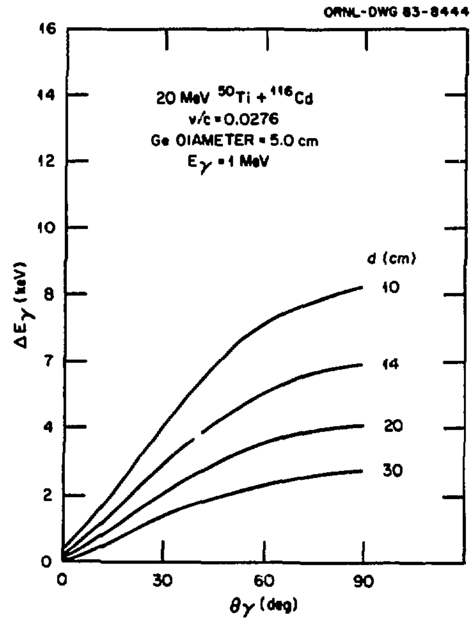

Fig. 4. Estimates of the Doppler broadening as a function of angle for a 1-MeV transition from a recoiling nucleus with v/c = 0.0276 observed with a Ge detector at the indicated distances in cm. Rapid loss in resolution with decreasing distance is seen, particularly for large angles.

To determine the feasibility of an experiment one must always assess the rate at which data can be taken. Thus, we must determine the minimum number of suppression units to achieve practical data rates. This is done in Fig. 6 where plots of event rate vs. the number of suppression units are given for different rejection factors (r) and different coincidence folds (k) where the target-detector separation is 20 cm. Within a given fold, the fact that event rates go down with higher suppression factors merely reflects the reduction in the number of undesirable events involving Compton scattering. From these curves we find that, for a Compton-suppression factor of ~ 9, it is possible to accumulate two-fold coincidence data of good statistical quality in 2-3 days running time if as many as 8-9 Compton-suppression units are used. However, three-fold coincidence data provide a richer reservoir of information and to obtain this at a meaningful statistical level (within a similar amount of beam time) it is necessary to have at least 17-20 suppression units.

Despite the fact that many experiments demand a large central cavity in which to place experimental apparatus such as particle detection devices and demand a spherical symmetry in order to carry out valuable spin-alignment measurements, the large cost to accomplish this has caused some groups to turn to

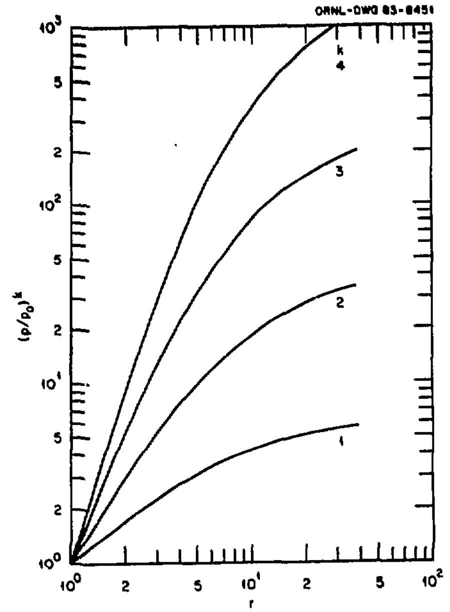

Fig. 5. Improvement factor $Q = (p/p_0)^k$ of peak/total ratio as a function of the Compton rejection factor r for different values of the coincidence fold k.

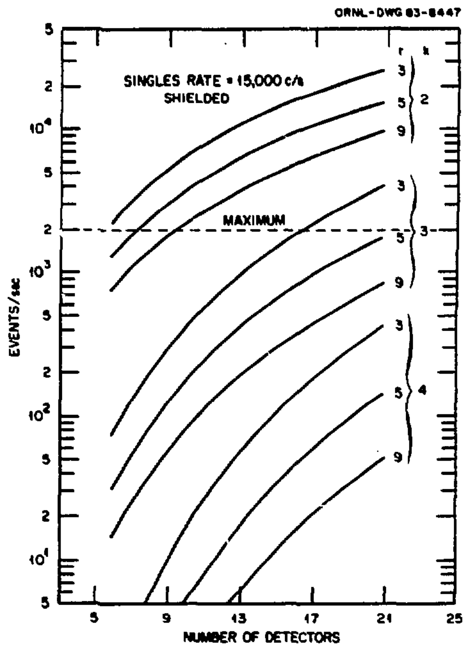

Fig. 6. Maximum event rate as a function of the number of anti-Compton spectrometers N, for coincidence folds k = 2, 3, 4, and for Compton-suppression factors r = 3, 5 and 9, as indicated. The singles rate in the Ge(unsuppressed) was assumed to be 15,000 c/s. The horizontal dashed line represents typical computer limitations.

a non-symmetrical tight-packed central castle of BGO elements for the measurement of total decay energy and γ-ray multiplicity. Their Compton-suppression devices are then arranged outside this castle and have window openings through it to the small target chamber. The Liverpool-Daresbury group[9] have constructed such a device (Tessa II) which is illustrated in Fig. 7. The Central region is comprised of a tight-packed castle array of ~ 62 BGO elements. Six NaI-suppressed Ge detectors have windows extending

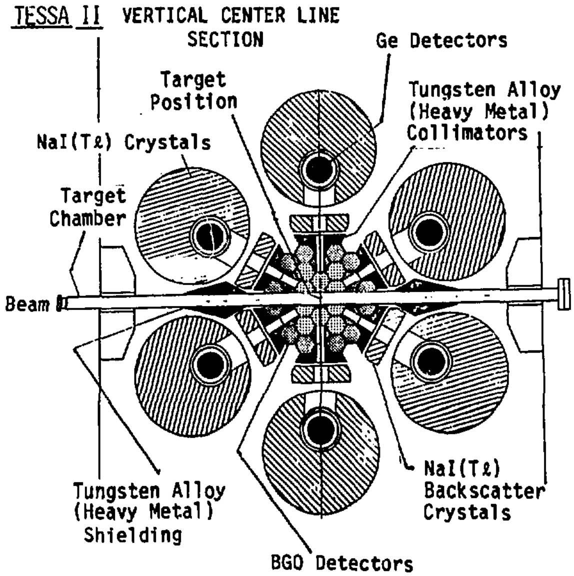

Fig. 7. The arrangement of BGO detectors and Compton-suppression spectrometers for the Liverpool-Daresbury TESSA II.

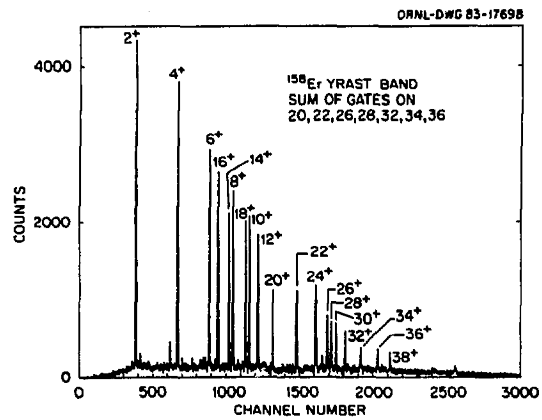

Fig. 8. Compton-suppressed spectrum of the yrast band of ^{158}Er taken with TESSA II by Riley et al.[10]

to the target through this array. In the next stage of development they will increase the number of suppression units considerably by using smaller volume BGO suppression shields. However, with the present units they have already been able to achieve very impressive results.

In Fig. 8 we show a spectrum of the yrast band of ^{158}Er taken with TESSA II by M. Riley and collaborators.[10] It is interesting to compare this spectrum with results we[7] obtained for ^{160}Yb with the spin spectrometer and six Ge detectors at Oak Ridge. The latter device represents one of the most sophisticated γ-ray spectroscopy coincidence devices available which does not employ Compton suppression.

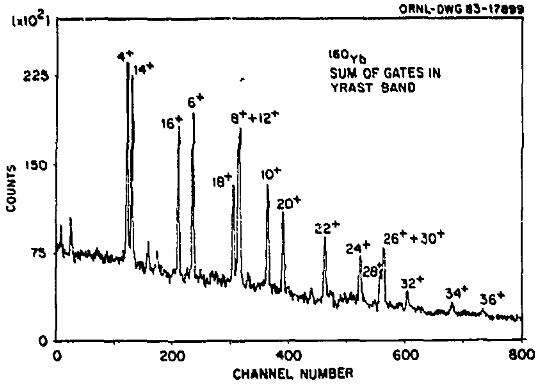

Fig. 9. Gamma-gamma coincidence spectrum for ^{160}Yb taken with six Ge detectors in the spin spectrometer at Oak Ridge.

But as can be seen in Fig. 9, the quality of these data in providing quantitative information on states *I*=*36-38* falls far short of the data in Fig. 8. In addition, with appropriate gating, the Compton-suppressed data for ^{158}Er reveal many weak non-yrast transitions that would not be resolved by other techniques. Riley and colleagues[10] have obtained similar high quality data on the neighboring odd-N isotopes ^{157}Er and ^{159}Er. With such information it is reasonable to ask what new insights into the structure of these nuclei does it reveal. The answer is that for the first time they have definitively established that the "second" band crossing in ^{158}Er at $\hbar\omega \sim 0.43$ MeV results from the alignment of a pair of $h_{11/2}$ quasiprotons. Further, they show that there is a neutron-dependent shift in these crossings and that it is probably associated with a change in the nuclear shape, i.e., that there is a systematic increase in the quadrupole deformation in going from ^{157}Er to ^{159}Er. Finally, their results showed that at about spin 38-40 the energy-level spacings depart from the more rotational-like pattern, despite the fact that their data on the γ-ray continuum indicate that there is still a distinguishable valley structure characteristic of collective behavior.

A yet more ambitious array of BGO detctors is being constructed at Berkeley by Stephens, Diamond and colleagues.[11] The inner ball is essentially a 4π castle comprised of 44 BGO elements. Surrounding this will be 21 (BGO) Compton-suppressed Ge detectors, each with its port to view the target. This device will be able to take 2-fold coincidence events at very high rates and 3-fold events at modest rates. There are several groups in this country and abroad who have proposed the construction of similar experimental devices. In one of these, an Oak Ridge — Washington University — University of Tennessee collaboration[12] has proposed a scheme which incorporates the unique advantages of the Oak Ridge spin spectrometer and provides all of the features listed above as desirable in a Compton-suppression system. As seen in Fig. 2, the spin spectrometer is a 4π array of 72 NaI detectors and it has a large central chamber (36 cm diameter) which can accommodate a variety of solid state detectors, gas counters, a mini-orange electron spectrometer or other experimental devices, all of which provide great flexibility in carrying out a wide variety of experiments.

We have proposed the replacement of 17 of the existing pentagonal and hexagonal NaI elements in the spin spectrometer with suppression shields comprised of 0.4-inch NaI at the front face followed by 7 inches of BGO. The purpose of the front 0.4-inch NaI is to provide the maximum light output for low energy "backscattered" photons. Each unit will have a 2.5-inch diameter axial opening to permit insertion of a large-volume Ge detector.

One problem with the axially configured suppression shield is that it is difficult to achieve a high rejection factor with it. In our case we calculate (from simple single-scatter considerations) this factor to be 6.5. Monte Carlo calculations now in progress will probably yield a somewhat smaller value. A difficulty is that forward-scattered (high-energy) photons are lost through the axial opening and, thus, contribute to an excess level of low energy counts in the primary spectrum. To counter this problem we have worked closely with engineers at EG&G (ORTEC) and Harshaw Chemical Co. to develop a new Ge+BGO detector combination. In this arrangement the cryostat arm extending from the preamp to the vacuum housing immediately surrounding the Ge detector is of only 0.75-inch diameter. At the rear of the Ge will be a 2.5-inch diameter annular (3.2 inches long) BGO detector which fills the opening and intercepts most of the photons scattered in the forward direction. A full detector assembly is illustrated in Fig. 10. With this detector design, simple one-scatter calculations indicate a Compton-suppression factor > 9 which in reality will probably turn out to be in the range of 7-8. This suppression power coupled with the inherent strength of the spin spectrometer will provide unique capabilities in the study of high-spin phenomena.

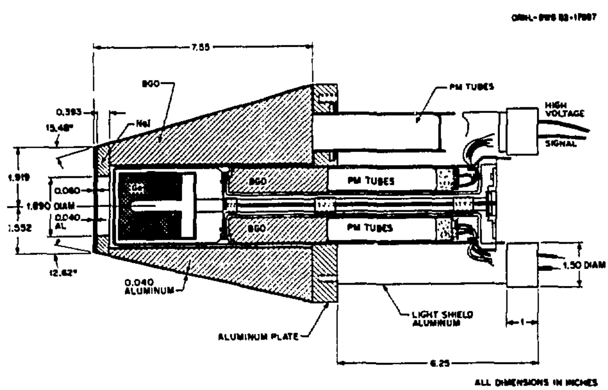

Fig. 10. Illustration of a full Compton-suppression pentagonal detector assembly to go in the spin spectrometer.

In conclusion, it seems quite probable that, with the advent of these new detector systems incorporating BGO, we will be able to make major strides forward in our understanding of nuclei at very high spin and high excitation. That is not to say, however, that all the detector needs for γ-ray spectroscopy have been mastered. As we seek out the finer details in these γ-ray spectra that contain the keys to a fuller understanding of the properties of nuclei at very high angular momentum, we are constantly pressing for improvements in detector technology. In the absence of a primary detector of better resolution and better photopeak response than germanium offers, we must continue in the search for Compton-suppression shields that provide the maximum stopping power for photons and yield improved light collection enhancing both good timing and good resolution. Large arrays of these detectors further demand improved technology in miniature light collection devices such as light-sensitive diodes that permit the demands for a very tight geometrical arrangement.

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