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THE GAMMASPHERE

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GAMMASPHERE is one of a new generation of gamma ray detector arrays. It consists of 110 Compton-suppressed large volume Ge detectors. The design goal is to achieve high efficiency and peak-to-total value for four to five fold coincidence experiments. Such high-fold coincidence capability will provide new physics opportunities in areas such as high spins, transfer reactions, giant resonances, and astrophysics. The design of the detector and shield has been developed through extensive simulation calculations and an "electronic honeycomb" design was chosen. The electronics and computer systems are capable of operating at 50,000 event/sec. The design and development tasks are being carried out at several laboratories in the U.S. The project is expected to be funded in the fall of 1990. The first experiment is planned in the summer of 1992.

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1. INTRODUCTION

Due to their good resolution, high efficiency, and low background, arrays of Compton suppressed Ge detectors have become a powerful tool for gamma-ray spectroscopy. Many recent advances in high spin physics, such as the observation of superdeformed states,[1] are the results of using these arrays. Presently, about ten such arrays are operational or near completion. These arrays typically have 20 detectors covering 10-15% of the total solid angle, and a total full-energy efficiency of about 2%. Although they provide high efficiency for gamma-gamma two-fold coincidence experiments and moderate efficiency for three-fold coincidences, they are not adequate for higher-fold coincidences. However, recent developments in high-spin gamma-ray spectroscopy have demonstrated the needs for higher fold coincidence experiments. In the meantime, due to advances in detector and computer technology, it is technically possible to build detector arrays with much higher efficiency and to acquire high-fold data at desired rates. The GAMMASPHERE is designed to carry out four- and five-fold coincidence experiment with high efficiency. The advantage of high-fold coincidence is the improvement of the resolving power and the ability to identify weak cascades from a large number of cascades.

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2. THE IMPACT ON THE PHYSICS

The high resolving power provided by the GAMMASPHERE will open up new scientific opportunities for a broad range of nuclear studies. In the following we will present a few examples which have been discussed in the GAMMASPHERE proposal[2] and in the talks presented in this conference to demonstrate the capabilities of GAMMASPHERE.

2.1. Super and hyperdeformed states

High-spin states corresponding to a superdeformed nucleus were found[1] for the first time in 1986. A rotational band of very large moment of inertia and deformation was discovered in ^{152}Dy in the $I = 22$ to 60 range. This discovery has opened a new direction in nuclear physics and subsequently, many other cases of superdeformation have been observed in the $A \approx 130$, 150, and 190 regions. These nuclei have an axially symmetric, prolate spheriodal shape and the principal axes have a ratio of lengths significantly larger than the "usual" 1.3 to 1. Like the usual deformed nuclei, they exist because shell effects provide extra stability for these shapes.

The observation and study of such highly deformed nuclei will give us a chance to explore new phenomena and ideas: (i) The particular grouping of the single particle levels which leads to the prediction of regions of superdeformed nuclei is more generally related[3] to special approximate symmetries (called pseudo-spin and pseudo-SU(3) symmetries) of the Hamiltonian. These can be studied by testing the location and strength of shell effects at large deformation. (ii) We will also have a first look at nuclei where the ratio of Coulomb to surface energy is significantly different from those we know. This means that the basic elements determining nuclear structure have a different relationship to each other. (iii) A truly new phenomenon which should be accessible with GAMMASPHERE will be the population of theoretically predicted "hyperdeformed" nuclei, represented by the 3:1 axis ratio shown schematically in Fig. 1. Indeed, such a "hyperdeformed" shape has been reported[4] at low spins in ^{231}Th, and possibly in molecular resonances in light nuclei. The orbitals occupied in these hyperdeformed states originate in very high shells whose position is quite uncertain. Therefore, experimental information on hyperdeformed states should provide important constraints to test theoretical models under quite unusual conditions.

The superdeformed states at high spins are hard to find. As shown in Fig. 2, the average intensity of these transitions is about 1-2%, and the connection to the low-lying normally deformed states is not known. Here, the higher-fold coincidences will be quite powerful. This was used recently[5] to

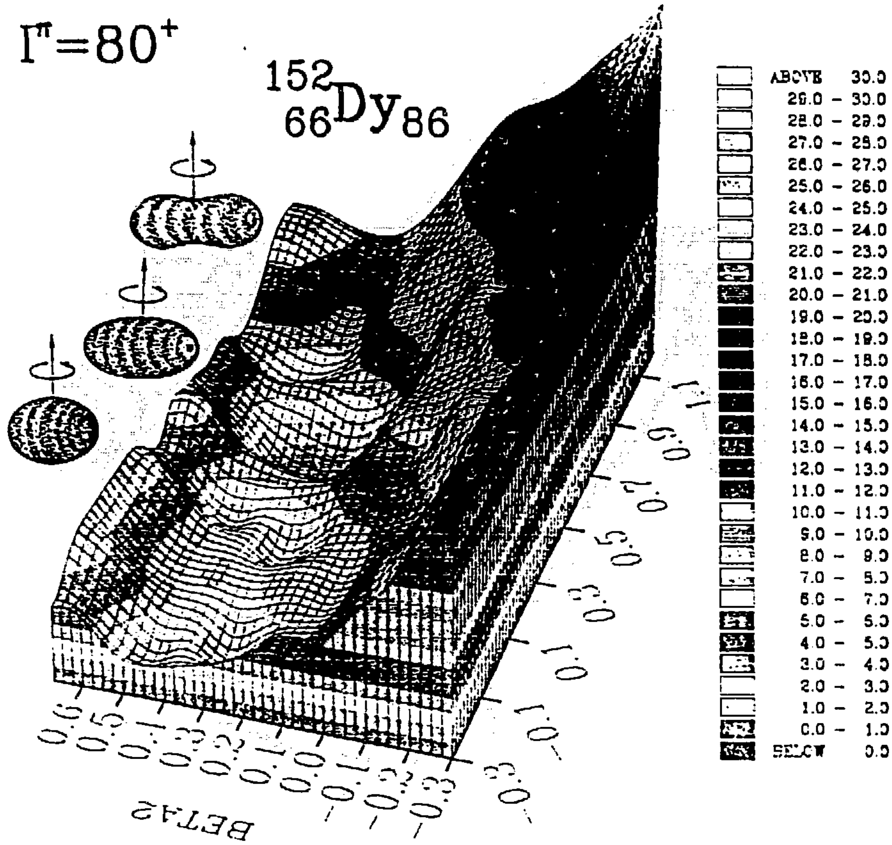

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FIGURE 1
The calculated potential energy surface for ^{152}Dy at spin 80. The inserts correspond to the shapes of the nucleus at three minima. The left axis is parallel to $\gamma = 60°$ line and the right axis to the $\gamma = -30°$ line.

identify a superdeformed band in ^{148}Gd. A factor of about ten in peak-to-background ratio was gained in the double-gated spectrum over the single-gated spectrum. The use of four- and five-fold coincidences with GAMMASPHERE will improve the resolving power by about 100. As indicated in Fig. 2, the GAMMASPHERE will enable us to study transitions with intensity $\sim 10^{-4}$. Thus, it will be easier to study superdeformed states with GAMMASPHERE than normal deformed states with currently available arrays.

2.2. Damping of rotational motion

In an isolated (discrete) rotational band near the yrast line, the gamma decay occurs through a unique set of states with spins I, I-2, I-4... . The nuclear level density increases exponentially with increasing excitation energy. At any excitation energy U of about 2 MeV (or temperature T ~ 0.3 MeV), where the average separation between states becomes comparable to the residual interaction between those states, many bands will become mixed.

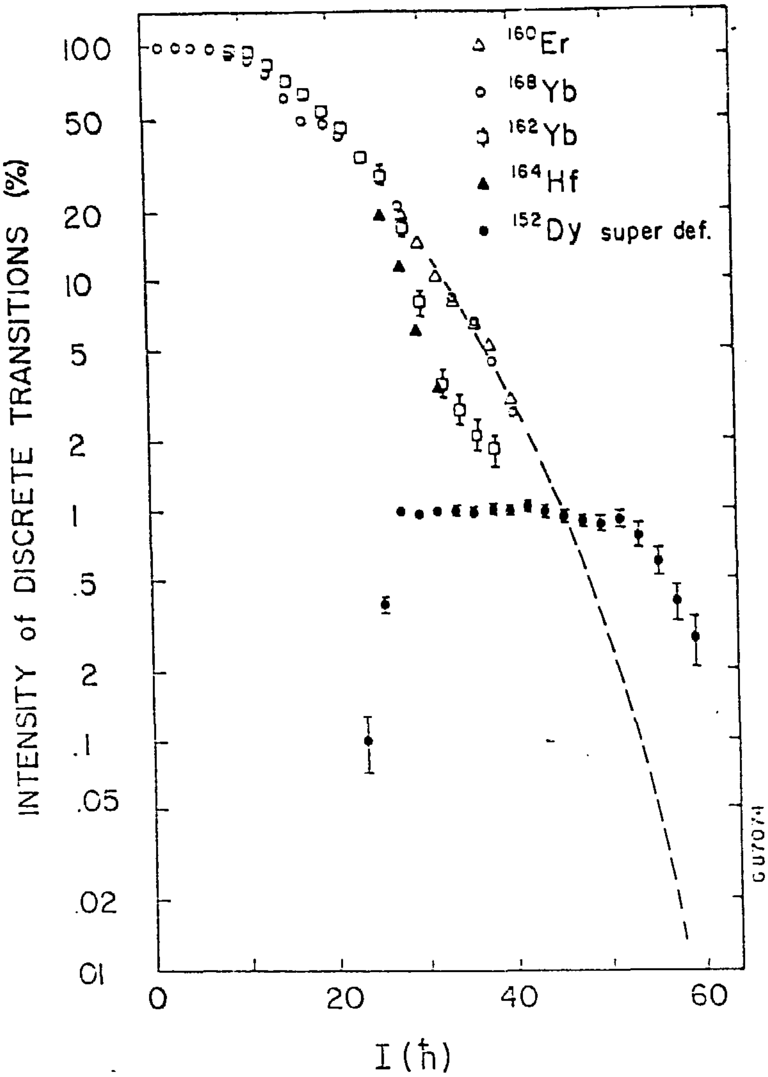


FIGURE 2
Discrete line intensities versus spin for some well-deformed nuclei and for the superdeformed band in ^{152}Dy. The lines show results from simulation calculations. The GAMMASPHERE will push the intensity limit of an observable state from 1% to 0.01%.

Calculations suggest that a given initial state, I, will no longer decay to a unique final state with spin, I-2, but rather to a distribution of states whose energy spread is related to the spread in the moments of inertia of the admixed bands. This situation is depicted in Fig. 3, is called "damping of rotational motion," and is contrasted with the normal rotational behavior shown near the yrast line.

The spectrum of a discrete rotational band consists of a "picket fence" of equally spaced gamma rays, and if a gate is set on one of these, the resulting coincident spectrum has a hole at the gate position. Even in spectra consisting of lines from many rotational bands which have a wide variation in

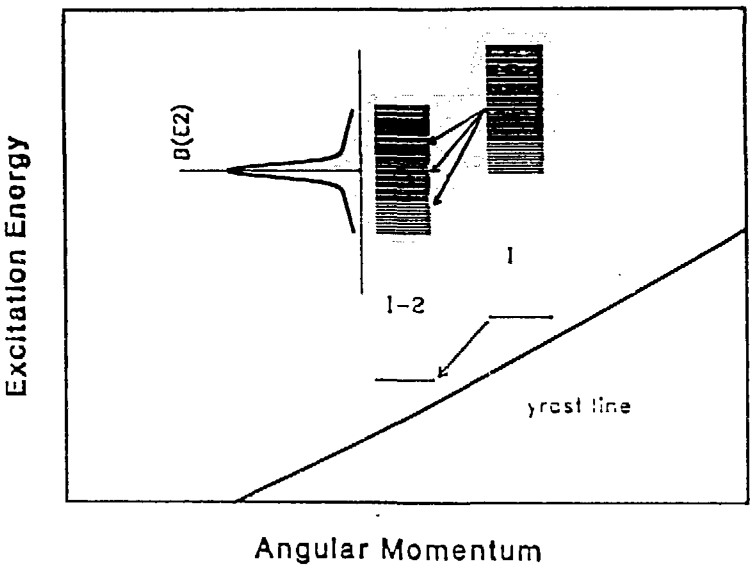


FIGURE 3
At high energy above the yrast line, a mixed state of spin I will decay to any one of a distribution of states at I-2. This is known as the "rotational damping" effect.

moment of inertia, such a hole, or "dip," should persist. In fact, no such dip exists at the higher gamma-ray energies, and it was to explain this absence that damping[6] was first introduced.

Damping modifies the expected behavior such that the observed dip should be wider, eventually approximating the (inverted) shape of the damping width, Γ_{rot}. For Γ_{rot} values above 300 keV, this dip would be a very broad shallow feature (the area is conserved, so that as it becomes wider it becomes shallower). Such a feature would be very difficult to observe in a spectrum whose shape is not well known. The shape is not well known because the gate also imposes a strong spin selection (and perhaps also other selections) that affects the shape of the spectrum. To date, there is good general evidence for damping (or something very much like it), but it has not yet been possible to measure damping widths directly, and certainly not as a function of excitation energy as would be needed to probe in detail the interesting region around $U \sim 2$ MeV.

The measurements made thus far have been mostly with single-gated spectra (double coincidences) and in just a few cases with double-gated spectra[7] (triple coincidences). In order to understand what to expect in these results, simulations of the cascades following heavy-ion fusion reactions, including damping effects, have been made. The simulation shows that there is a very large difference in the feeding effects between the single-gated and singles spectra. The double-gated spectrum is much more similar to the single-gated spectra, but the difference in feeding effects in these spectra is still about as large as that due to the dip associated with the damped rotational behavior. However, when comparing triple-gated (four-fold coincidence) with double-gated spectra, the simulations indicate that by far the largest difference between the two spectra is indeed due to the dip associated with the damped rotational behavior. Furthermore, the dip has a width that is related to the input damping width. Thus, the simulation strongly suggests that if we could work with triple-gated spectra, we could measure directly the damping width. Note that its variation with excitation energy can be obtained both from the variation with gamma-ray energy (related to excitation energy) and from total-energy and multiplicity gates provided by GAMMASPHERE.

The rates for such experiments with GAMMASPHERE are quite plausible. Considering a two-day run, and gates 20 keV-wide (small compared with both the ~60 keV average separation between rotational energies and the 300 keV damping width), we should get about 2.5×10^5 (full energy) events in the triple-gated spectrum, and a dip area of 10^4 counts. By contrast, the best existing arrays today would produce 200 counts in the full spectrum, and ~10 in the dip — clearly unusable.

2.3. Structure of giant resonances

Giant resonances can be excited by inelastic scattering. A study of the photon decay of these resonances, while difficult due to its small probability, can provide information different from that coming from nucleon decay. Recently, photon decay of the giant quadrupole resonances in ^{208}Pb has been studied[8] in the excitation energy region from 9 to 15 MeV. The nucleus was excited by a 381-MeV ^{17}O beam. Since this state decays predominantly by neutron emission with only a 10^{-4} branch for gamma decay, it was necessary to use the Spin Spectrometer, a 4π solid angle gamma ray detector array, and particle-gamma coincidence techniques to observe the gamma rays. The results are shown in Fig. 4. The giant quadrupole resonance was observed to decay by an E2 branch to the ground state and an E1 branch to several excited 1^- states. Most interestingly, the E1 decay to the collective 3^- state at 2.61

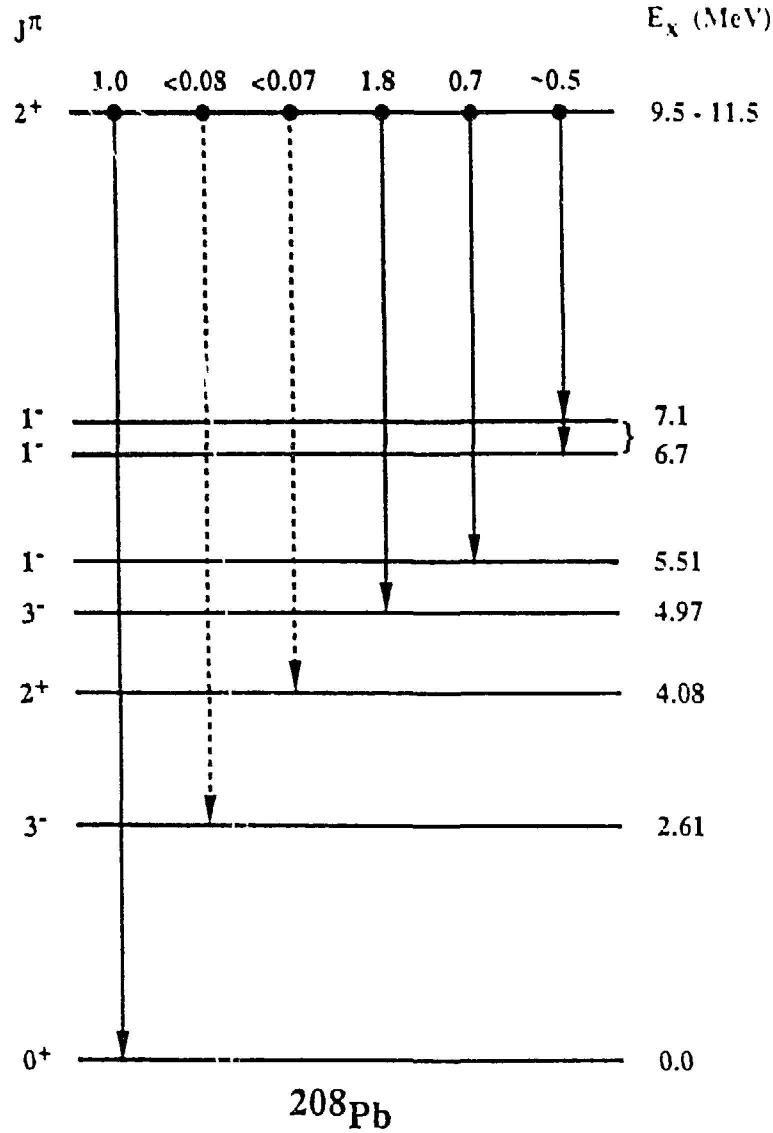


FIGURE 4
Gamma decay of the 9.5-11.5 MeV excitation energy region of ^{208}Pb.

MeV is strongly suppressed in comparison to the decay to the non-collective 3^- state at 4.97 MeV. These results confirm the isoscalar character of the 10.6 MeV resonance. Unfortunately, because of the limited resolution of the NaI detectors, it is only possible to study closed shell nuclei with low level densities for the low-lying states.

The strong coupling between the giant resonances and the low-lying surface vibrational modes of the nucleus has been studied theoretically since the 1960's. This coupling can be investigated experimentally by the study of photon decay branches from the dipole resonance to low-lying collective states. This area of study is currently of intense interest at electron accelerators where measurements are made of the inelastic scattering of tagged photons. GAMMASPHERE would make possible the study of scattered ion-gamma-gamma coincidences. In the experiment the forward Ge detectors would be replaced by BaF_2 detectors, leaving the backward hemisphere for low-energy gamma-ray detection. The inelastically scattered ion would give the excitation energy, a high-energy gamma ray detected in the BaF_2 detectors would define the primary decay from the giant resonance, and a low-energy gamma ray detected in the Ge detectors would indicate the final state of the primary decay. In this mode, the gamma decay of giant resonances of any nuclei can be studied.

2.4. Heavy-ion induced transfer reactions

One- and two-nucleon transfer reactions induced by heavy ions provide a means of studying transfer between high-spin states populated by Coulomb excitation prior to transfer. Thus, such reactions make it possible to study single-particle and pairing effects under the influence of considerable collective angular momentum, and provide a selective new population mechanism for studying high-spin states.

Recent studies of heavy-ion transfer reactions, using the Spin Spectrometer at the Holifield Heavy Ion Research Facility,[9,10] have given new insight into the reaction mechanism. The major conclusions are as follows. (1) Heavy-ion transfer reactions comprise a major fraction of the total reaction cross section near the Coulomb barrier. (2) Heavy-ion induced transfer reactions on deformed nuclei selectively populate "cold" states in the yrast domain, i.e., those close to the yrast "zero-temperature" line, up to spin 30 with large cross sections. (3) These reactions have been used[10] to populate states to spins of almost 30 in actinide nuclei. Moreover, the fission channel is unimportant, in contrast to the situation when other reactions are used to populate such states. (4) The most recent study of transfer to strongly-deformed rare-earth nuclei has shown that 2-neutron transfer to the ground band, at large separation distances between the colliding nuclei, exhibits an oscillatory behavior with separation distance and is strongly enhanced.

Heavy-ion-induced transfer reactions require detection of the scattered particles in coincidence with the deexcitation gamma rays in order to determine the two-body kinematics necessary to separate transfer from competing reactions, as well as to correct the gamma spectra for Doppler effects. GAMMASPHERE will have an inner sphere sufficiently large to accommodate the particle-detector arrays needed for this work. It will provide more than an order of magnitude increase in particle-gamma coincidence rate relative to what has been used in past transfer experiments, improving the sensitivity of the measurements. However, it is the two orders of magnitude increase in the particle-gamma-gamma triple coincidence rate and the ability to perform even higher-fold coincidence experiments that is the most significant advance and the one that will open new frontiers. Particle-gamma-gamma, or higher-fold coincidences, are needed for study of heavy-ion induced transfer reactions, since at least one of the coincident gamma rays is used to identify the reaction product, and it is the remaining coincident gamma rays that provide the interesting physics.

In addition, GAMMASPHERE will have sufficient resolution in both total energy and multiplicity to allow study of selective regions of spin and excitation energy in order to separate transfer to the interesting ground state band region from that to the dominant population of complicated multi-quasiparticle states which decay to the states of interest.

3. DESIGN AND SCHEDULE OF THE GAMMASPHERE

The design goal of the GAMMASPHERE detector system is to achieve high efficiency, good response function, high energy resolution, and detectors resistant to neutron damage. Within the limits of existing technology, the obvious choice of the detector is a 4π array of n-type Ge detectors with BGO Compton suppressors. The total efficiency of a detector array is $N\Omega\varepsilon_p$ where N is the number of the detector, Ω the solid angle covered by each detector, and ε_p the fraction of gamma rays hitting the front of the detector that result in a full energy pulse. The peak-to-total ratio which measures the quality of the resonance function is $P/T = \varepsilon_p / \varepsilon_p + (\varepsilon_c/R)$ where ε_c is the fraction of the incident gamma rays result in a less than full energy pulse and R is the background reduction provided by the suppression shield. A large ε_p value will give both a high efficiency and high P/T value. The ε_p value increases with the volume of the detector, therefore, we decided to use the largest available n-type Ge detector with dimensions 7 cm Dia. x 7.5 cm L. It has an ε_p value of about 0.2. With the ε_p value given, the total efficiency can be increased by increasing the total solid angle $N\Omega$. On the other hand, to improve the peak-to-total value will require increasing the rejection factor R. This can be achieved by an increase of the thickness of the shield at the expense of a smaller solid angle for the Ge detectors. In addition, the Doppler broadening and the chance of two gamma rays from a given event hitting the same detector are larger for a detector with larger solid angle. This implies a large number of Ge detectors each with a small solid angle. For GAMMASPHERE, we have chosen a design with 110 detectors (with $N\Omega$~0.5) arranged in a configuration with the symmetry of a icosahedron. Other factors which will affect the array performance are the false veto from the gamma rays hitting the shield either directly from the target or scattered from other detectors, signals produced by the neutrons and by gamma rays scattered from collimators and detectors.

We have studied the performance of three shield designs based on extensive simulation calculations. Illustrated in Fig. 5 are: 1) individual, 2) honeycomb, and 3) electronics honeycomb schemes. The "individual" design which is used in all of the arrays currently in use has the advantage of simplicity, but, as shown in Table 1, it has a low P/T value because the thickness of the shield is limited by the requirement of $N\Omega \sim 0.5$ for the Ge detector. In the "honeycomb" design, each Ge detector is surrounded by six suppressor elements and each suppressor element is shared by two Ge detectors. Since the effective thickness of the BGO is doubled, a better P/T value can be achieved. However, the sharing of the shield causes false vetoes of neighboring detectors and reduces the efficiency of the array. In the "electronic honeycomb" design the shield elements are divided into two parts and packaged as 110 suppressors, each comprising six optically-isolated sectors. The two adjacent elements are combined electronically to suppress both Ge detectors

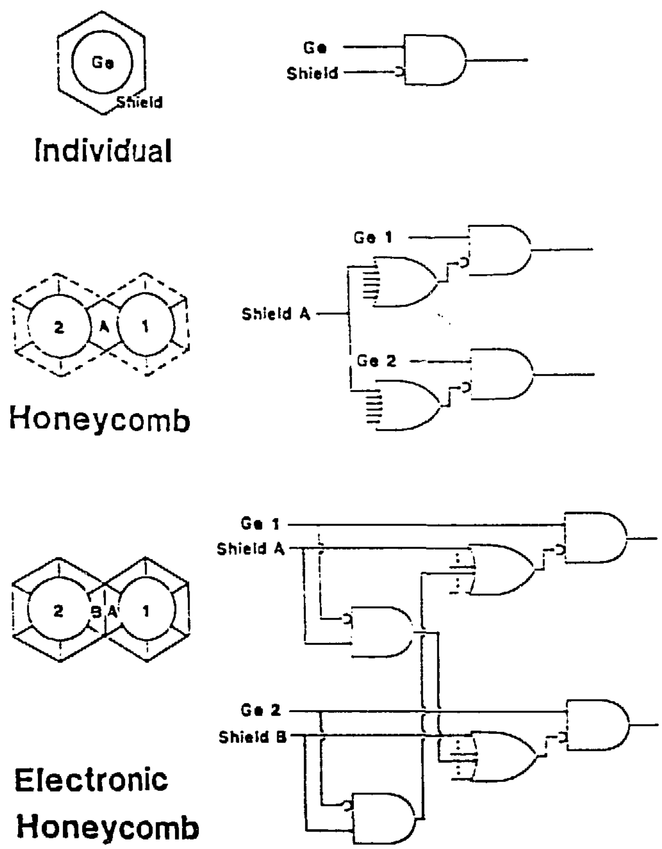


FIGURE 5
Schematics of three types of suppressor designs and suppression logic.

(hence the name electronics honeycomb), except when the neighboring Ge is triggered, then only the sector closer to the Ge is used. This design minimizes the false veto and maintains the excellent P/T value of the honeycomb design. Therefore, the electronic honeycomb design will be used for the GAMMASPHERE. The suppression logic of the three designs is shown in the left side of Fig. 5.

TABLE 1
Performance of Three Types of Shield From Simulation Calculations

Shield Design	Total Efficiency	Peak-to-Total
Individual	0.095	0.62
Honeycomb	0.079	0.70
Electronic Honeycomb	0.089	0.69

Figure 6 shows a typical Ge detector with the suppressor elements and a back plug. The front 2 cm of the Ge detector is tapered with a half angle of 7.45 degrees. The distance to target is 24.6 cm. The BGO element has a length of 18 cm and the front surface to target distance is 21.8 cm. An inner ball of 240 BaF_2 detectors can be placed in front of the suppressors. It would protect the suppressor elements from direct gamma-ray hits, and thus prevent false rejection from these gamma rays. It can also distinguish gamma rays from neutrons and give a better gamma-ray multiplicity value. For experiments studying high energy gamma rays (E_γ> 5 MeV), 55 BaF_2 detectors will be available to replace Ge detectors. A sketch of the GAMMASPHERE

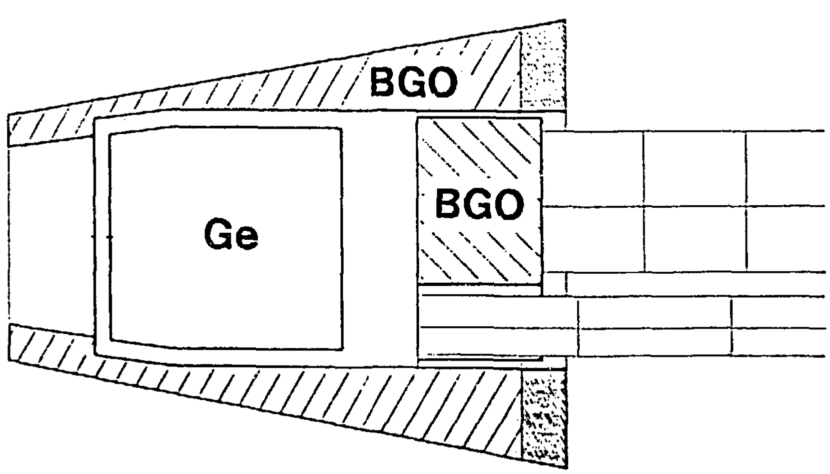


FIGURE 6
Side view of a Ge detector and BGO Compton suppressors.

will be available to replace Ge detectors. A sketch of the GAMMASPHERE detector system with the mechanical support is shown in Fig. 7. The support structure has a radius of 0.73 M and the beam line is 2.4 M above the floor.

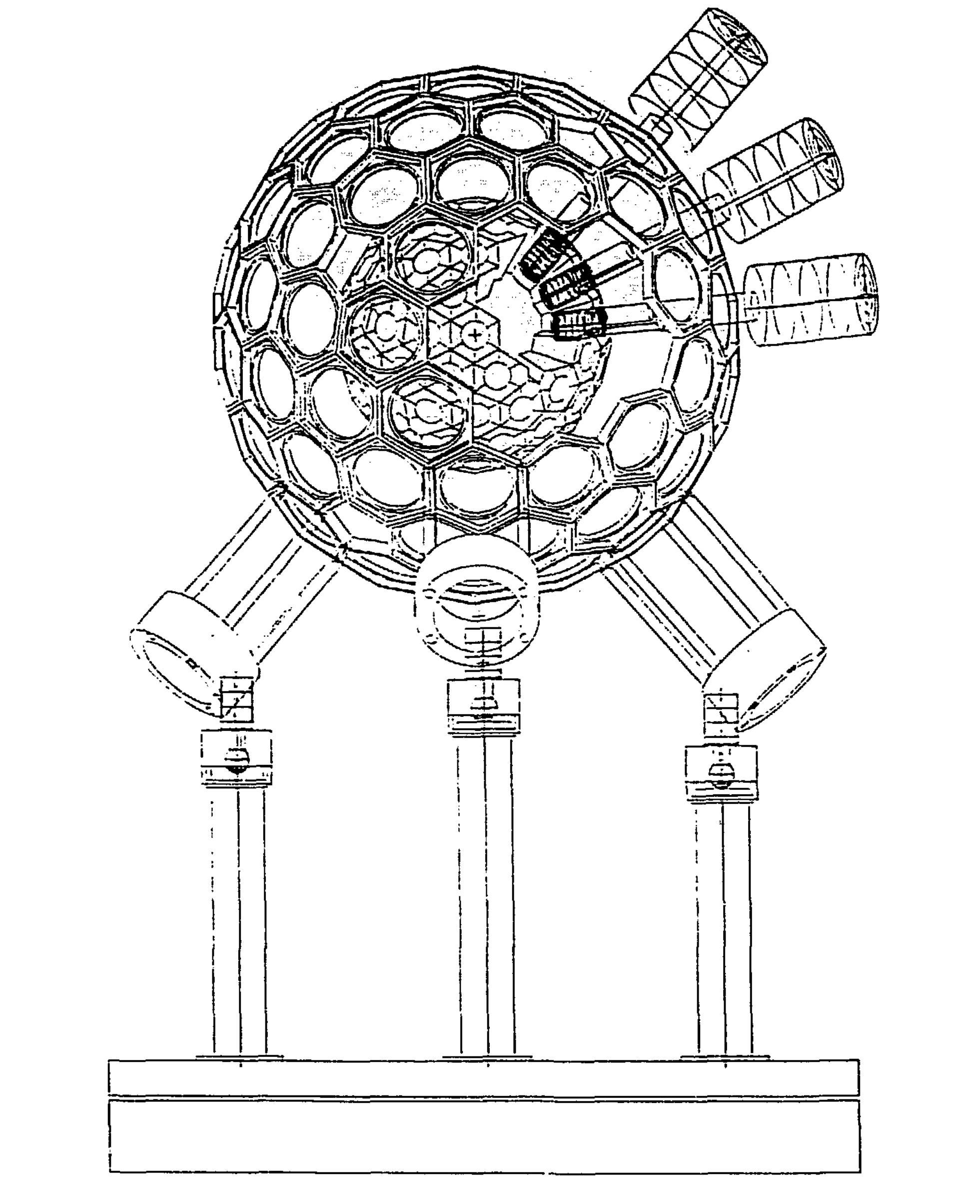
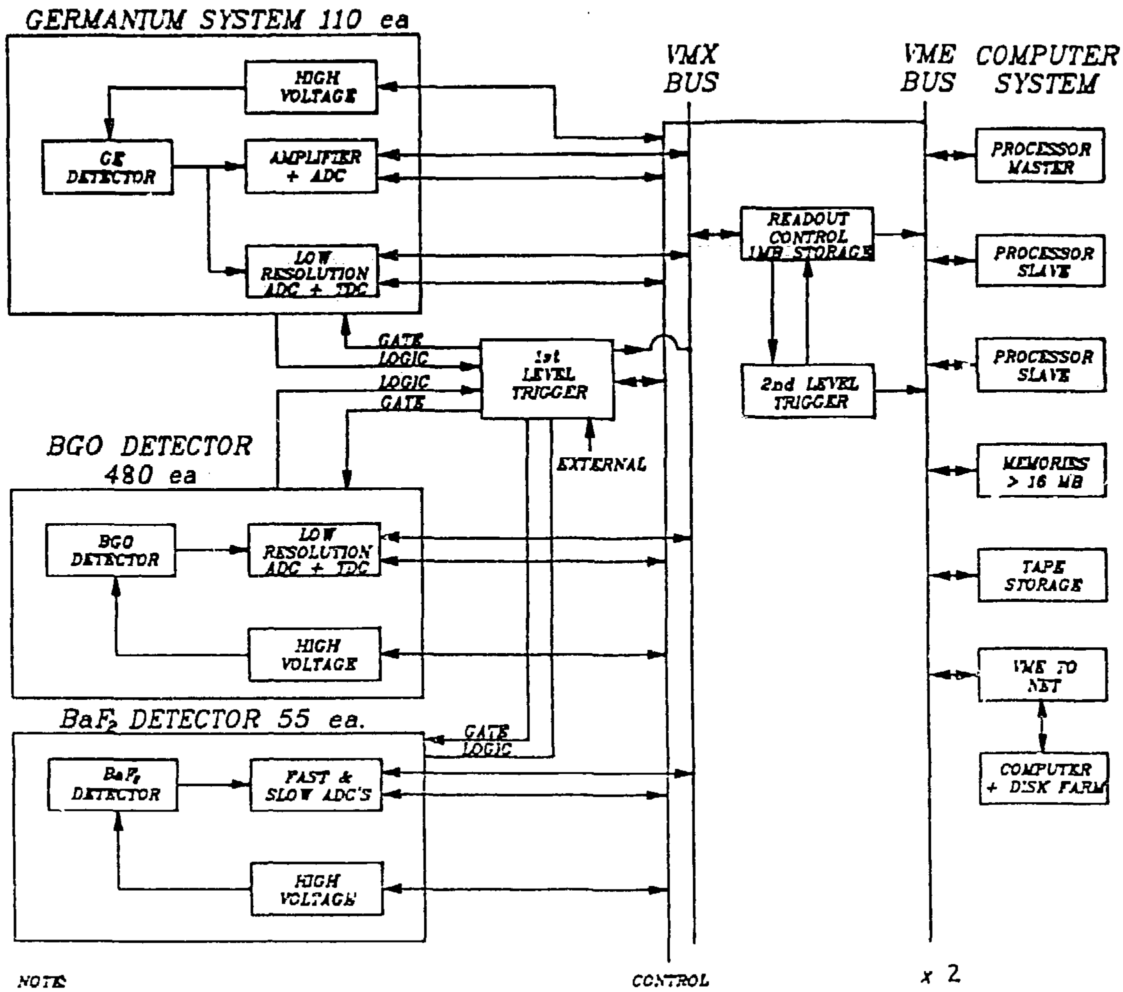


FIGURE 7
A sketch of the GAMMASPHERE detector system with mechanical support.

The electronics system illustrated in Fig. 8 is designed to have a system deadtime of 10 μsec. This is achieved by using ADC's and TDC's with 5 μsec digitizing time and a data read-out time of 100 nsec/word. At the designed maximum event rate of 50 k/sec and a typical length of event of 100 bytes,



NOTE

1) SCALERS BUILT INTO FRONT END ELECTRONICS

2) A SECOND PROCESSOR FARM IS USED FOR OFF-LINE ANALYSIS

FIGURE 8
Schematic diagram for the electronics system.

the data rate will be 5 M byte/sec. It has been decided to develop custom-built modules based on the new VXI bus. The VXI standard provides large board size, good shielding, high bus speed and high supply power. The large board size alone will reduce considerably, the cabling and improve reliability. It is expected that in most of the experiments, on-line data selection will be carried out so that only a small fraction of the data has to be stored in event-by-event mode. The on-line data modification (e.g., energy calibration and ballistic deficit correction), selection, histogramming, and storage require an estimated processing power of 65 Mips. Since the data from each event can be analyzed independently, parallel processing is the most straightforward and economical approach. Currently, a single-board computer can provide about 10 Mips per board. It is planned to use such a computer as the building block of a parallel computer based on VMEbus.

The schedule of the project is shown in Table 2. In the summer of 1988, the proposal was submitted to DOE for peer review and received strong endorsement. In November of 1988, the proposal underwent the Cost, Schedule, and Management review and again was highly endorsed. The project was presented to the DOE/NSF Nuclear Science Advisory Committee (NSAC) which on March 5, 1989, recommended that the project be funded and the site selection process be begun as soon as possible. Consequently, a DOE panel reviewed siting proposals from Argonne National Laboratory (ANL), Lawrence Berkeley Laboratory (LBL), and Oak Ridge National Laboratory (ORNL) and recommended that ORNL be the site of the GAMMASPHERE. DOE is expected to include initial funds for GAMMASPHERE construction in the FY 1991 budget which starts on October 1, 1990.

TABLE 2
GAMMASPHERE Schedule

Organizational Meeting	October	1987
Workshop	November	1987
Proposal	March	1988
DOE Mail Review	Summer	1988
Cost and Management Review	November	1988
NSAC Review	January	1989
Site Selection Review	May	1989
(Funding	October	1990)
(Initial Operation	Summer	1992)
(Full Operation	Summer	1993)

Currently, the design and prototyping of the components of the GAMMASPHERE are carried out in several laboratories. The designs of the Ge detectors and the BGO suppressors have been finished. A prototype Ge detector and seven associated BGO elements of the honeycomb design have been ordered and received by ANL. Extensive tests are being carried out. The design of the BaF_2 inner ball is being carried out at ORNL. One prototype element is being tested. Due to space limitation, a suitable method of reading out the scintillation light has to be found. Among the options being studied are the use of light pipes, small phototubes, and photodiodes. The detailed specifications of the electronics are being developed by electronics experts from ANL, LBL, ORNL, and Michigan State University. The design of the building and beam line are being carried out at ORNL. The GAMMASPHERE can be used in a stand-alone beam line, at the target position of a Recoil Mass Spectrometer (RMS), or at the focal position of the RMS.

According to the schedule, the project will be complete in three years at a cost of about 18M$. However, experiments can start after two years when about half of the detectors are delivered and the essential part of the data acquisition system is ready. It is expected that about 20 experiments will be carried out yearly for a total running time of 2500 hours. The exciting new opportunities provided by such an array will make the GAMMASPHERE together with a similar array being developed in Europe, the Eurogam, the premier facilities for nuclear structure studies for the next decade.

This project has made rapid progress since it was first proposed by Frank Stephens during the summer of 1987. The enormous amount of effort of Frank and the wide participation of the community are the main reasons for the success of the project at this stage. Most of the development tasks have been organized and carried out by the steering committee which currently consists of D. Cline (Rochester), chairman; R. M. Diamond (LBL); D. B. Fossan (Stony Brook); T. L. Khoo (ANL); and I. Y. Lee (ORNL).

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