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. GAMMASPHERE will be sited initially at the 88-Inch Cyclotron at LBL as a national facility. The first experiment is planned in early 1993.

1. INTRODUCTION

Due to their good energy 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, 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 gammaray 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 highfold 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.

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\(^2\) 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 \(A = 130, 150,\) and 190 regions. These superdeformed states 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. Theoretical calculations have predicted the existence of these superdeformed shapes and even hyperdeformed shapes.

Figure 1 shows the calculated potential energy surface of \(^{152}\)Dy at spin 80. It has three minima corresponding to oblate, superdeformed (2:1 axis ratio) and hyperdeformed (3:1 axis ratio) shapes, respectively.

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\(^3\) to 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 \(~10^{-4}\). Thus, it will be easier to study superdeformed states with GAMMASPHERE than normal deformed states with currently available arrays. These studies certainly will yield better understanding of many interesting but not yet fully understood phenomena associated with the superdeformed states such as 1) the unusual feeding pattern, 2) the decay path out of the superdeformed bands, and 3) the origin of identical bands.

The "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. GAMMASPHERE will provide the chance to observe the high spin states of hyperdeformed shapes.

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Fig. 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 $\gamma = 60^\circ$ line and the right axis to the $\gamma = -30^\circ$ line.

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 $\mathcal{U}$ 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. Calculations suggest that a given initial
Fig. 2. Discrete line intensities versus spin for some well-deformed nuclei and for the superdeformed band in 152Dy. The lines show results from simulation calculations. The GAMMASPHERE will push the intensity limit of an observable state from 1% to 0.01%.
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, depicted in Fig. 3, is called "damping of rotational motion," and is contrasted with the normal rotational behavior shown near the yrast line.

Excitation Energy

Fig. 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.

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 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 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, \( \Gamma_{\text{rot}} \). For \( \Gamma_{\text{rot}} \) 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~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 (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 $2.5 \times 10^5$ (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.

3. DESIGN AND SCHEDULE OF THE GAMMASPHERE

The design goal of the GAMMASPHERE detector system is to achieve high peak 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 $4\pi$ array of n-type Ge detectors with BGO Compton suppressors. The total efficiency of a detector array is $N_0\varepsilon_0$, where $N$ is the number of the detector, $\Omega$ the solid angle covered by each detector, and $\varepsilon_0$ 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 $P/T = \varepsilon_0 / \varepsilon_0 + (\varepsilon_0/R)$ where $\varepsilon_c$ is the fraction of the incident gamma rays that result in a less than full energy pulse and $R$ is the background reduction provided by the suppression shield. A large $\varepsilon_0$ value will give both a
high efficiency and high P/T value. The $\varepsilon_D$ value increases with the volume of the detector, therefore, we decided to use the largest available n-type Ge detector with dimensions 7.1 cm Dia. x 8 cm L. It has an $\varepsilon_D$ value of about 0.2. With the $\varepsilon_D$ value given, the total efficiency can be increased by increasing the total solid angle $N_0$. 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 $N_0$=0.5) arranged in a configuration with the symmetry of a icosahedron.

It has been found experimentally that the resolution degradation of the Ge detector is accelerated at crystal temperature above 90°K. Therefore, the Ge crystal will be kept below 90°K. Other factors which can affect the array performance and have been considered in the design are the false veto from the gamma rays hitting the shield either directly from the target or scattered from other detectors, and 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. 4 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 $N_0$=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 (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. 4.
Fig. 4. Schematics of three types of suppressor designs and suppression logic.
Table 1
Performance of Three Types of Shield From Simulation Calculations

<table>
<thead>
<tr>
<th>Shield Design</th>
<th>Total Efficiency</th>
<th>Peak-to-Total</th>
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</thead>
<tbody>
<tr>
<td>Individual</td>
<td>0.095</td>
<td>0.62</td>
</tr>
<tr>
<td>Honeycomb</td>
<td>0.079</td>
<td>0.70</td>
</tr>
<tr>
<td>Electronic Honeycomb</td>
<td>0.089</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Figure 5 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 7.5 degrees. The distance from the front face of Ge crystal to the target is 25 cm. The BGO element has a length of 19 cm and the front surface to target distance is 21.5 cm. A 4 cm thick BGO back plug fits inside the shield behind the Ge cryostat which is connected by an off-center cooling rod to the liquid nitrogen dewar. A sketch of the GAMMASPHERE detector system with the mechanical support is shown in Fig. 6. The support structure has a radius of 0.7 M and the beam is about 2 M above the floor.

Fig. 5. Side view of a Ge detector and BGO Compton suppressors.
Fig. 6. A sketch of the GAMMASPHERE detector system with mechanical support.
The data acquisition system, illustrated in Fig. 7 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 with 32 bit wide buses. At the designed maximum event rate of 50 kHz and a typical length of event of 100 bytes, 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.

In addition to the usual pulse height signal, the Ge electronics will provide two signals for ballistic deficient correction; one corresponds to the pulse height difference of the unipolar and bipolar signals, the other corresponds to the peaking time of the unipolar signal. From extensive tests done at ANL, it is found that by using these two signals, not only the ballistic deficit can be corrected, but also the energy degraded pulse due to neutron damage can be identified. The event trigger will be based on the total γ-ray multiplicity and the multiplicity of clean Ge. External triggers will be accepted as first level trigger within 1 µsec after the event and as second level trigger within 10 µsec. Digital data from ADC's, TDC's, and pattern registers will be read out sequentially and sent to the front end processor.

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 have to be stored in event-by-event mode. The on-line data modification, selection, histogramming, and storage require an estimated processing power of 200 Mips. Since the data from each event can be analyzed independently, parallel processing is the most straightforward and economical approach. A group of VME based processing units will be used as the front end processor. Each unit contains a single board computer, FIFO memory, a tape writing processor and a networking module. These processors will perform gain alignment, ballistic deficit correction, and Compton rejection by the second ring of BGO shield. The processed events are written to tape and to a network of workstations for on line histogramming and analysis.

The design and prototyping of the components of the GAMMASPHERE has been carried out in several laboratories. The Ge and BGO detectors have been designed with the help of simulation calculations carried out mainly at ORNL. A prototype Ge detector and seven associated BGO elements of the honeycomb design have been purchased by ANL and extensive tests are being carried out. The results, as shown in Fig. 8, indicated that a peak-to-total ratio of 0.68 is achieved for 60Co γ-rays and the back plug provided significant improvement of the performance. Both of these aspects agree with our expectations. The detailed specifications of the electronics and computer were developed by experts from ANL, LBL, ORNL, and Michigan State University.
Fig. 7. A schematic diagram for the data acquisition system.
Fig. 8. Spectra of a $^{60}$Co source measured with the prototype Ge detector. In the bottom figure, suppressed and unsuppressed spectra are compared. In the middle figure, suppressed spectra with and without the backplug are shown. In the top figure, ratios of the unsuppressed to the suppressed spectra with and without the backplug are shown.

The recent development and the schedule of GAMMASPHERE is shown in Table 2. In December of 1990, a meeting of ANL, LBL, ORNL, and DOE representatives agreed on the selection of the 88" cyclotron as the initial site for GAMMASPHERE. A baseline review was conducted by DOE in June 1991, on an engineering implementation plan prepared by LBL. Frank Stephens was appointed the project director. The funding is expected to start in August 1991. An early implementation plan calls for starting experimental programs in June 1993, when about 30 detector units are available. Half of the detectors and the electronics will be ready by January of 1994, and the detector will be completed in October 1994. 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.
Table 2
GAMMASPHERE Schedule

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
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<tbody>
<tr>
<td>Site agreement</td>
<td>December 1990</td>
</tr>
<tr>
<td>Baseline review</td>
<td>June 1991</td>
</tr>
<tr>
<td>Funding</td>
<td>August 1991</td>
</tr>
<tr>
<td>Early implementation (30 det)</td>
<td>January 1993</td>
</tr>
<tr>
<td>55 detectors</td>
<td>January 1994</td>
</tr>
<tr>
<td>Project complete</td>
<td>October 1994</td>
</tr>
</tbody>
</table>

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).

REFERENCES

7. M. P. Carpenter et al., submitted to NIM.