A NATIONAL PLAN FOR DEVELOPMENT OF GAMMA-RAY TRACKING DETECTORS IN NUCLEAR SCIENCE

BY

THE GAMMA-RAY TRACKING COORDINATING COMMITTEE

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Appendices

1 Executive Summary

The Gamma-Ray Tracking Coordinating Committee [GRTCC] was appointed, on 21 January 2002, by the Directors of the nuclear science divisions at the Argonne National Laboratory, Lawrence Berkeley National Laboratory, and Oak Ridge National Laboratory, at the request of the DOE Division of Nuclear Physics, to promote the development of γ-ray tracking detector technology in nuclear structure research. The goal is to help organize the γ-ray tracking community, to provide widespread support and to provide an effective plan for the future. The DOE Division of Nuclear Physics intends to use this committee to obtain timely advice on issues and proposals in γ-ray tracking.

The initial charge, made to this committee is to take a broad role in the development of γ-ray tracking detectors in this country. In particular there are three elements of the charge that should be addressed in a timely manner.

- *Develop the various physics justifications for γ-ray tracking and establish the performance goals that are required in each area.*
- *Formulate a national R&D plan for γ-ray tracking detectors.*
- *Examine the currents efforts in γ-ray tracking that are underway in the United States and provide the Department of Energy with advice about how they should proceed.*

This charge is focused on γ-ray tracking detector technology in nuclear structure research. However the committee should also examine progress in other areas of science.

The recommendations of the Committee are based on requested written answers to questions that were posed to the major γ ray tracking detector projects in this country, GRETA, GARBO, and SeGA, the Gamma-ray Tracking Fact Finding Meeting held at Argonne 29-30 March 2002 and extensive discussions by the Committee. The attendees to the fact-finding meeting included active participants developing the projects mentioned above, the European AGATA project, the NRL Astrophysics Tracking Group, the GRETA Steering Committee, and representatives of the Gammasphere User Group. The current and planned efforts in γ-ray tracking were discussed frankly and openly leading to unanimous support for a set of important and unambiguous conclusions.

This report, by the Gamma-ray Tracking Coordinating Committee, makes five recommendations that are focused on the development of γ-ray tracking detector technology for nuclear physics research. It also includes an observation regarding the cost of implementing a national 4π γ-ray tracking array. The Committee also recognizes that development of γ-ray tracking detector technology has much broader applicability to science, technology and society as mentioned in the second observation.

Recommendations:

1 A 4π Gamma-Ray tracking facility is an important new initiative within the 2002 NSAC Long Range Plan. This committee unanimously recommends a shell of closely packed coaxial Ge-detectors as outlined in the GRETA conceptual design for this 4π γ-ray tracking facility. We strongly recommend that DOE support this effort with highest priority.

As stated in the 2002 Long Range Plan for Nuclear Science, a 4π γ-ray tracking array facility will play a key role in the future success of the national and international nuclear research programs at both stable and radioactive beam facilities in this country. Such a 4π γ-ray tracking array also will build upon the extraordinary success of Gammasphere with regard to both scientific output and training the next generation of scientists in the field. The Tracking Coordinating Committee is in unanimous agreement that a major 4π γ-ray tracking array facility is required to address the exciting physics opportunities at RIA as well as existing stable and unstable-beam facilities. The physics justification for a 4π γ-ray tracking detector is presented in the NSAC 2002 Long-Range Plan for Nuclear Science, the report of the 2001 Lowell Workshop on Gamma-ray Tracking Detectors for Nuclear Science, and chapter 3 of this report. The Committee strongly recommends that DOE fully support this exciting opportunity.

Preliminary computer simulations made at Argonne, based on current technology, show that the predicted performance of a 4π γ-ray tracking array of planar detectors is not competitive with the predicted performance of a 4π tracking array of coaxial Ge detectors. As a consequence, there was unanimous agreement of the Committee, and the attendees of the Gamma-ray Tracking Fact Finding Meeting held at Argonne, that a shell of closely packed coaxial Ge tracking detectors, as exemplified by GRETA (and AGATA in Europe), is the only practical approach for proceeding with the implementation of this major 4π γ-ray tracking array.

2 R&D necessary to demonstrate the full functionality of this detector was identified and has to be addressed immediately. We note that a substantial fraction of this R&D effort is manpower that must be supported.

The Committee strongly recommends the highest priority to immediate and adequate funding of the remaining R&D efforts in order to facilitate rapid progress towards completing construction of a national 4π tracking array facility.

The analysis of the tests to demonstrate the performance of the prototype segmented GRETA detector should be completed. The next critical detector milestone is to complete construction and testing of the first GRETA (3-crystal) cluster module to confirm that the performance meets or exceeds the functional requirements using both radioactive sources and in-beam tests. The second R&D critical detector milestone is to construct and test performance with an array of two, or more, tightly-packed cluster modules to confirm full functionality when tracking across separate cluster modules with radioactive sources and with in-beam tests. The final system critical milestone is a demonstration of full functionality for signal processing and tracking across an array of three closely packed cluster modules for an in-beam source. The projected costs are $750K in FY2003 for the first module, which is already funded, plus $1,030K in FY2004 for the second two modules plus a mount. Testing will require 3 FTE of scientist effort plus 0.3 FTE technical.

Development of digital electronics must occur in parallel with detector development. The first critical milestone is completion and successful use of the 8-channel digital signal-processing unit with a tracking detector. The second and final critical digital electronics milestone is construction and demonstration of full functionality with a GRETA module using the 40-channel digital signal processing boards. The digital electronics development could have a significant impact on data acquisition technology both for nuclear science and science in general. The digital electronics R&D will require $225K plus 2.5 FTE of engineering effort spread over FY2003/2004.

Further signal analysis of available data, development of improved and fast minimization procedures and complete signal-shape parameterizations including crystal orientation effects will require 6.5 FTE of scientific effort. About 5.5 FTE of scientific effort is needed to refine available tracking algorithms. These efforts can be spread over several years and will be done by scientists based at national laboratories and universities.

The signal analysis and tracking development work will be applicable to all types of γ-ray tracking detectors. The broad applicability of the digital electronics, signal analysis and tracking makes it important that this R&D be a national coordinated and collaborative effort.

3 The R&D phase, the subsequent final design, and the construction of GRETA should continue to be a community effort; in particular, it should involve significant participation by the low energy nuclear physics national laboratories and universities.

The importance of GRETA to the future scientific program in this country, as well as the magnitude of the task, plus the manpower involved for the R&D phase, the subsequent final design, and the construction, requires that this national endeavor continue to be a community effort. Moreover, it would be very beneficial to nuclear science, both in this country and Europe, if the GRETA development were done in close coordination with development of the European AGATA project. Current efforts to facilitate such coordination should be encouraged. The GRETA Steering Committee should continue to be responsible for overseeing all aspects of the GRETA project.

4 Tracking with planar detectors is of interest to the nuclear science community and has a wide range of applications outside of nuclear physics. R&D efforts in this direction should be supported as part of the drive to develop tracking, as most of the electronics and software challenges are common to all tracking detectors.

The flexibility and versatility of planar tracking detectors makes them useful for applications to nuclear science that complement the coaxial tracking detectors used for the GRETA 4π array. Planar γ-ray tracking detectors also have other uses in space science, and applications in medicine, environmental surveying and security. The first major R&D effort on planar detectors for nuclear science is to develop and test functionality of an improved Ge wafer, as outlined in Chapters 5 and 6, and to house it in a compact detector packaging to facilitate efficient detector geometry. The second R&D goal is construction of a stack of planar detectors for efficient detection of higher energy γ rays. These development efforts will require $625K during FY2003-2005 and will require 1.0 FTE of scientific effort.

The R&D required for planar γ-ray tracking detectors involving digital signal processing and tracking algorithms is similar to that required for all γ-ray tracking applications including GRETA. Signal analysis specifically for planar detectors will require an additional 2.5 FTE of scientific effort. The R&D of these common aspects for tracking detectors should be unified and coordinated efforts.

5 Gammasphere continues to be the premier national γ-ray facility until GRETA becomes operational. This research facility must be supported to sustain the vitality of the field.

Assuming even the most optimistic funding scenario, it will be 2009 before construction of GRETA will be completed and 2007 before an early implementation of GRETA will significantly overtake the capabilities of Gammasphere. It is crucial to the vitality of the field that Gammasphere be supported in a manner befitting its role as the premier high-resolution γ-ray facility until GRETA becomes operational. Gammasphere still can play a significant supporting role in nuclear science even after GRETA is fully commissioned.

Observations:

1 GRETA construction costs

The GRTCC finds that there are compelling scientific arguments for GRETA, and strongly recommends rapid implementation of this project. It is noted that preliminary cost estimates for construction of GRETA have been indicated as a concern of the DOE. The GRTCC encourages the GRETA Steering Committee to continue to study ways to reduce the projected cost. Tracking detector procurement is a major component of the cost of GRETA. Consequently, the current situation of a sole vendor for GRETA detector modules will have a significant impact on the cost, as well as the delivery schedule, for construction of GRETA. The availability of a second vendor will encourage competitive bidding that will help to reduce this cost, the required contingency, and also reduce the uncertainty in the delivery of the product. This could become an issue because of the large number of detectors required, and the possibility of a similar number of segmented coaxial detectors procured in Europe for AGATA or other programs. Negotiations with a second vendor to develop and construct a (3-crystal) GRETA cluster module should have a high priority. Collaborations should be forged with other tracking detector projects, such as the European AGATA project, as these will reduce GRETA development or construction costs. Manpower contributions from universities, national laboratories, and other agencies, should be solicited as another avenue to reduce costs. Finally the trade off between cost and performance is an area that should be carefully evaluated. The GRTCC has not identified performance or scientific goals that could be changed.

It is important to proceed with procurement of the GRETA module and subsequent testing. Results of this work will provide an excellent basis for program cost and risk analysis.

2 Other applications of Gamma-ray Tracking

Gamma-ray tracking, for all practical purposes, is an entirely new technique in γ ray detection, enabled for the first time by the new detector technologies that are now being developed.

Tracking has important applications for homeland security in the detection of nuclear materials, with an emphasis on imaging and sensitivity. Tracking provides the possibility of achieving higher detector efficiency, higher peak to total ratio (rejection of the Compton shelf), and better background rejection than conventional detectors in a variety of applications. Urgent homeland security needs represent an immediate application of this new technology. It should improve capabilities for a variety of diverse threats from the use, deployment or transport of nuclear materials. There is a critical need for more sensitive detectors to detect and locate ~kg size strategic nuclear materials at a distance, monitor boarder crossings, and for nuclear surveillance.

Tracking has applications in diverse areas of science such as astrophysics (Compton telescopes, polarimetry), and diagnostic medical uses (Compton imaging). All of these applications are currently active areas of research in many institutions throughout the country. A common thread between them is the need for electrically segmented detectors, the need for robust tracking algorithms, and the need for data acquisition capabilities that are necessary to implement them.

This report has focused on applications of tracking detectors in nuclear physics. However, it will be useful to have the Gamma-Ray Tracking Coordinating Committee continue to function with the goal of developing a γ-ray tracking user community, consisting of scientists with a broader range of application agendas, and supported from as wide of a range of sponsors as possible. This task will take further study by the committee, with a range of options including organizing workshops or soliciting inputs from the user base, either of which will result in a summary report to the DOE.

2 Introduction

For many years the study of γ-ray emission from excited states in nuclei has played a pivotal role in discovering and elucidating the wide range of phenomena manifested by the structure of the atomic nucleus. Each major technical advance in γ-ray detection devices has resulted in significant new insights into nuclear science. The culmination of these technical advances are the two current state-of–the-art 4π arrays of Compton-suppressed Ge detectors, Gammasphere in the US and Euroball in Europe. Gammasphere was the first national γ-ray facility in the US. The tremendous advance in sensitivity provided by this array has made it the central component of a highly successful national, and international, nuclear structure program involving about 400 scientists. The physics impact and productivity of Gammasphere, commissioned in 1995, has been extraordinary. For example it has now produced about 400-refereed publications; of these about 80 were published in Physical Review Letters or Physics Letters which is a strong reflection of the profound influence it has already had on the field. It also is playing an important role in graduate education leading to many completed Ph.D theses and Ph.D.'s in progress. The 6 auxiliary detectors developed by university groups for Gammasphere have been excellent for graduate training as well as contributing greatly to the scientific output. Gammasphere will continue to be a prime focus for both the national and international nuclear structure community until a 4π tracking array is built.

The development of γ-ray tracking systems capable of measuring the location and energy deposition of every γ-ray interaction in a detector will lead to a dramatic advance in γ-ray physics, and will have wide applications in medical imaging, astrophysics, nuclear safeguards, and radioactive material characterization. The tracking concept will allow construction of γ-ray detector systems with tremendous improvements in sensitivity and resolution, providing remarkable new discovery potential in a broad range of nuclear science. The compelling physics opportunities provided by a γ-ray tracking array have been discussed at workshops in LBNL (1998), MSU (2000), and the University of Massachussets at Lowell (2001). These opportunities were already recognized at the time of the 1996 Long Range Plan for Nuclear Science. The 4π tracking detector concept mentioned in the 1996 LRPNS is called GRETA [**G**amma **R**ay **E**nergy **T**racking **A**rray] and was first proposed by LBNL in 1994. Substantial R&D has been carried out on a coaxial 36-segment GRETA prototype leading to a highly successful proof of principle. Pulse-shape digitization and digital signal-processing methods have been developed to determine excellent energy, time and position (< 2 mm) resolution, while tracking algorithms have been developed that are capable of assigning charge deposition points to a particular γ-ray enabling the reconstruction of the energy of the γ-ray. The Europeans have enthusiastically embraced this new technology that was conceived and developed in the US, and are making plans to build AGATA, a 4π array of more than 120 coaxial Ge detectors similar in concept to GRETA.

The NSF-funded SeGA array of eighteen 32-fold segmented coaxial germanium detectors has just been commissioned at MSU for experiments employing fast exotic beams.

Significant advances in detector technology based on planar strip Ge detectors also have been made in the past few years. Segmented planar detectors can provide important complementary features for tracking compared to the 4π coaxial array.

The considerable success in R&D for γ-ray tracking detectors has led to strong endorsement of a 4π γ-ray tracking array in the 2002 Long Range Plan for Nuclear Science, which identifies it as an important new initiative. This 2002 LRPNS states, "The physics justification for a 4π tracking array that would build on the success of Gammasphere is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions. This new array would be a national resource that could be used at both existing stable and unstable accelerators, as well as at RIA." The 4π-tracking array also will build on the extraordinary success of Gammasphere with regard to both scientific output and training.

Much of the R&D required for developing γ-ray tracking arrays is common to all types of tracking detectors as well as having broad applicability to many branches of science and technology. For example, digital signal processing will become the premier signal processing technique in many fields, while tracking algorithms will have broad applicability to many other sciences and applications outside of nuclear science. Thus a need was apparent to coordinate the R&D for these techniques that have such wide applicability. The Gamma-Ray Tracking Coordinating (GRTCC) was appointed, on 21 January 2002, by the Directors of the nuclear science divisions at Argonne National Laboratory, Lawrence Berkeley National Laboratory, and Oak Ridge National Laboratory, at the request of the DOE Division of Nuclear Physics, to promote the development of γ-ray tracking detector technology in nuclear physics research. The goal is to help organize the γ-ray tracking community to provide widespread support and to provide an effective plan for the future. The DOE Division of Nuclear Physics plans to use this committee to obtain timely advice on issues and proposals in γ-ray tracking. The membership of the Coordinating Committee, listed in appendix A, consists of eight members from the nuclear and astrophysics research community.

The charges, made to this committee are listed in appendices B and C. One charge is to take a broad role in the development of γ-ray tracking detectors in this country. In particular there are three elements of the charge that should be addressed in a timely manner.

- *Develop the various physics justifications for γ-ray tracking and establish the performance goals that are required in each area.*
- *Formulate a national R&D plan for γ-ray tracking detectors.*
- *Examine the currents efforts in γ-ray tracking that are underway in the United States and provide the Department of Energy with advice about how they should proceed.*

This charge is focused on γ-ray tracking detector technology in nuclear physics research. However the committee should also examine progress in other areas of science.

The Committee has held regular conference calls and requested written answers to questions that were posed to the major γ-ray tracking detector projects, GRETA, GARBO, and SeGA. This initial fact-finding activity culminated in the Gamma-ray Tracking Fact Finding Meeting held at Argonne 29-30 March 2002. The attendees to this meeting included active participants developing the projects mentioned above, the European AGATA project, the NRL Astrophysics Tracking Group, the GRETA Steering Committee, and representatives of the Gammasphere User Group. Copies of the meeting program and list of attendees are given in appendices D and E. The current and planned efforts in γ-ray tracking were discussed frankly and openly leading to important conclusions. There was complete agreement that a major 4π γ-ray tracking array facility is required to address the exciting new physics opportunities at RIA as well as existing stable and unstable-beam facilities. There was unanimous agreement that a shell of closely packed coaxial Ge detectors, as exemplified by GRETA (and AGATA in Europe), is the only practical approach for proceeding with the implementation of this major 4π γ-ray tracking array. The GRETA Steering Committee should be responsible for overseeing the latter effort. In view of the unanimity in opinions expressed during the deliberations the Committee believes that the recommendations in this report are robust, and sound, as well as having broad support in the nuclear structure community.

Chapter 3 of this report presents an outline of physics opportunities justifying the need for γ-ray tracking arrays in nuclear science. This leads to a set of performance goals presented in chapter 4. Chapter 5 presents a survey of current efforts in tracking in nuclear science. A proposed national R&D plan for γ-ray tracking detectors in nuclear science is presented in chapter 6. The five recommendations and two observations made by the Coordinating Committee are described in the Executive Summary and summarized in chapter 7.

3. Physics Opportunities with Gamma-Ray Tracking

The strongly interacting aggregation of fermions we call the nucleus displays a remarkable diversity of phenomena and symmetries. Its structure continues to surprise and fascinate nuclear scientists, as unexpected properties are revealed by fresh experimental results arising from increasingly sensitive instrumentation along with new accelerator developments. A central component in the highly successful US nuclear structure program has been through the utilization of γ-ray spectroscopy techniques, in particular, using Gammasphere. The latter is a National Facility funded by the DOE and was designed and built by US national laboratories and universities. It is a spectrometer of unparalleled detection sensitivity to nuclear electromagnetic radiation. Its resolution, granularity, efficiency, and ability to be used in conjunction with a powerful suite of auxiliary detector systems, have made it a superb device for studying rare and exotic nuclear properties. Since its commissioning in 1995 its physics impact has been extraordinary. Many of these success stories have been those studies whose major focus was to investigate the behavior of nuclear systems at the limits of, for example, spin, extreme N and Z values, and at high excitation energy. As scientists we will always strive to continue to push back these limits.

While the present state-of-the-art detector arrays, which consist of large volume germanium crystals surrounded by a suppression shield, have pushed this particular detector technology to its limit, it has become apparent that significant further gains in sensitivity will be possible as a consequence of an innovative and new design utilizing the concept of γ-ray energy tracking in electrically segmented Ge crystals. The detector design, which was already mentioned in the 1996 Long Range Plan, is called GRETA (Gamma-Ray Energy Tracking Array). It would contain about 100 co-axial Ge crystals each segmented into 36 portions and arranged in a highly efficient 4π geometry. It is anticipated that GRETA would have about 100-1000 times the sensitivity of Gammasphere for selecting weak exotic signals, and thus give as big a jump in capability compared to Gammasphere, as Gammasphere was to previous detector generations, as illustrated in the accompanying "resolving power" figure 3.1.

The improved sensitivity or resolving power is due to the new technique of "gamma-ray tracking", which identifies the position and energy of γ-ray interaction points in the detector segments. Since most γ-rays interact more than once within the crystal, the energy-angle relationship of the Compton scattering formula is used to "track'" the path of a given γ-ray. The full γ-ray energy is obtained by summing only the interactions belonging to that particular γ-ray. In this way there are no lost scatters into suppression shields

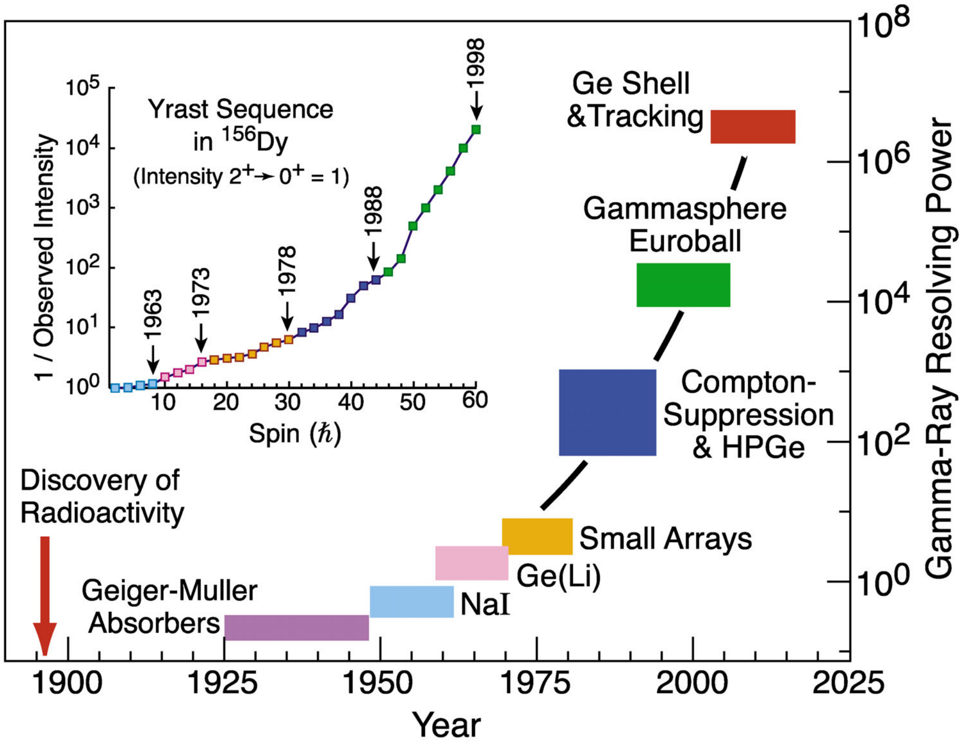


Figure 3.1: Evolution of γ-ray detection technology with time. The large performance gains provided by the proposed 4π tracking array GRETA is clearly shown. The calculated γ-ray resolving power (y-axis) is the inverse of our ability to observe the faint emissions from rare and exotic nuclear processes. This is illustrated in the inset, which indicates the progression of the experimental observational limit for excited states in a typical rare-earth nucleus as a function of time and detector developments.

(which cover nearly 50% of 4π in Gammasphere) and so a much higher overall efficiency can be achieved, for example, by a factor of 6 (GRETA vs Gammasphere) and 100 (GRETA vs SeGA) for a single 1 MeV γ-ray. An efficiency gain of about 20 times over Gammasphere is also expected for 15 MeV γ-rays. Other key design benefits of a highly segmented Ge array include high energy resolution, high counting rate capability (~factor of 5 over Gammasphere), good position resolution (<1° versus 8° for Gammasphere) which is critical for Doppler shift corrections since many experiments involve high recoil velocities, the ability to handle high multiplicities without a high double-hit probability, and the ability to pick out low-multiplicity events hidden in a high background environment due to background rejection by direction. Another asset is that the high segmentation also makes high precision linear polarization measurements possible. The modularity of the detector design makes it extremely versatile and flexible for use in many different configurations. Of course, any final design would also be optimized to take full advantage of coupling with auxiliary detector devices, which continue to prove themselves of immense value in Gammasphere and other γ-ray experiments.

For off-line decay spectroscopy, tracking detectors have slightly different advantages from their in-beam applications. Without the need for Doppler corrections a detector array can be more compact, with detectors placed only a few centimeters from the source of radiation. For low cross section activity, spatial, directional and time correlations increase the sensitivity by discriminating against background events. However, time correlations usually lose their selectivity when the state of interest has a half-life longer than a few ms. Here, tracking of the de-excitation γ rays reduce the background by demanding a spatial correlation with a prior residue implant or α decay. In β^+-activity, tracking will reduce the intense background from annihilation radiation by identifying and eliminating the back-to-back 511-keV γ-rays, from the spectrum and, thereby, greatly enhancing the sensitivity for other γ rays.

Many detailed R&D projects have been carried out since the 1996 LRPNS on all the main ingredients necessary to show that building a 4π tracking detector array is now feasible. The US nuclear structure community, which conceived of this next revolutionary step in γ-ray detection capability, is therefore poised and eager to build a new generation of γ-ray spectrometer with unsurpassed sensitivity.

There is no doubt that with its enormously increased resolving power, GRETA and γ-ray tracking, will provide discovery potential far beyond Gammasphere and will usher in a new era in nuclear structure, nuclear astrophysics, and fundamental interaction studies both before and after RIA is built**.** It also holds the promise of important spin-off applications in other fields, such as, medical, environmental, security, and space exploration. It is a time of great opportunity and some of these exciting physics topics are discussed below but of course, as we have seen many times over previous decades in our field, the most important discoveries are often those that were unforeseen.

The field of nuclear structure covers a broad range of study. The examples below illustrate that a large overlap and considerable synergy exists between them. More detailed physics discussions can be found in the 2002 NSAC Long Range Plan, the GRETA White Paper contribution to the 2002 NSAC Long Range Plan, the 2001 Filippone Report on Low Energy Nuclear Physics, and also the report from the 2001 Lowell Workshop on Gamma-ray Tracking Detectors for Nuclear Science plus several other Workshop and Town Meeting reports.

3.1. Properties of nuclei far from stability

A forefront challenge in nuclear structure physics today is to broaden our understanding of nuclei to encompass all bound systems of protons and neutrons. As we move away from the valley of stability towards the driplines, our overall view of the nuclear landscape has improved and our understanding of the underlying physics has become clearer. However, γ ray spectroscopy of the nuclear landscape far from stability is always difficult. Cross-sections for producing the most interesting nuclei are always low and there are backgrounds (from impure beams or beam decay). In these hostile environments, all approaches which glean new information, and all methods to increase efficiency and sensitivity will be useful. In recent years, we have made great progress in moving away from stability towards the proton rich nuclei. This has been possible by fusing or fragmenting stable heavy ions, and developing sophisticated experimental techniques that can pick out the interesting new isotopes that lie farthest from stability. By these means we can now reach, and even pass, the proton drip line for many elements. While much important work remains at the proton drip line another major future challenge lies near the neutron drip line. Here, there are several reasons to expect that many features of nuclear structure are quite different from the stable and proton-rich isotopes. Reaching this domain needs a new generation of accelerators, such as RIA, the Rare Isotope Accelerator and new detection devices such as GRETA. Access to the nuclei near the neutron drip line will not only enhance our overall picture of nuclear structure, but will provide vital data on nuclei along the r-process nucleosynthesis path, the route through which we believe most heavy elements were synthesized. A very recent key breakthrough, for example, is the demonstration that important information on n-rich nuclei can be obtained using rare isotope beams of only 10^5-10^6 particles per second using transfer, Coulomb excitation, and fusion reactions, with γ-ray spectroscopy. This bodes well for the future.

Understanding the structure of marginally bound systems near the driplines will focus on obtaining a detailed picture of the wave functions of low-lying states, and the ground states themselves. It is clear that the experimental difficulties will be different to those that have been encountered before. However, there is no doubt that γ-ray spectroscopy will play a key role in these investigations, and tracking detectors are perfectly suited to face these challenges. Many of the experiments will involve studies in "inverse kinematics", in which a beam of exotic nuclei from near the dripline, produced from fission, fragmentation or spallation, will need investigation. The most interesting nuclei are usually those furthest from stability, which are most difficult to produce. Thus, in all cases, the experiments must be as efficient as possible, and be selective to differentiate between the states of interest and copious decays from other sources. For off-line spectroscopy, isomer-γ decay will play an important role in our studies of the structure of nuclei far from stability. With the ability to track, more sensitive measurements of γγ angular correlation and polarization, which yield important spin and parity information, become possible. Some key themes related to studies of far-from-stability nuclei are mentioned below.

Do dramatic changes in shell structure occur far from stability? Single-particle and pairing degrees of freedom play a pivotal role in nuclear structure. Single-nucleon transfer reactions are the most direct and unambiguous probe of single-particle structure while pair transfer is a direct and unambiguous probe of pairing correlations. Shell structure in nuclei is expected to change dramatically when approaching the extremes of isospin far from line of stability. This should be manifested by large changes in single-nucleon and pair transfer cross sections to individual nuclear states. For example, the valence single particle orbitals will be different in nuclei at extreme isospin which can be probed by studying single-nucleon transfer reactions with radioactive beams. Similarly, extreme neutron-rich nuclei should exhibit strong new neutron pairing behaviour in the tail of the nuclear wavefunction that will lead to fascinating nuclear Josephson effects such as strongly enhanced pair transfer cross sections and diabolical pair transfer. A γ-ray tracking array used in conjunction with scattered ion detection will provide the opportunity to measure the transfer angular momentum and spectroscopic factors to individual states in nuclei both far from stability as well as to closely spaced states at higher excitation energy, in deformed nuclei and in very heavy nuclei. Studies of transfer using heavy ions can simultaneously probe the interplay of single-particle, pairing and collective degrees of freedom. These new opportunities will provide a new dimension to the study of the evolution of shell structure in nuclei.

What new information can we learn about collective shape degrees of motion in nuclei? Collective rotational and vibrational shape degrees of freedom are a dominant and ubiquitous feature of nuclear structure. Studies of coexistence of states with very different collectivity in individual nuclei, as well as the evolution of collective correlations with isospin and temperature all are required to elucidate and better understand the pivotal role of collective correlations in nuclear structure. Coulomb excitation is the preeminent probe of collective shape degrees of freedom in that it selectively populates collective bands of states with cross sections that are a direct measure of the collective matrix elements. The efficiency and resolving power of a 4π tracking array, when coupled with detection of scattered heavy ions, provides the opportunity to measure quite complete sets of both the excitation energies and collective matrix elements coupling these states. The completeness of such data adds a new dimension to the study of quadrupole and octupole collective shapes degrees of freedom in nuclei. For example one can directly measure the magnitude and distribution widths for both quadrupole deformation and triaxiality. The much superior resolving power and efficiency provided by a tracking array will make it feasible to study collective modes in odd-A nuclei, transuranic nuclei and at higher excitation energies, all cases where the γ-ray transition density challenges the energy resolution of current γ-ray detectors. Studies of odd-A nuclei are especially sensitive probes of nuclear structure. The new opportunities provided by exploiting tracking arrays with heavy-ion Coulomb excitation will greatly advance the study of both collective and single-particle degrees of freedom, plus their interplay, in nuclear structure and their evolution with temperature and isospin. In all cases, high efficiency, peak-to-total, and granularity are key issues for excellent spectroscopy.

Experiments with Fast Rare Isotope Beams:

An efficient high-resolution γ-ray tracking detector will greatly enhance the scientific reach of any fast-beam rare isotope facility. Experimental techniques with fast beams of rare isotopes and γ-ray detection have been developed during the last decade. High-resolution in-beam γ-ray spectroscopy is possible if both the energy and emission-direction of the photons originating from the moving projectile are measured. Gamma rays traverse matter with known attenuation and much less scattering than particles for the same amount of matter. Experiments employing γ-ray detection to indicate inelastic scattering to bound states can be performed with secondary targets about 100-1000 times thicker than similar experiments using particle detection. The increased target thickness translates directly into lower possible beam rates – and thus farther scientific reach – for given luminosities.

The instrument crucial to realizing the physics opportunities described below is a large solid-angle γ-ray detector, which can detect photons with energies up to 10 MeV with a resolution of 0.5% or better and which can measure photon-emission angles with an accuracy of better than 2°.

With the availability of fast beams of rare isotopes we can measure key quantum-mechanical observables needed to understand the evolution of nuclear structure with isospin. A GRETA-like device will be needed to answer the following questions:

How does nuclear collectivity evolve with isospin? Coulomb excitation of even-even nuclei provides a direct measure of the collectivity of the protons in the nucleus via the energy and probability for exciting low-lying states. Coulomb excitation of odd-even nuclei provides additional information regarding single-particle structure and how single-particle degrees of freedom are connected to collective states. The in-beam γ-ray spectroscopy measurement of the energy and quadrupole (E2) transition strength to the first excited 2^+ state in ^{32}Mg (Z = 12) at RIKEN experimentally established a large degree of collectivity in this N = 20 nucleus. This is an example of the change in shell structure away from that found in nuclei near the valley of stability, where N = 20 is a magic number. Other such dramatic changes to the “magic numbers” are expected as one moves away from stability.

Are the proton- and neutron fluids in nuclei deformed differently? Protons and neutrons contribute differently to transition strengths between low-lying collective states. While Coulomb excitation measurements are sensitive to protons, a strongly interacting experimental probe is needed to probe the neutron distribution in the nucleus. Measurements of both the proton and neutron matrix elements then provide a tool for understanding the relative importance of valence and core contributions to these transitions and provide an additional means for testing the predictive power of theoretical models far from stability.

Close to the valley of β stability, the proton and neutron distributions in the nucleus generally have similar degrees of deformation. However, microscopic calculations suggest that for example in the most neutron-rich sulfur isotopes (N > 28) the proton distributions are more deformed than the neutron distributions by up to a factor of two. By comparing deformations of neutron distributions with proton distributions for the most neutron-rich nuclei, it will be possible to experimentally address the question of whether very neutron-rich nuclei have deformed neutron distributions.

Experimental methods for the determination of proton and neutron matrix elements involve the comparison of measurements of a transition using two experimental probes with different sensitivities to proton and neutron contributions. Such studies have been performed on stable targets with a variety of combinations of experimental probes. For β-unstable isotopes it is possible to deduce information on the ratio of proton-to-neutron transition matrix elements by comparing electromagnetic excitation strengths to hadronic excitation strengths. The latter can be measured by proton scattering in inverse kinematics (since proton targets are available and neutron targets cannot be made). A γ-ray detector system of high efficiency, granularity and peak to total, such as GRETA is required for such studies.

What is the detailed wave-function for exotic nuclei? Direct reactions with fast beams are a powerful tool that allows the determination of orbital angular momentum quantum numbers and spectroscopic factors for reactions leading to individual excited states. Special promise is shown by single-nucleon knockout reactions. They have been used to extract spectroscopic factors, which have been compared with the results from large-basis shell-model calculations. Measuring the longitudinal momentum distribution provides the basic information about the shell structure of the occupied states. With γ-ray coincidences, the method can be successfully extended in a major way to excited-state spectroscopy.

Knockout reactions can be used to study states that are reached by removing a nucleon from any projectile produced by the fast fragmentation method. Although the initial experimental work has been carried out for light nuclei, in principle the method is applicable to any mass region, and work with neutron-rich nuclei at N = 20 and 28 has already started. With RIA, even heavy fission fragments should come within reach. Early tests of the technique show that precise orbital angular momentum assignments and spectroscopic factors are obtained in known cases. It seems realistic to expect that knockout reactions, in those cases where they are applicable, will have spectroscopic sensitivity comparable to that of classical transfer reactions. The theoretical strength of the method has been underlined in calculations that compare two different models that are in excellent agreement. Other important assets are, that with increasing energy the theoretical models become more reliable, with the cross sections remaining essentially constant. An important open question is how the knockout technique will be modified in the case of nuclei with large quadrupole deformations; recent theoretical work suggests that the shape of the momentum distribution is sensitive to the single-particle motion in a deformed potential

3.2. Nuclear structure at the limits of angular momentum and at high excitation energy

What are the new symmetries, shapes and excitation modes at the limits of angular momentum and excitation energy? How high in spin and excitation energy nuclei survive and what symmetries are responsible for any stabilizing shell effects are fundamental questions in nuclear physics. Indeed the recent observation of very high spin states in ^{254}No far beyond those expected in such a fissile nucleus has surprised us all. The future of high spin studies of transuranium nuclei seems especially promising. In addition, super-exotic hyperdeformed shapes associated with a third energy minimum in the potential energy surface of rapidly rotating nuclei have been predicted at the very limit of sustainable spins most notably in the rare-earth region. Experimental searches have begun to try to find these structures at the very limits of deformation and spin, but most scientists in the field believe that GRETA is needed to discover and characterize such important but weak ultra-high spin signals among a large fission background.

The whole question of stable triaxial nuclear shapes is one that has been debated for decades. Therefore the recent observation of candidates for “chiral” partner bands brought about by the relative orientations of the angular momentum vectors of odd proton and odd neutron valence particles with that of a triaxial core is extremely exciting. This result along with the recent discovery of high spin triaxial superdeformed shapes has opened up a broad new field of research involving triaxial nuclei where new symmetries and new collective (e.g. wobbling) modes of excitation are possible.

In the past several years we have made the stunning discovery that superdeformed nuclei are the best examples of single-nucleonic motion in a deformed potential. However, satisfactory answers still elude us with regard to the mysterious phenomena of isospectral structures in different nuclei and $\Delta I=4$ bifurcation. While some spectacular progress in fixing the excitation energies and spins of several superdeformed bands have been made, a truly general understanding of the many facets of nuclear superdeformation must await GRETA.

Does proton-neutron pairing really exist, and what are the true indicators of the survival or demise of like-fermion pairing correlations at high angular momenta? Nuclear pairing correlations play a central role in the low to medium spin properties of nuclei. One key phenomenon keenly sought after for many years is a signature for the existence of the T=0 proton-neutron pairing phase. Hints of its presence are perhaps beginning to be found in N = Z nuclei near A = 80 from high spin band crossing systematics. Such studies are at the limit of present experimental capabilities and therefore a new generation detector system is needed to perform the necessary spectroscopy of yrast and near yrast sequences in order to build up a compelling case for p-n pairing based on Pauli blocking arguments. Another fundamental question relates to the quenching or collapse of the nuclear superfluidity at high rotational spins, where the angular momentum behaves like an external magnetic field and tries to destroy the correlations between nucleonic “Cooper” pairs. Exactly how the nuclear superfluid correlations evolve with angular momentum in the finite quantum system of the nucleus remains an important and unfinished chapter. An enormously more efficient detector, such as GRETA, will allow “complete” spectroscopic studies of discrete states over a wide range of spin, excitation energy and seniority which will allow fresh insight into these critical questions.

How do collective excitation modes evolve in heavy nuclei at high angular momenta and excitation energy? Coulomb excitation is an excellent way to study collective excitations in nuclei. Recently a very successful series of experiments studying β, γ, and octupole vibrational modes in heavy Pb, Th, U, Pu and Cm nuclei have been demonstrated using a highly efficient γ-ray detector with a particle detector. However many open questions remain concerning fundamental excitation modes in nuclei, such as the evolution of such structures to higher angular momenta, and the fragmentation of multi-phonon states. A γ-ray detector system of much greater efficiency, particularly at higher energies, and granularity would provide this class of experiments with a huge improvement in discovery potential.

When do shell effects melt away above the yrast line and how does chaos emerge out of order? GRETA, because of its great efficiency and granularity will also provide revolutionary progress in the study of the behavior of nuclei far above the yrast line allowing highly selective decay pathway analyses of the “continuum” where the level densities are so high that individual “bands” in the traditional sense cease to exist. There are many fundamental questions. How high does one go above the yrast line before there is a melting of shell structure? When are the commonly used characteristic quantum numbers no longer conserved, leading to chaos?” In highly collective superdeformed structures, there are very recent indications that the transition from order to chaos goes through an ergodic regime, where rotational coherence is retained despite the emergence of complicated wavefunctions arising from band mixing. The investigation of the transition from order to chaos in a quantal system, is of significant interest in other branches of science.

What are the giant dipole resonances built on superdeformed states and loosely bound nuclei? Giant Resonances are fundamental collective excitations of nuclei and they play an important role in the understanding of basic nuclear structure properties. The γ-ray decay of the giant dipole resonance for example is sensitive to the size and shape of nuclei. It would be very exciting to discover and study the giant dipole resonance built on a superdeformed shape, where two peaks widely separated in energy are expected corresponding to oscillations along the two different length nuclear radii. Gamma decays of giant resonances are a weak branch, emitting γ-rays in the energy range of 10-20 MeV. GRETA combines excellent energy resolution at low energy with high efficiency at high energy. Hence, it will be possible for the first time to gate on superdeformed transitions to observe the giant resonances built on those states. The N and Z dependence of giant resonances, which is predicted to change dramatically near the neutron dripline, can be studied with Coulomb excitation of fast beams from RIA. The large Doppler broadening due to the high-energy beams requires the excellent position resolution available with GRETA.

In conclusion, detailed high-resolution γ-ray based studies of the properties of atomic nuclei continue to reveal a dizzy variety of exciting new discoveries and compelling opportunities. In the near future there is no doubt that a highly efficient 4π γ-ray tracking array will provide enormous discovery potential beyond Gammasphere both before and after RIA is built.

3.3 Nuclear astrophysics

Nuclear astrophysics is one of the forefront applications of nuclear physics to understand our universe. It is concerned with the impact of the microscopic aspects of nuclear structure and reactions on the macroscopic phenomena we observe in our universe. There are a number of measurements in the area of nuclear astrophysics that will benefit greatly from γ-ray tracking detectors.

Low-Energy Capture Reactions: Nuclear reactions play the crucial role in the energy production and element synthesis in most astrophysical sites, and models of these environments require the rate and energy release of the relevant nuclear reactions as critical input. Thermonuclear capture reactions are the most important, since they provide the pathway to forming heavy nuclides out of lighter nuclides. Furthermore, because hydrogen and helium comprise 99% of the baryonic matter in the Universe, and because they have the lowest Coulomb barriers, almost all heavy element charged particle nuclear reactions in the cosmos involve interactions with isotopes of H and He, burning them as fuel to form even heavier nuclides. The determination of the rates of such reactions, by both direct and indirect techniques, is the focus of much international effort.

Direct measurements of reactions such as $^{12}C(\alpha,\gamma)^{16}O$ or $^{14}N(p,\gamma)^{15}O$ at very low energies are of great interest, but are also very time consuming because of their extremely low cross sections. To provide the required high beam intensities, these measurements are usually performed by bombarding solid targets with intense (several μA) beams of light ions, which would preclude the use of recoil separators. Therefore, capture γ rays, detected in singles, could be easily masked by backgrounds from cosmic rays and natural radioactivity in a typical experimental hall. Surrounding such a target with a tracking detector could perhaps reject the majority of the background γ rays, while giving a very high efficiency for detecting the capture γ rays of interest. This would, for example, make it unnecessary to build expensive and cumbersome accelerator facilities deep underground to carry out these measurements. There are probably more than 30 measurements that could benefit from this approach. A dedicated array of tracking detectors would be necessary for these experiments, since each of them could last several months.

Many studies of stellar explosions involve inverse capture reactions of radioactive ion beams on gas targets. The approach for current and next-generation radioactive beam facilities is to use a radioactive beam incident on an extended, windowless, hydrogen or helium gas target, and measure the capture γ rays in coincidence with the heavy recoils. A tracking detector can help reduce the backgrounds from 511 keV annihilation radiation. The directional information provided by tracking of the γ ray can help establish where in the (~30 cm long) target the reaction took place. This information can be used to correct ion-optical aberrations, and to determine the energy losses of the beam and recoil in an extended target. Tracking can furthermore help with angular distribution measurements. A tracking detector should have high efficiency for ~MeV γ rays, and high resolution to reconstruct the cascade γ ray decays in cases where there is a reasonably high level density. Of the order of ~20 measurements can benefit from this technology. However, coupling of a closely-packed tracking array to an extended (~30 cm) target and its associated pumps poses some technical challenges that need to be addressed.

Nuclear Structure Studies: This category of measurements is very broad, and includes studies used for indirect determinations of important reaction rates. Specifically, nuclear levels that may dominate an astrophysical reaction rate are populated by a reaction different from that occurring in the cosmos, and the decay properties of those levels (branching ratios, lifetimes, spins and parities, level densities) are measured. These studies are particularly important near the proton- and neutron-dripline, where structure information is both greatly lacking and is very important for studies of stellar explosions. The high efficiency of a tracking array will allow studies to go several mass units closer to the drip line than possible with current arrays. There are hundreds of studies that can benefit from this technology, utilizing both stable and radioactive beams.

3.4 Fundamental Interactions and Rare Processes

A γ-ray tracking array with high efficiency, high segmentation and thus high spatial resolution, and excellent background rejection could be used to perform important experiments in weak interaction physics. One possible experiment would be a greatly improved measurement of the superallowed branching ratio of the β-decay of ^{10}C. The strength of superallowed β decays can be simply related to the V_{ud} element of the CKM matrix. The decay of ^{10}C is the least susceptible of the superallowed decays to theoretical uncertainties. The superallowed branching ratio of ^{10}C can be measured by observing a γ-ray cascade, and the largest systematic error in such a measurement is caused by accidental pileup of 511 keV photons. Very high spatial resolution in a new array could essentially remove this error from current measurements, allowing an improvement in the precision of the branching ratio of a factor of 10 or more. An array with extremely good spatial resolution and high detection efficiency would also be useful in further studies of positronium annihilation. An experiment with only one week of data acquisition could improve existing measurements of positronium annihilation to four and five photons, which test QED predictions at high orders of α. This experiment would also significantly improve limits on Charge Conjugation Symmetry violating currents. The decay of polarized positronium in a highly segmented detector could provide an extremely sensitive test of CPT. Measurements of β-γ correlations could be improved in an array with good spatial resolution. Several cases would be interesting as tests of recoil-order weak interaction form factors including ^{22}Na, ^{14}O, and ^{20}Na-^{20}F, ^{24}Na-^{24}Al, and ^{28}Al-^{28}P. A particularly interesting, although challenging, experiment would be investigating the β-γ correlation of polarized ^{19}Ne in order to study the parity mixing of the $1/2^{+}$,$1/2^{-}$ levels in ^{19}F. This could help resolve the current uncertainty in nuclear parity-violating meson couplings.

4 Functionality and Performance Goals for a 4π Gamma-Ray Tracking Array

Generally speaking, studies of nuclei at the limits of spin, excitation energy, or isospin require use of very efficient and selective detector systems. This is because the states of interest are either populated very weakly with stable beams, or are reached with very weak radioactive ion beams (RIBs). Therefore, these studies benefit greatly from the use of a universal, nearly 4π γ-ray detector that simultaneously provides large photopeak efficiency, high peak-to-total ratio, good position resolution, and excellent resolution in the energy range of a few tens of keV to about 20 MeV. Realization of these conflicting requirements requires a new concept, namely γ-ray tracking in a Ge shell with nearly 4π solid angle coverage.

Current state-of-the-art detector arrays, such as Gammasphere, comprise approximately 100 individual Compton-suppressed Ge detectors. They have an efficiency of about 10% for detecting the full energy of a 1.33 MeV γ ray in a Ge crystal. In comparison, the maximum efficiency of a realistic Ge shell with 4π coverage is theoretically limited to about 70%. The drawback of this arrangement comes from events involving the simultaneous emission of multiple γ rays. For such events it becomes impossible to distinguish when two different γ rays hit two different detectors or when one γ ray scatters between the two detectors. To circumvent this problem, the number of detectors has to be increased to identify all interactions of each incident γ ray. Unfortunately, this approach is prohibitively expensive since it requires more than 1000 individual detectors to regain the maximum theoretical efficiency. The new approach is to “track” the interactions of all emitted γ rays detected in an array of highly segmented Ge detectors.

Tracking takes advantage of the recent technological advances in the electrical segmentation of Ge crystals. It is now feasible to build an array of approximately 100 highly segmented Ge detectors, retaining high efficiency, but allowing a pulse-shape analysis of signals from each segment to be used to reconstruct the energy and three-dimensional positions of all γ-ray interactions. This in turn allows the scattering of all the γ rays from an event to be tracked and reconstructed. The concept of γ-ray tracking is illustrated in figure 4.1. It is the basis of the proposed next-generation γ-ray detector system discussed below.

4.1 General characteristics of a 4π tracking array

Large full-energy efficiency (ε), good energy resolution (ΔE_γ), and high peak-to-total ratio (P/T) are the most crucial parameters for any γ-ray detection system. In a K-fold γ-ray coincidence experiment, the sensitivity for detection of the weakest reaction channel or decay path increases as $\{(1/\Delta E_\gamma)(P/T)\}^K$, while the counting statistics improve as $(\varepsilon)^K$. Therefore, our primary design goals are to maximize the efficiency and peak-to-total of the array, and to preserve the energy resolution close to the intrinsic values, even in experiments involving fast-moving sources.

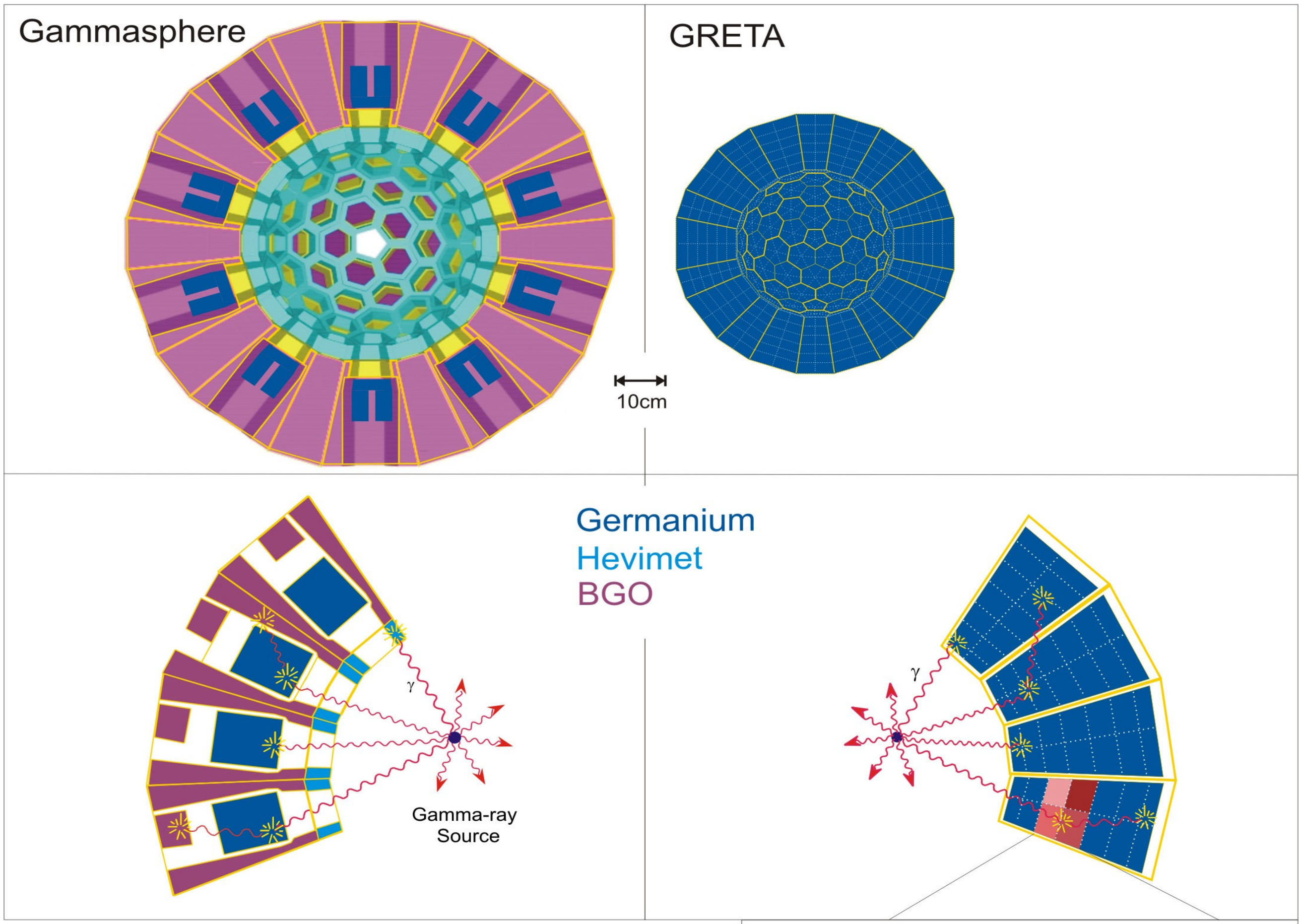
Full-Energy Efficiency: The full-energy efficiency of a 4π Ge shell is related to the average interaction length of the γ ray vs. the depth of the Ge crystals. For example, to achieve a full-energy efficiency of ~23 % for 15 MeV γ rays requires a 9 cm deep Ge crystal.

In a tracking array, efficiency depends on not only the volume of active Ge, but also on the ability to track and reconstruct the full-energy events. Hence, to obtain an optimal tracking efficiency (and peak-to-total ratio), the individual elements of the array have to satisfy a set of requirements on their energy and position resolutions, noise and trigger levels, etc. Specifically, test results and Monte Carlo simulations indicate that a position resolution of 2 mm is needed.

Segmentation: Multiple interactions in the same pixel increase the uncertainty in position and energy determination and, hence, reduce the tracking efficiency. Therefore, the number of detection elements (segments) must be very large compared to the total interactions to reduce the multi-hit probability. Optimum segment sizes vary with γ ray energy (interaction length) and event multiplicity. Simulations indicate that a depth segmentation of approximately 1.5 cm and angular segmentation of nearly $\sim 10^{-3}$ of 4π provides 50% tracking efficiency for a 1.33 MeV γ ray and total γ multiplicity of M=25.

Peak-To-Total Ratio: Since the sensitivity to detect the weakest γ ray in a reaction increases as $(P/T)^K$, a high peak-to-total is essential for all experiments, especially those involving high-multiplicity. In conventional arrays, a peak-to-total value of ~0.60 is achieved with the help of an active BGO shield to suppress the Compton-scattered events. In a tracking detector, tracking algorithms may be tuned to optimize the peak-to-total or full-energy efficiency, depending on the experimental requirements. Yet, even when a tracking algorithm is optimized to achieve the highest efficiency, simulations predict a peak-to-total ratio of 0.78 for a 1.33 MeV γ ray.

Energy Resolution: In fast-beam fragmentation reactions and in the majority of other in-beam experiments, γ rays are emitted from nuclei that are moving with velocities (v/c) that range from a few percent for fusion reactions in normal kinematics, up to ~50% for relativistic beams. Therefore, the energy resolution of the array is adversely affected by Doppler broadening, which depends on the source velocity, γ-ray energy, and angle of emission with respect to the source velocity. This is a serious limitation for the conventional arrays, such as Gammasphere, whose individual elements subtend an angle of approximately 8^{o}. In experiments where



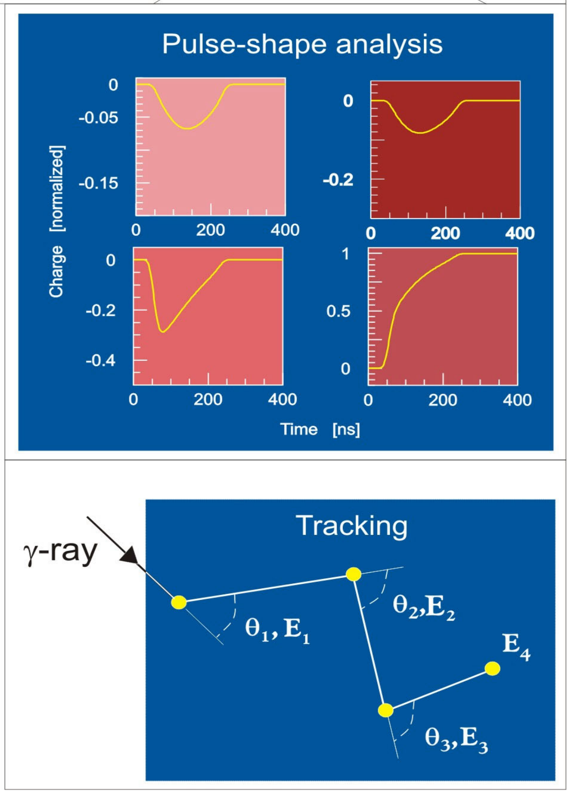


Figure 4.1 This figure illustrates the basic principles of tracking concept. Instead of individually shielded Ge detectors and collimators, as in Gammasphere, a tracking array will consist of a closed shell of segmented Ge detectors. Pulse-shape analysis of signals from segments containing the interaction(s), as well as analysis of transient signals in adjacent segments, allows the determination of the three-dimensional locations of the interactions, and their energies. Tracking algorithms, which are based on the underlying physical processes such as Compton scattering or pair production, are able to identify and separate gamma rays and to determine the scattering sequence. Note, while the topmost drawings are to scale, to illustrate the dimensions of the arrays, the expanded drawing showing 4 individual detectors are not to scale. They are shown to illustrate the two different concepts, and the gain obtained by removing Compton suppressors and hevimet absorbers. Gamma rays, which hit a Compton suppressor or an absorber, are lost for spectroscopic purposes.

the positions and velocities of the emitting sources are well known, Doppler broadening may be corrected by determining the position of the first interaction of the γ ray in Ge. To approach the intrinsic energy resolution of the array an angular resolution of better than 1º, corresponding to a first-interaction position determination of ~2 mm is highly desirable. However, it should be noted that the recoil angle of the emitting nucleus needs to be determined with the same accuracy in order to realize the full energy resolution of the array.

Timing Resolution: Invariably, studies of far-from-stability nuclei or other rare and exotic phenomena require detection of γ rays in coincidence with other γ rays, or with signals from auxiliary detectors, or both. These experiments greatly benefit from having good time resolution (*e.g.,* FWHM of better than 5 ns at 1332 keV) for detection of γ rays.

Geometry: It is highly desirable for a large 4π array to have azimuthal symmetry (to facilitate analysis of angular correlation data), and to provide good efficiency and resolution for total-energy pulse height (H) and total fold (K) measurements. Using the response functions of the array, the measured (H,K) could be transformed into two-dimensional maps of total energy (E*) and multiplicity (M), which define the entry-state distribution for each reaction product. Knowledge of (E*,M) is required for the selection of specific entry-state regions in a given nucleus to study the evolution of nuclear structure with spin and excitation energy. Another powerful technique is to combine (H,K) with the measured energies of the evaporated particles to select the reaction Q-value and, thus, the interesting reaction products. These measurements require an efficiency of better than ~80% for H and K.

Properties of a Single Ge Detector: General characteristics of a single HPGe element of the array, along with its performance requirements are specified in Chapter 6. In tracking mode, the energy and time resolutions of the array should meet or exceed these specifications. Also indicated in Chapter 6 are performance specifications for each segment (such as noise, threshold, cross talk, and energy resolution) that affect signal decomposition and three-dimensional position resolution of the device. Furthermore, one needs to minimize the inter-crystal gaps and inactive materials in the 4π array, which adversely affect its tracking efficiency.

To put the performance of a realistic tracking array in perspective, Table 4.1 compares its basic properties with those of an ideal Ge shell that provides 4π solid angle coverage. The specified numbers are based on extensive Monte Carlo simulations that have taken into account results of tests performed with highly segmented prototype detectors.

4.2 Reaction-specific requirements

A 4π γ-ray tracking array must be a universal instrument that is capable of addressing the wide range of physics opportunities outlined in Chapter 3. Therefore, in addition to the general characteristics mentioned above, it also has to meet a number of requirements that are imposed by specific classes of experiments. Since many of these requirements strongly depend on the specifics of the reaction kinematics (*i.e.,* beam energy and asymmetry of the projectile and target masses), we have summarized in Table 4.2 the characteristics of reactions that are commonly used for γ-ray spectroscopy. Also listed in this table are the auxiliary detectors needed for these studies, as well as special requirements posed by the presence of the background β and γ radiation that emanates from the decay of the scattered radioactive ion beams.

Fast-Beam Experiments: Fragmentation beams, which have very high velocities (v/c up to 50%), low emittance (beam spots of a few cm^2) and low intensities (a few pps in the case of the most interesting species), pose several significant challenges for γ spectroscopy. However, a 4π tracking array provides an ideal detector for these experiments because of its large efficiency and, most importantly, its high angular resolution for Doppler correction. For example, an energy resolution of better than 1% is expected for a secondary reaction with M=15 and v/c=50%.

Slow-Beam Reactions: Coulomb excitation, transfer and fusion, as well as deep inelastic collisions are the most common reactions used to study single-particle and collective properties of nuclei. (Typical beam energies, recoil velocities, and other important attributes of these reactions are listed in Table 4.2.) With stable beams and targets, one generally has the choice of performing these reactions in either normal or inverse kinematics. Normal kinematics use lighter beams that are both easier to accelerate to the desired energies, and result in smaller Doppler corrections.

Table 4.1 Comparison of full-energy efficiencies (ε) and peak-to-total (P/T) ratios for a realistic tracking array vs. an ideal Ge shell with an inner radius of 13 cm, outer radius of 22 cm, and 4π angular coverage.

Detector		Ideal Ge Shell		Realistic Array	
Multiplicity	Gamma-ray Energy (MeV)	ε	P/T	ε	P/T
M=1	0.122	100	1.00	70	0.95
M=1	0.662	85	0.88	60	0.88
M=1	1.332	71	0.78	50	0.78
M=1	15.1	32	0.41	23	0.41
M=25	1.332	31	0.78	22	0.57

For Coulomb excitation and heavy-ion transfer reactions, inverse kinematics is preferable since it results in lower recoil velocities for the more interesting back scattering events than does normal kinematics. Also the isotopic purity of the beam makes it preferable to use projectile excitation, which removes Coulomb excitation of adjacent isotopes that can be troublesome when using target excitation. Inverse kinematics is also the preferred mode in experiments that require detection of the recoils in a mass separator, or those using radioactive ion beams. This is because kinematic focusing increases the efficiency to collect recoils, and reduces large-angle scattering of beam particles. However, the large recoil velocities resulting from these reactions produce significant Doppler broadening of the emitted γ rays. High angular resolution of a tracking array helps rectify this problem, as discussed earlier.

Suppression of Background Due to ISOL Beams: In ISOL radioactive ion beam experiments, especially those with extremely weak intensities, having large γ detection efficiency is the most important factor. However, another factor that greatly facilitates these studies is the ability to isolate the rare decays from the large background of other radioactive decay in the environment. Here tracking plays another crucial role since it is possible to identify and suppress γ rays that originate from sources other than the target.

All γ rays that satisfy the Compton scattering formula for the observed energies and positions lie on the surface of a cone with a half-angle equal to the first Compton scattering angle. The axis of this "event cone" is defined by the vector that joins the first two interaction points in the crystal (Also see chapter 5.3 for illustration of tracking with Compton cameras.) Therefore, the uncertainty in the direction of the incident γ ray depends on how well one could determine the first scattering angle, and the positions of the first two interaction points. The dispersion in the cone angle depends largely on (i) the separation between the first two interaction points (which depends on the γ energy), and (ii) the position resolution, provided the interactions occur in two different segments. For a 1 MeV γ ray, a position resolution of 2 mm, and energy resolution of ~2 keV, a spread of about $\pm 7^{\circ}$ in the cone angle is expected. The angular spread becomes considerably larger for γ energies below a few hundred keV because the two interaction points get closer. When two interactions occur in the same segment, both position and energy determination become more uncertain, resulting in a very poor reconstruction of the incident angle.

High γ-Ray Multiplicity Reactions: Many reactions between heavy ions and heavy targets at or above the Coulomb barrier produce residues at very high spins and are used to study high angular-momentum properties of nuclei. Gamma-ray decays of these products may result in γ-ray multiplicities in the range of M=15-25, which increase the chance of multiple hits in a single crystal, or multiple interactions in a segment. To be able to correctly deduce the energies and positions of multiple interaction points in a single segment, a three-dimensional position sensitivity of better than 0.4 mm is needed.

It is quite common to encounter overlapping γ-ray energies in reactions that produce many residual nuclei at high spins. Good energy resolution (Doppler correction) is needed to

Table 4.2 Characteristics of reactions used for γ ray spectroscopy, including special requirements posed by the presence of the background β and γ radiation that emanates from the decay of the scattered radioactive ion beams, and auxiliary detectors needed for these studies.

Reactions	Physics	Energy (MeV/u)	v/c %	γ Mult.	Eγ (MeV)	Energy Resolution	(H,K)	RIB Back G.	γ Vector	Auxiliary Detectors
Fragmentation beams	Coulex, knock out, soft dipole	>70	>25	few	<5	0.5-1%	-	-	y	Tracking, particle detectors
Capture, inverse	Astrophysics	1-4	<10	low	<3	~0.5%	-	-	y	Micro-channel plate (MCP), separator
Coulomb Excittaion:										
Inverse Kinematics	Collective properties	~4	7-10	1-15	<5	~0.3%	-	-	y	Particle detectors, MCP
Normal Kinematics	Collective properties	~4	2-4	1-15	<5	few keV	-	y	y	Particle detectors
Transfer Reactions:										
Inverse, heavy target	Single & multi-particle transfer	4-6	<10	<15	<3	~0.3%	y	-	y	Gas & Si det., MCP, separator
Inverse, light target	Single-particle transfer	<15	<20	<5	<3	~0.3%	y	-	y	Position sensitive Si, MCP, separator
Normal, light ion	Single-particle transfer	4-15	<3	<5	<3	few keV	-	y	-	Particle detectors
Normal, heavy ion	Single & multi-particle transfer	4-6	<7	<15	<3	few keV	y	y	y	Particle detectors
Fusion:										
Inverse Kinematics	Hi spin, decay tagging, p-rich	4-5	<10	<25	<4	~0.3%	y	-	y	Particle and neutron det., separators, plunger
Normal Kinematics	Hi spin, decay tagging, p-rich	4-5	<6	<25	<4	few keV	y	y	y	Mini-orange
Deep Inelastic Collisions:										
Inverse Kinematics	Hi spin, n-rich,	>5	<10	<25	<5	~0.3%	y	-	y	Particle detectors
Normal Kinematics	Hi spin, n-rich,	>5	<5	<25	<3	few keV	y	y	y	Particle detectors
Hot GDR	Giant Resonances	4-5	<6	<25	<25	-	y	-	-	Particle detectors
Decay Tagging	Particle unbound, isomerism	4-5	<6	<25	<3	few keV	y	y	y	Separator, variety of focal plane detectors

resolve the γ rays that lie very close to each other.

As mentioned before, (H,K) measurements offer a valuable tool to isolate the high-spin states of interest. To do so effectively, the array needs to provide an efficiency of better than 80% for measurements of H and K.

High-multiplicity events also pose the most restrictive constraints on the data processing and data acquisition rates that array has to meet, as will be discussed in Chapter 6.

Auxiliary detectors: The partial cross section for the production of exotic nuclei decreases rapidly as we approach extremes of spin and isospin. To cope with this difficulty, we need to combine γ detection with one or more auxiliary detectors that would help select the reaction channels of interest cleanly and efficiently. While many of the auxiliary detectors are deployed in the inner cavity of the array, some devices are mounted outside the cavity and may have to replace some elements of the array. The requirements posed by auxiliary devices will be briefly discussed below.

Very proton-rich nuclei are produced via fusion-evaporation reactions with very small cross sections (down to a few μb) in the presence of tens of other products. These nuclei are commonly identified and studied with the help of charged-particle detectors placed around the target, and neutron detectors placed at forward angles. Therefore, the inner cavity of the array should be large enough to accept a nearly 4π array of charged-particle detectors, and the forward elements of the array should be modular to allow their replacement with neutron detectors.

Many binary reactions between heavy ions and heavy targets, such as Coulomb excitation, transfer and deep inelastic collisions, require coincidence detection of target- and projectile-like fragments. Examples of such detectors are parallel-plate avalanche counters (CHICO at Rochester), and energy-loss telescopes of segmented or position-sensitive silicon detectors. Other types of internal devices are mini-orange spectrometers to measure conversion electrons, and plungers for lifetime measurements. To accommodate such a large variety of detectors, a minimum inner-cavity radius of 13 cm is required.

Recoil mass separators (RMS), which identify reaction products by their charge-to-mass ratios, provide another powerful tool for the selection of weakly produced nuclei that are kinematically focused at forward angles. At high-enough recoil energies, gas counters at the final focus of an RMS may be used to identify the atomic numbers of the products. In recoil-decay tagging experiments, prompt γ emission at the target position is detected in coincidence with some characteristic decays of the recoils at the focal plane (*e.g.,* particle or isomeric γ decay) that uniquely identify the nucleus of interest. This technique requires that the data acquisition and readout systems be versatile enough to accept both prompt and delayed coincidence triggers from a variety of auxiliary detectors.

Depending on the reaction of interest and the nature or severity of the contaminating background, one may have to use the tracking array in conjunction with different types of mass separators. Examples of these separators are recoil mass spectrometers with high mass resolution for nuclear structure (FMA at ANL and RMS at ORNL), gas-filled separators with very high collection efficiency but low mass resolution (BGS at LBL and RITU at Jyvaskyla), and separators suitable for radiative-capture reactions of interest to astrophysics (DRS at ORNL and DRAGON at ISAC). Since no separator can singularly meet the conflicting requirements of the above experiments, it should be possible to move the tracking array to different beam lines.

Finally, to fully utilize the Doppler correction capabilities of the array, one needs auxiliary detectors that would allow determination of the recoil angle to better than 1°. With low-intensity radioactive ion beams, this may be achieved with the help of micro-channel plates, or other tracking detectors. Recoil direction may be also determined either directly by position-sensitive recoil detectors such as HERCULES (Washington University), or indirectly by kinematic-reconstruction technique for reactions that involve only emission of charged particles. The γ-ray tracking array should be able to accommodate these auxiliary detectors with no, or only small adverse effects on its overall performance.

4.3 Data acquisition and electronics

Requirements for digital electronics and digital processing of the large amount of data generated by a γ ray tracking array have been discussed at the Argonne (March 2001) and Lowell (June 2001) Workshops. The main conclusions of these meetings are discussed in Chapter 6, and summarized below.

The electronics should be able to handle: (i) a dynamic range of 10 keV to 20 MeV for the incident γ rays and a trigger threshold of better than 5 keV, (ii) count rates of up to 50 kHz per detector, and (iii) an event rate of ~1 MHz for M=5 and 300 kHz for M=25. The trigger logic and data acquisition systems should be versatile enough to accept both prompt and delayed coincidence triggers from a variety of auxiliary detectors, and to incorporate an adequate level of signal processing to select the interesting events with minimum loss of data.

4.4 Summary of the characteristics and performance parameters

4.4.1 Geometry:

- *Segmentation: Approximately 1.5 cm radial, about 10^{-3} of 4π angular*
- *Azimuthal symmetry (desirable for angular correlations)*
- *Minimum size of the target cavity (important for auxiliary detectors): 13 cm*
- *Modularity: Ability to accommodate external auxiliary detectors, and to easily mount or dismount elements of the array*
- *Portability: Ability to use the array at different beam lines.*

4.4.2 Performance with tracking:

- *Energy resolution (FWHM) of 1.2 and 2.2 keV for 122 and 1332 keV γ rays, respectively.*
- *Angular resolution: Better than 1º for a 1332 keV point source at target position*
- *Directional information: Spread in the half angle of the cone that defines the direction of the incident γ-ray to be nearly ±7º @ 1 MeV*
- *Efficiency of better than ~80% to measure H and K*
- *Timing resolution (FWHM) of better than 5 ns at 1332 keV*
- *Efficiencies and peak-to-total ratios similar to the values indicated in Table 4.1.*

4.4.3 Electronics and data processing rates

- *Energy dynamic range: 10 keV to 20 MeV for the incident γ/x ray*
- *Compatibility with auxiliary detectors*
- *Ability to incorporate a variety of prompt and delayed triggers from auxiliary detectors*
- *Count rate per detector: ~50 kHz*
- *Event rate: Approximately 1 MHz for M=5, 300 kHz for M=25.*

5. Current Efforts in Gamma-Ray Tracking

5.1 Coaxial Detectors

5.1.1 GRETA (Gamma Ray Energy Tracking Array)

The first conceptual design study for applying γ-ray tracking to a proposed major new detector for nuclear structure physics was done at LBNL in 1994 and an array named GRETA was proposed. This detector was mentioned as a desirable future development project in the February 1996 Long Range Plan for Nuclear Science. The first prototype 12-fold segmented coaxial Ge detector was tested in 1997; the first working tracking algorithm for Compton scattering was successfully developed and 2D sensitivity demonstrated at LBNL. This success led to the first workshop of GRETA Physics held at LBNL February 1998. A GRETA Advisory Committee was formed April 1998, which later became the GRETA Steering Committee. In 1999 the second prototype 6x6 fold segmented GRETA detector was tested. Pulse-shape analysis of transient and net charge signals was used to obtain three-dimensional position information of individual γ-ray interactions, and the realization of γ-ray tracking algorithms based on the two dominant interaction processes, the Compton and the photo-electric effects. This success demonstrated the crucial first proof of principle for γ-ray tracking in segmented detectors with regard to detector manufacture, signal processing, and tracking algorithms.

The current design of GRETA is based upon a geodesic configuration, consisting of either 110 or 120 hexagons plus 12 pentagons. For the 110 hexagon geometry there are three types of slightly irregular hexagons, shown in Fig. 5.1.1, forming three rings surrounding the inner pentagon. The inner radius of the array depends on the size of the Ge detectors. Considering a detector with 8 cm diameter and 9 cm length, this inner radius is ~14 cm, matching the requirements needed to accommodate auxiliary devices. The two packing schemes being considered by the GRETA Steering Committee do not significantly change the following discussion. It is envisioned that 3 detectors (one of each type) will be mounted in a common cryostat (see the discussion in 6.1), as a compromise to minimize both the dead layers between and the complications that arise in sharing a common vacuum by many detectors. A total of 37 to 40 cluster modules will form GRETA.

Guided by the results obtained so far, and by Monte Carlo simulations, one expects the characteristics listed in Table 5.1.1 for the system described above, in comparison to Gammasphere. The resolving power expected under different experimental conditions covering most of the physics needs, can be estimated for a “realistic” GRETA configuration using the properties presented above. When compared to Gammasphere, the most conservative estimates, shown in the final column of table 5.1.2, show that GRETA will be hundreds to thousands of times more sensitive than the world’s most sensitive existing spectrometer. The large increase in resolving power reflects the corresponding increase

Table 5.1.1: Expected characteristics of GRETA in comparison with Gammasphere (GS). The peak-to-total ratio quoted for Gammasphere, and used in the resolving power calculations, is from simulations (the actual value is 0.60).

	GS	GRETA
Solid angle coverage	0.45	0.80
Efficiency (1.3 MeV)	0.08	0.50
Efficiency (15 MeV)	0.005	0.23
Position resolution	≥20 mm	2 mm
Peak-to-total ratio (1.3 MeV)	0.66	0.78
Energy resolution (1.3 MeV)	2.3 keV	2.0 keV
Time resolution (1.3MeV)	8 ns	5 ns
Direction information	No	Yes
Polarization sensitivity (1.3 MeV)	0.04	0.3
Counting rate (per detector)	10 kHz	50 kHz

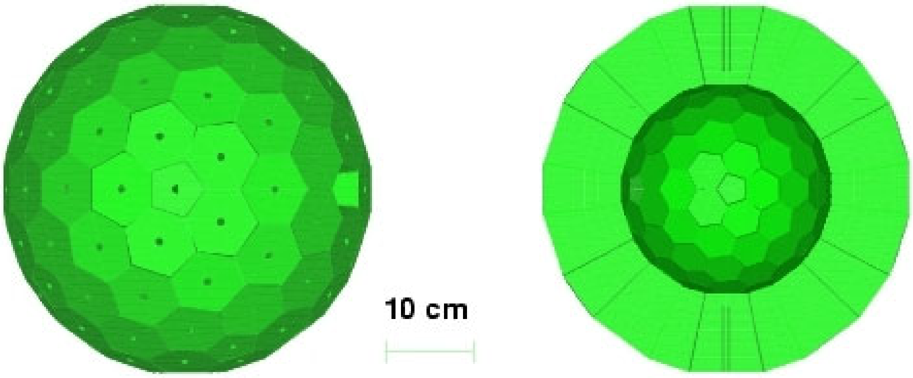


Fig. 5.1.1 Picture of a geodesic design for GRETA , based on the Gammasphere geometry. There are 110 hexagons and 12 pentagons.

Table 5.1.2: The calculated resolving power of GRETA for a variety of different reaction types ranging from β-decay (low multiplicity and v/c = 0) to fragmentation of fast beams, to very high spin fusion evaporation reactions. The final three columns list the improvement in the resolving power of GRETA, relative to Gammasphere, for three different assumptions about the total solid angle coverage and position resolution of GRETA.

Type of Reaction	$\langle E_\gamma \rangle$ (MeV)	v/c	M_γ	Resolving Power	Improvement Factor (Relative to Gammasphere)		
				Δx = 2 mm Ω=80%	Δx = 0 mm Ω=100%	Δx = 1 mm Ω=90%	Δx = 2 mm Ω=80%
Stopped	5.0	0.0	4	2.1×10^7	370	290	200
	1.5	0.0	4	4.4×10^7	170	120	77
High-spin Normal Kinematics	1.0	0.04	20	2.4×10^6	240	140	55
High-spin Inverse Kinematics	1.0	0.07	20	2.2×10^6	600	340	120
Coulex/transfer	1.5	0.1	15	3.7×10^6	2200	1320	510
Fragmentation	1.5	0.5	6	5.9×10^6	137600	46570	12490
In beam Coulex	5.0	0.5	2	$2.7 \mathrm{X}\ 10^3$	1510	440	110
	1.5	0.5	2	4.1×10^3	1800	180	50

in optimum fold for an array like GRETA, as compared to Gammasphere. The numbers show both the power of γ-ray tracking and the fact that this design matches very well the requirements of a 4π device. The predicted energy resolution as a function of recoil velocity is shown in figure 5.1.2. The calculations assume that there is no contribution to the energy resolution from the uncertainty in the direction of the emitting fragment.

During the Fact-finding Meeting at ANL, I-Yang Lee presented a cost estimate and budget profile for such an array, these are shown in table 5.1.3 and Figure 5.1.3. They include both purchase and manpower in FY02 Dollars with no contingency and no inflation. According to this spending plan, the available number of cluster modules in FY06 (of order 10) already will exceed the performance of Gammasphere.

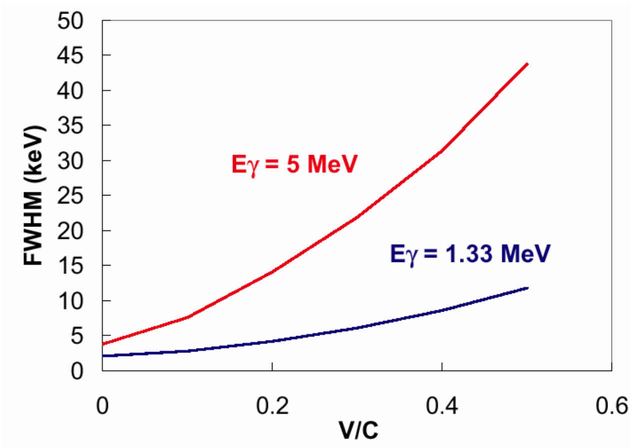


Fig. 5.1.2 The predicted energy resolution for GRETA as a function of recoil velocity for 1.33 MeV and 5 MeV γ rays.

Ge detectors

Two two-dimensionally segmented closed-ended HPGe detectors have been built by Eurisys Mesures and tested at LBNL. Both detectors have a regular hexagonal shape and are tapered by 10º, they were 9 cm long with a maximum diameter of 7 cm at the back. The first prototype was 12-fold segmented (6 azimuthal x 2 longitudinal) and the second prototype was 36-fold segmented (6 azimuthal x 6 longitudinal), shown in Fig. 5.1.4.

Extensive measurements have been performed to determine basic properties, such as noise characteristics, three-dimensional position sensitivity and resolution for single interactions, crystal orientation effects and energy resolution. On average, an energy resolution of 1.94 keV at 1.33 MeV was obtained for the segments and a total integrated noise of 4 keV at a bandwidth of 40 MHz, both indicating the excellent noise properties of this detector [NIM A452 (2000) 105]. A position sensitivity of about 0.5 mm at 374 keV was measured indicating that the combination of two-dimensional segmentation and pulse-shape analysis is able to provide sufficient sensitivity for a γ-ray tracking system [NIM A452 (2000) 223]. In addition, electrical field and pulse-shape calculations as well as Monte-Carlo simulations have been performed to understand the measured properties and to parameterize measured signals in terms of calculated signals which is necessary for the signal decomposition to determine energies and three-dimensional position of the individual γ-ray interactions. An example of these results is shown in Fig. 5.1.5; it clearly demonstrates the sensitivity of both the main and induced signals to the position of the interaction. The agreement between the calculated and measured signals is very impressive.

Table 5.1.3: A cost estimate for GRETA in FY02 Dollars. The effort assumes $200K/FTE.

Item	Purchase (M$)	Effort (FTE)
Mechanical	0.8	5
Liquid Nitrogen	0.5	4
Detector	17.0	7
Electronics	3.2	10
Computer	1.0	13
Installation		6
Management		15
Safety		3
Sub-total	22.5	63
Total(M$)	**35.1**	

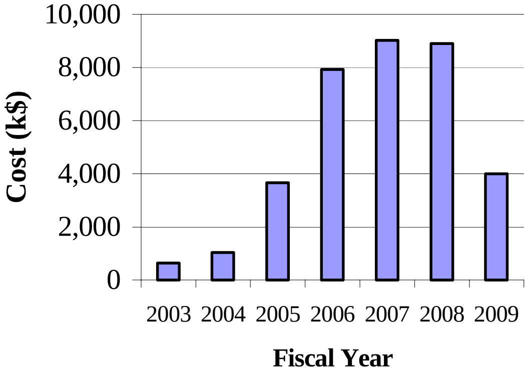


Fig. 5.1.3: GRETA cost profile as a function of Fiscal Year.

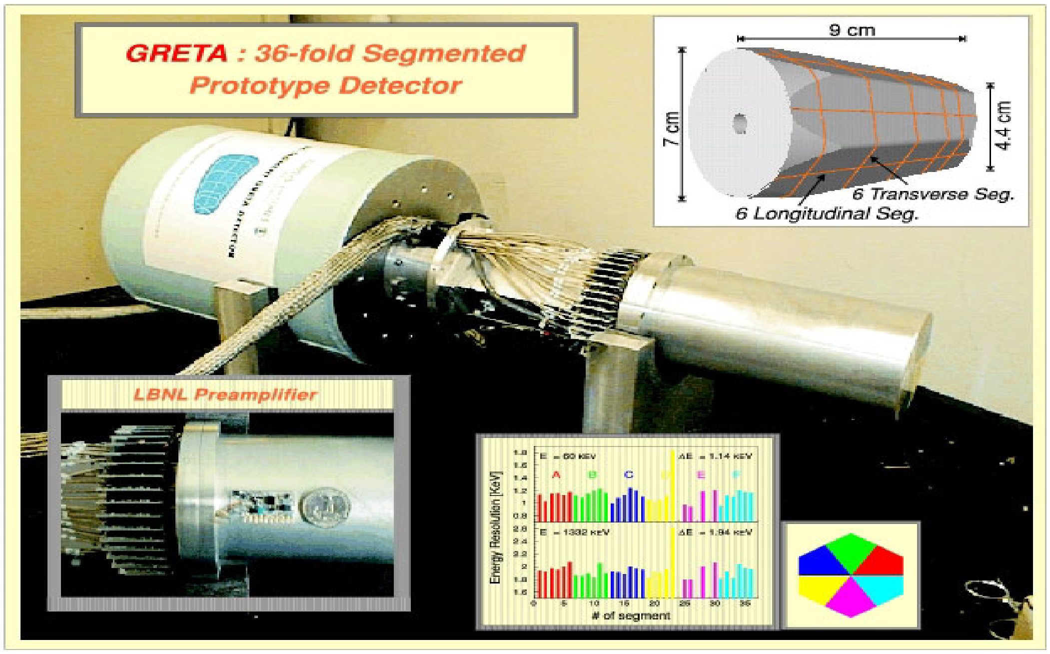


Fig. 5.1.4 Picture of the GRETA detector prototype. The insets show the preamplifier configuration, the crystal segmentation and the energy resolution for each segment.

By employing the event-by-event decomposition of measured signals with purely calculated signals a position resolution - again for single interactions – of better than 1 mm at 374 keV was obtained. These results are presented in Fig. 5.1.6; position resolutions in 3D (x, y and z) are compared for fitted positions and positions obtained by Monte Carlo calculations.

Currently, source data are being analyzed to compare simple properties as peak-to-total and efficiency with and without tracking [A. Kuhn, UC Berkeley]. The latter includes all the ingredients of γ-ray tracking, starting with the measurements of all the channels, the decomposition of measured signals with the calculated basis, and finally the tracking calculation. Data were also measured from different sources and different locations. This will allow study of the imaging capability of the GRETA prototype detector for a range of γ-ray energies.

Results for the ^{137}Cs source are presented in Fig. 5.1.7. The left panel corresponds to a full simulation and the right panel to the real data. Once again the agreement is excellent. The tracking algorithm improves the peak-to-total from ~16% to 31% with a tracking efficiency of 62%

Previous attempts to image the location of a ^{152}Eu by using the 244 keV transition were unsuccessful, probably due to the noise level at this low energy. We expect to be able to determine source locations by using γ-ray energies above 500 keV (^{137}Cs, ^{60}Co, ^{152}Eu source data have been measured).

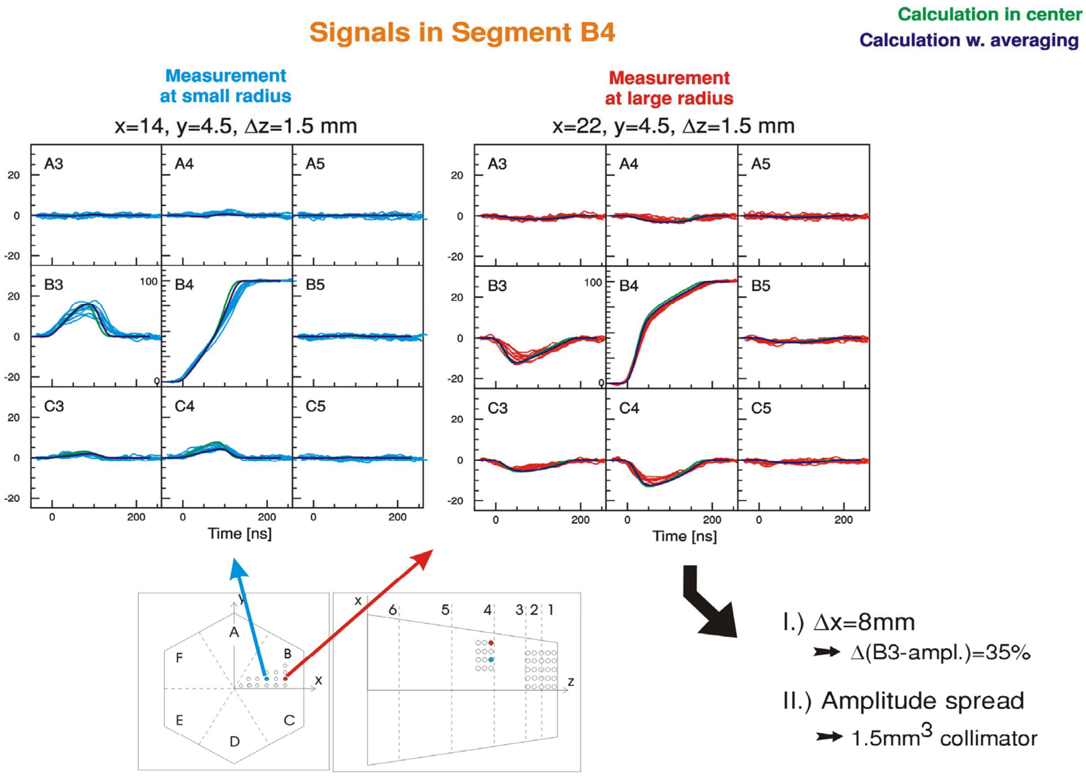


Figure 5.1.5. Comparison of measured and calculated signals at two positions in a given segment of the prototype detector, as indicated in the inset. Note the sensitivity of both main and induced signals to the position.

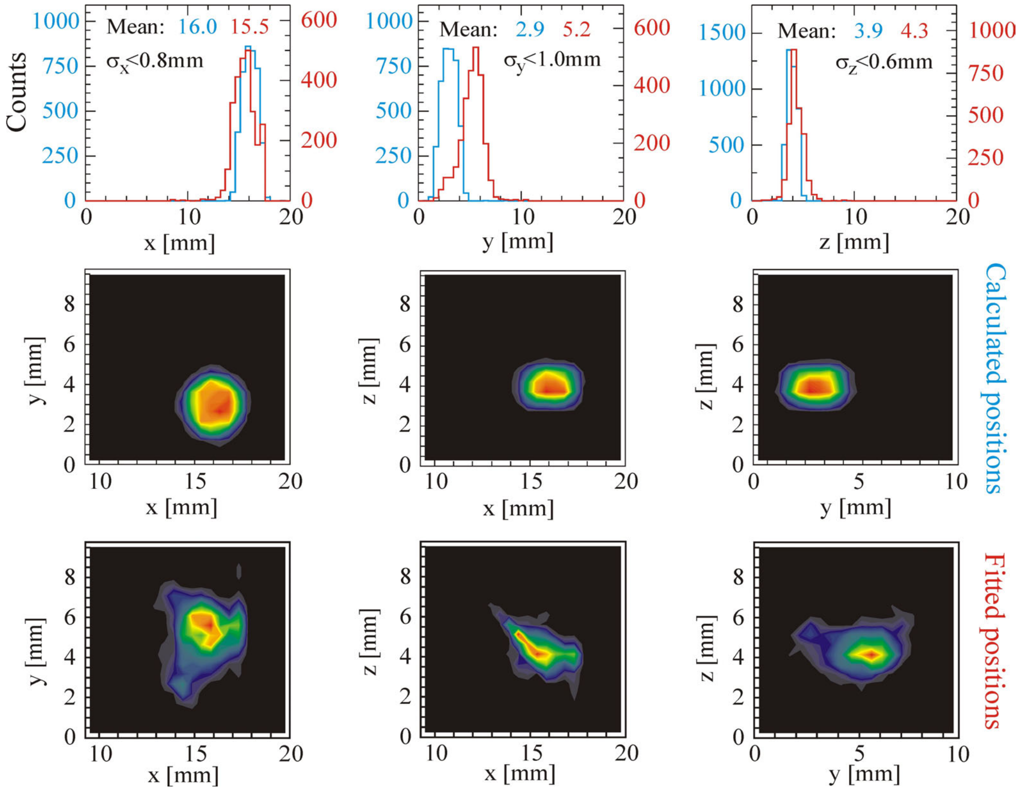


Fig. 5.1.6. Three dimensional position resolution of the prototype for a single (374 keV) interaction.

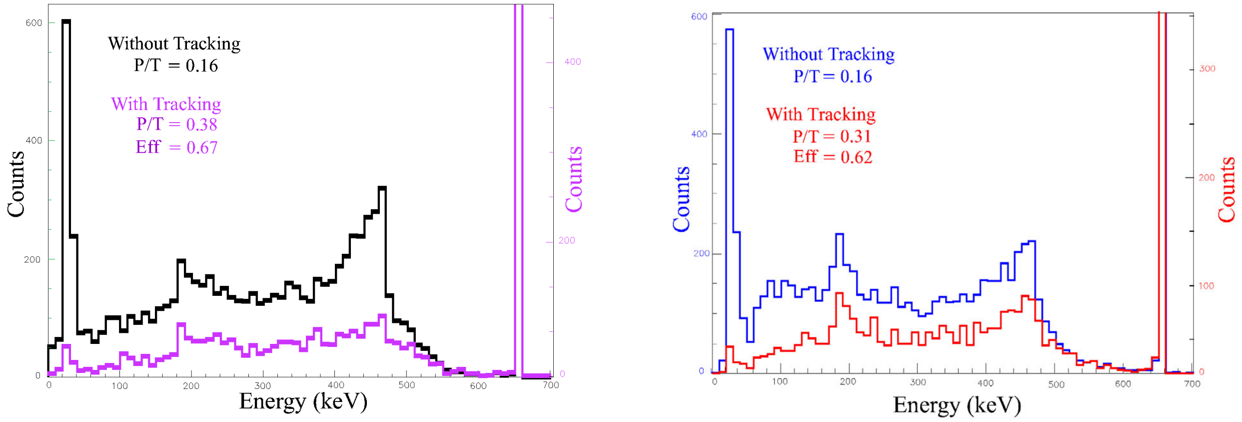


Fig. 5.1.7. Singles spectrum for the ^{137}Cs source (662.7 keV) obtained with and without tracking. The left panel corresponds to a full simulation while the right panel is for the real data.

Electronics and Data Acquisition

Compact low noise preamplifiers have been built at LBNL for the second prototype detector. All 37 preamplifiers are arranged on a circular motherboard close to the feedthroughs (See Fig. 5.1.4).

The measurements to determine noise characteristics, position sensitivity and position resolution were performed with 8bit, 500MHz Tektronix RTD modules (16 channels in total on loan from LLNL). The recent measurements were performed with eight 4-channel XIA modules. With the XIA modules, and its implemented algorithms, it was possible to improve the energy resolution by about 0.1 keV.

Tracking analysis software

Tracking analysis software includes two components: extraction of information about individual interactions and the tracking calculation itself. The first task is associated with the decomposition of the measured segment signals into individual interactions, the second task with converting this information into γ rays.

All signal decomposition approaches studied so far are based on fitting the measured signals with calculated signals. Fitting procedures such as adaptive grid search, singular value decomposition and state-of-the art χ^2 minimization algorithms have been developed and implemented in the time domain, the latter has been also explored in the wavelet domain.

So far, the different algorithms achieve position resolution in the order of a few millimeters and take in the order of seconds for each event, consisting of 2-3 interactions.

Significant effort went into the development of a γ-ray tracking algorithm based on the Compton and the photo-electric effect [NIM A 430 (1999) 69]. It consists of three steps:

(1) Identification: the interaction points within a given angular separation, as viewed from the target, are grouped into a cluster.

(2) Evaluation: each cluster is evaluated by tracking, using the Compton scattering energy-angle relation to determine whether it contains all the interaction points belonging to a single γ ray. If the interaction points had infinite position and energy resolution, the tracking would be exact and the properly identified full-energy clusters will show no deviation from the scattering formula. Wrongly identified clusters or partial-energy clusters will deviate from the formula and the separation of the good and bad clusters would be easy. However, in reality, with finite position and energy resolution, the good clusters will also have a non-zero χ^2 and they cannot be separated cleanly from the bad clusters. This causes a lower efficiency and poorer peak-to-total ratio (Fig. 5.1.8).

(3) Recovery and filter: recover some of the wrongly identified γ rays by either adding two bad clusters or by splitting a bad cluster into two. The clusters, which do not satisfy any of the above criteria, are rejected.

With a position resolution of 2 mm and realistic assumptions concerning the geometry (e.g. gaps and can thickness) an efficiency of about 25% and a peak-to-total of about 0.65 can be achieved for events with 25 emitted γ rays. This has to be compared with Gammasphere which has an efficiency of about 8% and a peak-to-total of about 0.66 under the same conditions, which implies a gain of four in efficiency for each of 25 emitted γ rays.

Another advantage of a tracking array is the high photo-peak efficiency for high-energy γ rays (e.g. 0.23 at 15.1 MeV). This results from the large probability of pair production. (At 10 MeV, this probability is about 60%) and therefore pair-production events need to be identified with a high efficiency. A “pair-tracking” algorithm was developed based on

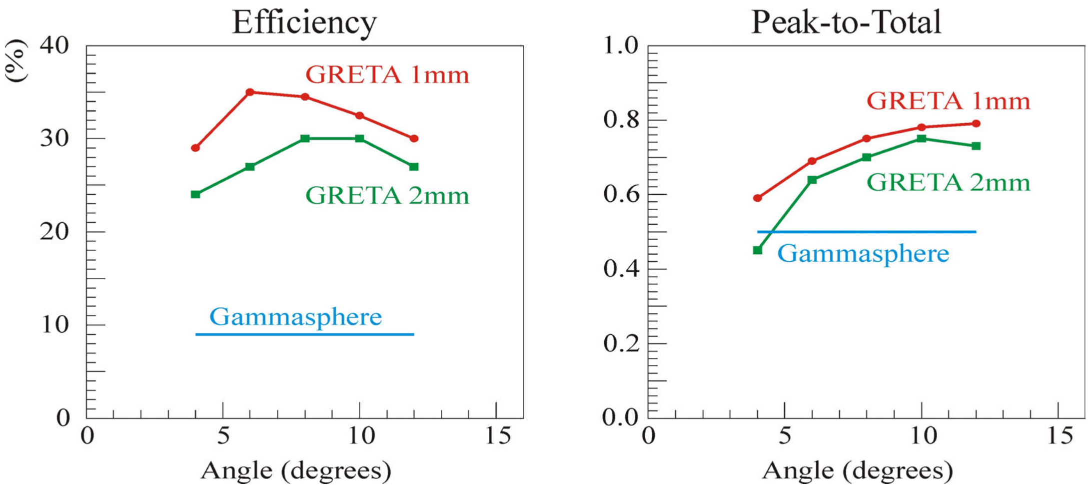


Fig. 5.1.8 Efficiency and Peak-to-Total for GRETA for a multiplicity of 25, as a function of the angle used to define a cluster in the tracking algorithm.

the characteristic features of the pair-production process and the subsequent position annihilation radiation.

5.1.2 AGATA: The Advanced GAmma-Tracking Array

The European efforts in γ-ray tracking were presented at the Argonne Fact-finding Meeting by Dino Bazzacco from INFN-Padova. This R&D work was supported by the TMR Network project and included work on simulations and tracking, calculations of pulse shapes, signal decomposition and development of segmented detectors (such as MARS). These efforts resulted in the AGATA proposal. It is important to note that most AGATA results are consistent with those obtained by the GRETA team. The AGATA collaboration includes 38 institutions from Bulgaria, Denmark, Finland, France, Germany, Italy, Poland, Sweden and UK. The main properties of AGATA are summarized in table 5.1.4

The geometrical structure of AGATA is based on the geodesic tiling of a sphere with 12 regular pentagons and 180 hexagons as shown in Figure 5.1.9. Owing to the symmetries of this specific bucky-ball construction only 3 slightly different irregular hexagons are needed. To minimize inter-detector space losses while still preserving modularity, 3 hexagonal crystals (one of each type) are arranged in one cryostat. The pentagonal detectors are individually canned. The inner radius of the array is 17 cm. The total solid angle covered by germanium material is close to 80% and the photo peak efficiency is 50% for an individual 1 MeV γ-ray.

Table 5.1.4 Basic properties of AGATA

Property	Condition	
Photo-peak efficiency	E_γ=1 MeV, M_γ=1, β<50%	50%
	E_γ=1 MeV, M_γ=30, β<50%	25%
	E_γ=10 MeV, M_γ=1	10%
Peak-to-total ratio	M_γ=1	60-70%
	M_γ=30	40-50%
Angular resolution	ΔE/E<1%	<1°
Event rates	M_γ=1	3MHz
	M_γ=30	0.3MHz

The total number of segments in the array is 6780. This granularity provides optimum position sensitivity. Realistic simulations of the tracking performance indicate efficiencies of 40% for individual transitions and of 25% for a cascade of 30 γ-rays. A key feature of AGATA is the high precision for determining the emission direction of the detected γ-rays of <1° for a point source located at the target position. This

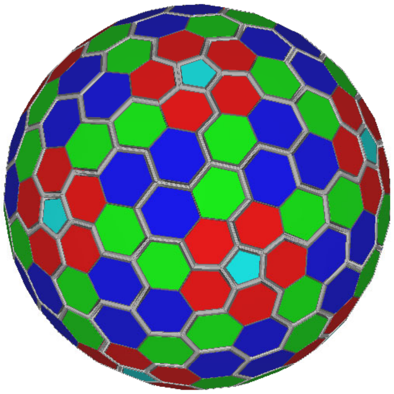


Figure 5.1.9: Artist's view of AGATA. The three slightly different hexagonal crystal shapes are shown in red, green and blue. Three Crystals are packed in a cryostat, as indicated by the grey aluminium walls. The total number of such triple cluster detectors is 60. The pentagonal detectors are shown in light blue color.

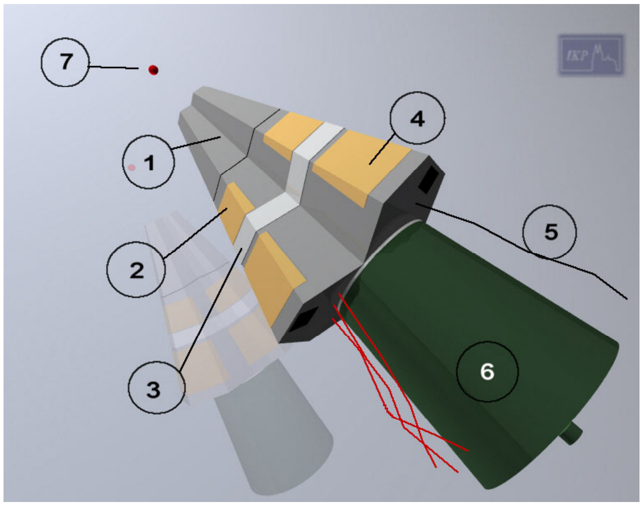


Fig. 5.1.10: Simulation of the AGATA Detector Module consisting of (1) three 36-fold segmented Ge detectors, (2) preamplifier, (3) frame support, (4) digital pulse processing electronics, (5) fiber-optics read-out, and (6) LN_2 – dewar. The (7) target position is indicated.

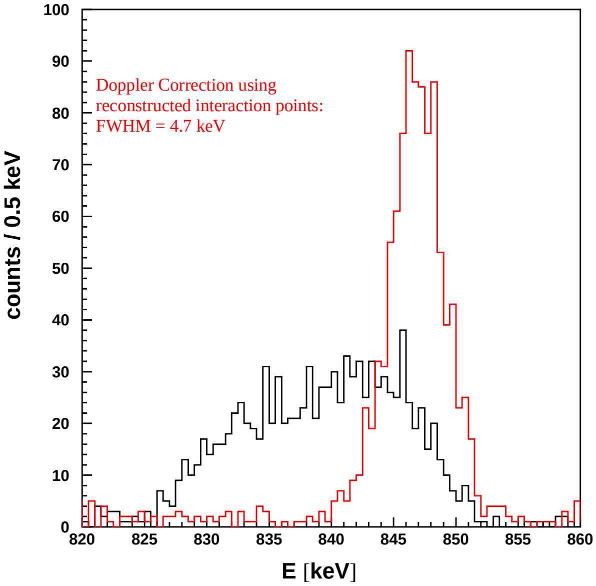


Fig. 5.1.11: The 2^+ transition in ^{56}Fe before and after Doppler reconstruction using a genetic algorithm. The expected energy resolution is 3.5 keV for perfect tracking and 4.2 keV for a position resolution of 5 mm.

ensures an energy resolution better than 0.5% for transitions emitted by nuclei recoiling at velocities as high as 50% of the speed of light. This value is only a factor of two larger than the intrinsic resolution of Ge detectors and is comparable with the values currently observed at 10 times smaller recoil velocity.

Fig. 5.1.10 shows a simulation of how an AGATA detector module will look. Each cryostat contains three 36-fold segmented Ge detectors of hexagonal, tapered shape (8 cm diameter, 10 cm length). The individual Ge crystals are encapsulated in a very thin Al can – a new technology, developed in the framework of the Euroball and Miniball projects, which strongly improves the reliability of the detectors. The 111 preamplifiers consist of a cold part including the FETs mounted inside the cryostat and a warm part behind the Ge detectors. Highly integrated digital pulse processing electronics could be mounted in a second layer behind the preamplifiers. The data are transferred via a fiber-optic channel for further analysis. A central support frame is situated between the preamplifier and the pulse processing-section. The Ge detectors are cooled with liquid nitrogen contained in conical dewars.

The estimated cost for this project is 40MEuros and the manpower 150 FTEs. It could be completed in 8 years.

A segmented prototype detector (MARS) was built by Eurisys for the Legnaro-Padova group. It is a cylindrical crystal with 6(azimuthal)x4(longitudinal) segments plus an extra segment in the front. The results of the test of this detector are important and provide an important milestone in the application of the tracking concept in realistic conditions. In one experiment a beam of ^{56}Fe at 240 MeV was Coulomb excited by a ^{208}Pb target. The recoils, with v/c ~8%, were detected in an array of 15 tightly collimated particle counters positioned at approximately 90º from the prototype. Figure 5.1.11 shows the Doppler corrected spectrum was generated by the reconstructed points obtained by a tracking using a genetic algorithm. The FWHM of 4.7 keV for the 2^+ transition in ^{56}Fe (846 keV) is very close to the 4.2 keV expected from simulations including a position resolution of 5 mm. The full analysis of the experiment is still in progress.

5.1.3 The SeGA Array

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University has developed the SeGA 32-fold segmented germanium detector array. The project was funded via the Major Instrumentation Program (MRI) of the NSF. The array was optimized for in-beam γ-ray spectroscopy experiments with fast (v/c = 0.3-0.5) exotic beams.

The SeGA array consists of 18 individual detectors. Each cylindrical crystal is 8 cm long and 7 cm in diameter and made of n-type high-purity germanium. The outer p-type ion-implanted contact of the crystal is vertically segmented into four longitudinal segments and horizontally segmented into eight transverse segments. The inner contact is lithium diffused and each crystal is individually encapsulated. The gap between the crystal and the can is 8 mm and 4 mm in the front. The full volume energy signal is collected from the inner contact by an AC coupled preamplifier and each segment is grounded through a DC-coupled preamplifier which

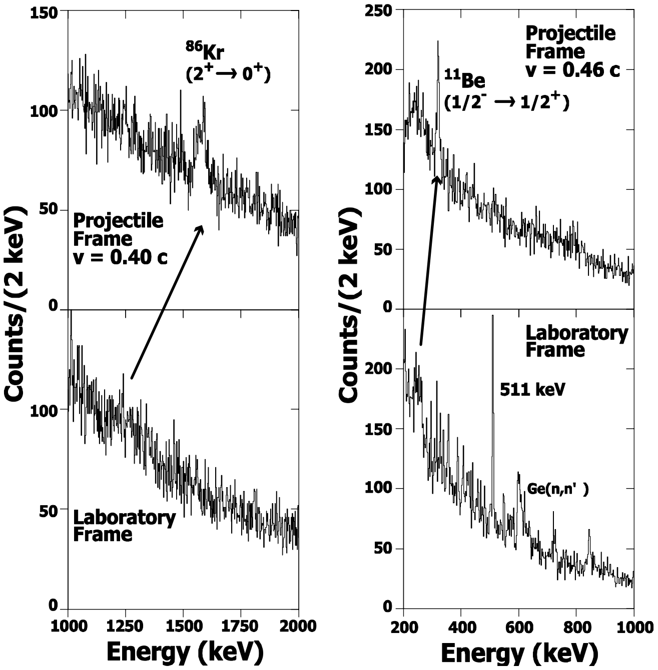


Figure 5.1.12: Coulomb excitation spectra at intermediate beam energies for ^{86}Kr and ^{11}Be scattered of secondary gold targets.

gives the position information. All FETs are warm and can be easily accessed without breaking the vacuum.

The detector array is in operation and the design goals have been achieved. The central contact energy resolution varies between 2.5 keV and 2.8 keV. The average resolution of the 32 side channels is 2.5 keV for all but the four segments at the front where the average resolution is 3.3 keV (all resolutions were measured at 1332 keV). Each crystal is about 75% efficient relative to a 3”x 3” NaI detector. Peak-to-total values range from 0.210 to 0.216. The time resolution ranges from 7.0 ns to 9.0 ns (FWHM) for energies greater than 100 keV from a ^{60}Co source. The flexible design of the array was optimized for fast beam experiments. The detectors can be arranged in several configurations with distances to the target varying from 10 cm to 100 cm.

Figure 5.1.12 shows the γ-ray spectrum following Coulomb excitation of a 83 MeV/nucleon ^{86}Kr on a 184 mg/cm^2 thick gold target (left) and of a 121 MeV/nucleon ^{11}Be on a on a 968 mg/cm^2 thick gold target (right). The importance of the position determination is obvious by comparing the spectrum in the laboratory (bottom) and projectile (top) rest frame. The spectra correspond to six detectors at 109° at a distance of 14 cm from the target.

The detector hardware of the project is complete and the next step is the upgrade of the analog electronics with digital electronics to improve the position resolution. The digital readout of the detector signals allows the reconstruction of the position to better than the intrinsic resolution of 0.6 cm FWHM. The detectors could then be placed closer to the target increasing the efficiency while maintaining the energy resolution.

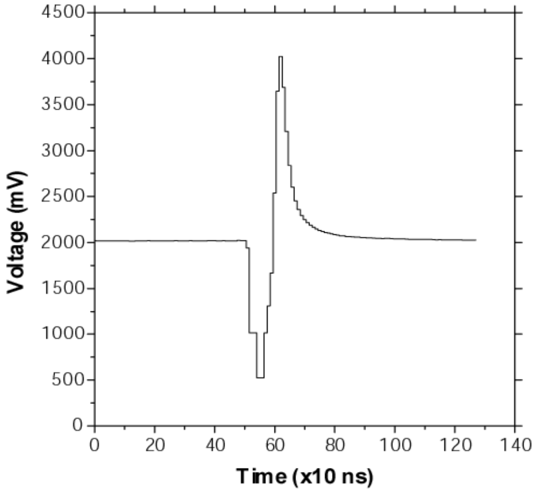


Figure 5.1.13: Signal from a Struck SIS 3300 12-bit 100 MHz flash ADC read out by the NSCL VME/PCI real-time Linux based data acquisition system.

This project is an ideal first opportunity to test the tracking algorithms because the γ-ray multiplicity in these intermediate-energy experiments is low resulting in digital position determination significantly simpler compared to the full tracking required in fusion-evaporation reactions. This effort should be coordinated with the broad development of digital signal processing of GRETA. The hardware will be based on the Struck SIS3300 100 MHz 12-bit 6U VME flash ADC (Figure 5.1.13) and is being developed using NSF funds in coordination with the working group on Digital Electronics. The VME/PCI real-time Linux based data acquisition developed at the NSCL is capable of processing the signals. It is anticipated that the hardware cost to implement all 18 detectors with digital readout (estimated to be $450k) can be secured through the MRI program of the NSF. The manpower needed to implement the tracking algorithms is estimated to be two FTE. This would be directly connected to the GRETA effort and should be supported within this effort.

5.2 Planar Detectors

Planar double-sided strip Ge detectors (HpGeDSSDs) have been procured for photon imaging and for tracking of γ rays by several laboratories (see section 5.3). Such detectors have multiple strips in orthogonal directions on either side of the wafer; the “intersection” of a pair of orthogonal strips defines a pixel. The uniform, high field of the planar geometry has many advantages. For imaging and tracking of photons a key benefit is that each pixel provides inherently good (x,y) position resolution without the need to process the shape of the signals. For many applications, for example Doppler correction, 5 mm pixels are sufficiently small, but it is straightforward to obtain smaller resolution, < 1 mm, either

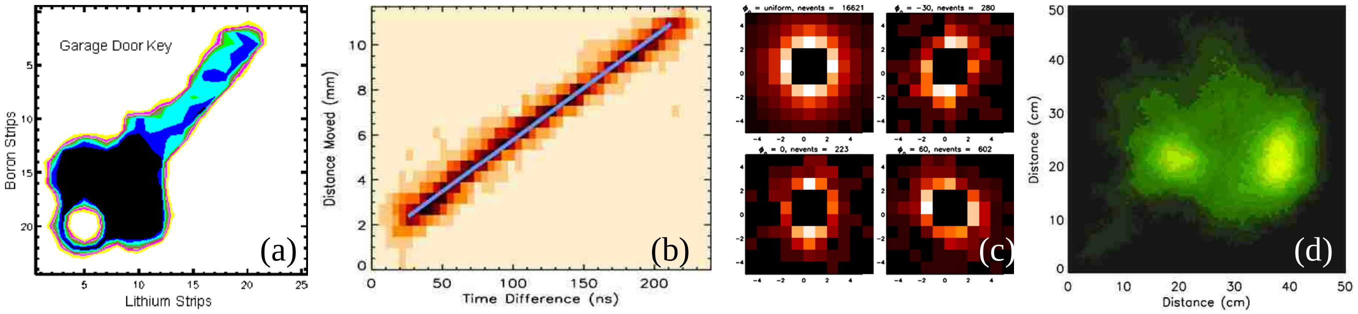


Fig. 5.2.1: Results from NRL planar HpGeDSSDs, showing: an example of tomography with (a) a key image, (b) depth resolution, (c) polarization sensitivity and (d) an image of two radioactive sources (which requires full tracking).

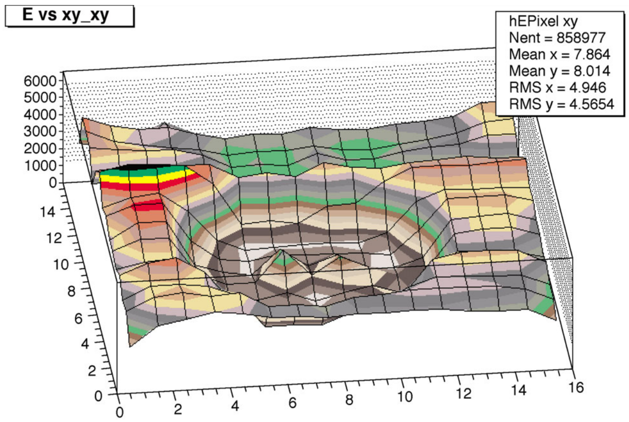


Fig. 5.2.2: An X-Ray absorption image of a NASA "martian" test sample, imaged with silver X-rays (~23 keV) from a ^{109}Cd source, measured with the ANL detector. The circular depression is from enhanced absorption in a quartz matrix; the left and right peaks inside reveal diminished absorption from embedded paraffin and carbon objects. The relative absorption at 23 keV and, say, 88keV allows the effective atomic numbers of the objects to be determined. The experimental geometry has a 8:1 magnification, so an ANL HpGeDSSD pixel has an effective area of 700 x 700 microns on the object.

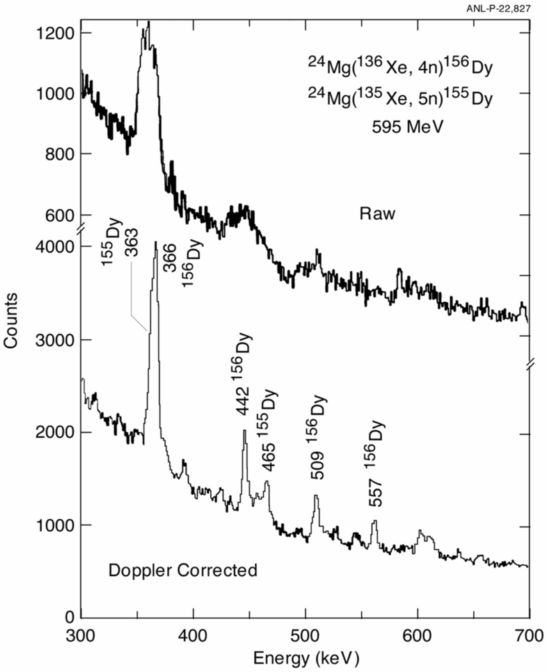


Fig. 5.2.3. Raw and Doppler corrected γ-ray spectra from the ^{24}Mg(^{136}Xe,xn)^{155,156}Dy reactions at 595 MeV. Data were collected using the "Mark 2" detector placed 10 cm from the target at 90°. The recoil velocity was β~8.0%.

by making detectors with finer strips, or by exploiting the image signals on strips adjacent to that with the photon interaction. Analysis at ANL shows that, for single-interaction events, ~1 mm lateral position resolution can be very easily reached with a very simple algorithm which relies only on the size of the image charges and not at all on their shape. Approximate algorithms of this type are ideal for executing in real time in an FPGA or similar device. Depth (z) information can come from the time difference of the signals in the opposite electrodes; sub-mm resolution has been demonstrated at the Naval Research Laboratory (NRL), again without resorting to digital analysis. Already Ge DSSDs have been successfully demonstrated in several applications at NRL, as shown in Fig. 5.2.1, and at Argonne as shown in Figs. 5.2.2 plus 5.2.3.

In the GAmma-Ray BOx (GARBO) project at Argonne, large planar double-sided Ge strip detectors have been tested, with the eventual goal of using them for tracking photons. Collaborating institutions in this project are Argonne, Bio-Imaging Systems, DePaul, Liverpool, Purdue-Calumet, U. Massachusetts Lowell, ORTEC and NRL. Currently, tests are being conducted on a 92 x 92 x 20 mm p-type planar detector, with sixteen 5.3 mm wide strips. There is a 3.5 mm guard ring around the edge of the detector. Contacts are made through boron implantation on one side and through lithium on the other. Fig. 5.2.4 shows a photograph of the

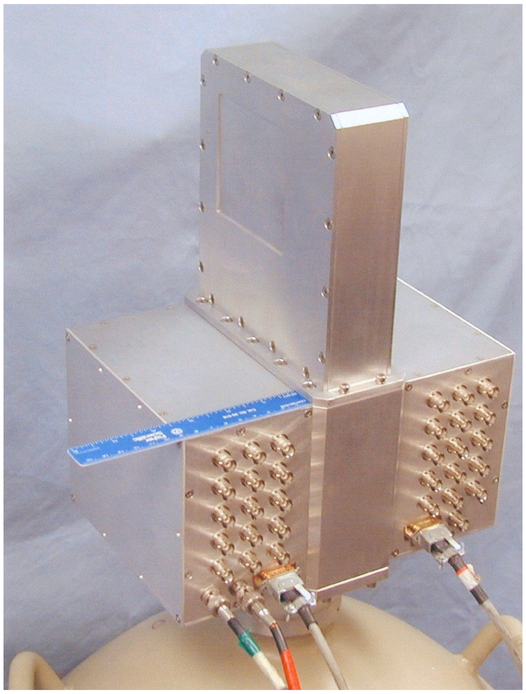


Fig. 5.2.4. The ANL “Mark 3” HpGeDSSD. It is a 92 mm x 92 mm x 20 mm germanium wafer, with 16, 5.3 mm strips on each face.

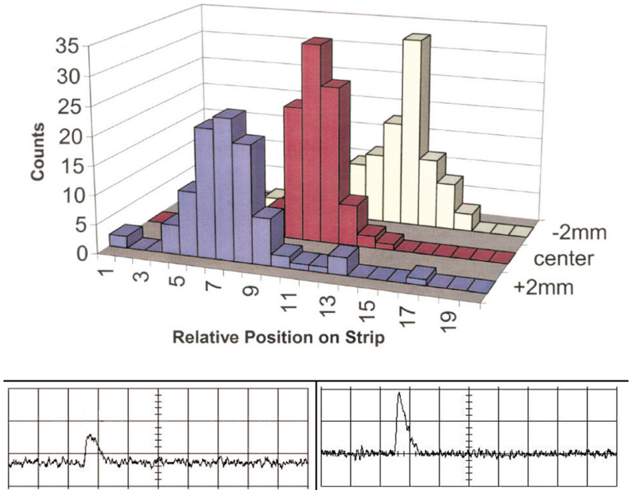


Fig. 5.2.5. Probability distribution *vs* position, measured with a collimated ^{137}Cs source located at three locations within a strip (center and ∓ 2 mm from center). Each bin corresponds to 0.28 mm and the position resolution is ~0.8 mm FWHM. The position information is given by the relative magnitudes of the image charges on adjacent strips. The lower panels show digital scope traces of a pair of image charges, with the source at the –2-mm position. Events with more than one interaction were excluded in the analysis.

detector. This is the largest and thickest planar Ge wafer that has ever been manufactured. Preliminary results are very good. With all warm FETs, the average resolution for 122 keV photons is 1.8 keV on the Li side and 2.2 keV on the B side. The average resolution for 1.3 MeV γ rays for all strips is 2.8 keV. (Two strips, which have poor resolution due to fabrication problems, are excluded from the average.) The efficiency response is uniform within 10% across the face of the detector. The efficiency profile across a strip in consistent with its width.

Two prior versions, which did not have guard rings, showed poorer performance, both in resolution and in uniformity of efficiency, but served for refinement and improvement of manufacturing techniques. These detectors also allowed a number of useful measurements to be made. Among these are of the measurements of the digitized pulse shapes from the strip in which the interaction took place and from the two adjacent strips. The latter revealed the image charge signals, which have either a positive or negative polarity, depending on the depth of the interaction point. Hence, they can provide additional depth information. It is clear that these pulses can always provide sufficient data for locating the three coordinates of the interaction point when there is one dominant interaction in a pixel (by far the most common case), and can often provide multiple coordinates if the interactions are well separated (>5 mm apart). Detailed knowledge of the pulse shape is not needed for single interactions due to the linear electric fields and simple geometry, unlike in the coaxial detector geometry. For example, the location of an interaction point has been determined within < 1 mm from the relative magnitudes of the two image charges – see Fig. 5.2.5. Investigations are being conducted on multiple interactions in a pixel, but even then simple “multiple peak” fitting may allow position extraction without recourse to fitting calculated pulse shapes. Full analysis is in progress, but it is estimated that the position of the interaction point normally can be located within 0.5-1 mm, depending on the interaction depth and on the photon energy. At worst, at the depth where the mirror-charge pulse changes sign, the resolution will be given by the strip width, i.e. ±2.5 mm.

Extraction of multiple interactions within a HpGeDSSD will require digital signal processing, deconvolution of the digital data to infer interaction points and energies, and then the development of algorithms to track the incident photon by reconstructing the successive photon interactions. The two largest areas of R&D are the digitization and reconstruction, which are common for photon tracking with both planar and coaxial detectors.

Monte Carlo simulations have been performed at Argonne to evaluate detection efficiencies and peak-to-total ratios of several detector configurations. A stack of four 92 x 92 x 20 mm wafers is an efficient detector with an absolute photo-peak efficiency of 0.17% and peak-to-total ratio of 0.27 for a 1.3 MeV source at 25 cm [142%, compared to a 3x3” NaI detector]. With removal of inert material (Li contact, boron nitride, guard ring) the relative efficiency rises to 210%. Investigations were also performed for a 6-sided cube, with four stacks of planars on each face, to evaluate its performance as a 4π detector for in-beam γ spectroscopy. The calculated absolute photo-peak efficiency was 15%, with a peak-to-total ratio of 0.28, without tracking. Although the performance will improve with minimization of inert material, better packing and tracking, it is not competitive with that of the GRETA array.

Thin planar detector contacts have been developed recently that do not require lithium. Further, a device without a guard ring should be possible. However, from devices produced for both Argonne and NRL, it is evident that detectors with guard rings perform better. This is an issue, which needs to be further investigated, with the potential of providing a significant boost in packing efficiency.

5.3 Astrophysics and other applications

Gamma Ray Tracking is of broad interest, both within and outside of the low-energy nuclear physics community. Significant support for tracking is provided by various branches within DOE, as well as by the National Aeronautics and Space Administration (NASA), Defense Threat Reduction Agency (DTRA), Office of Naval Research (ONR) and the National Institute of Health (NIH). The power of this technique naturally leads to new capabilities and better detector performance. These include the ability to locate the position of the first interaction with high precision in a large detector. Without tracking, spatial resolution is limited to the size of the interaction volume, which is typically the size of the physical detector. Thus, millimeter spatial resolution is traditionally limited to low energies or small-inefficient detectors. Tracking solves the efficiency problem at medium to high energies, while providing spatial resolution, potentially better than sub-mm.

Tracking is particularly important in space-based instrumentation where weight constraints place severe limits on the size of a detector system. It also creates new opportunities in other fields such as medicine, diagnostic testing, and other terrestrial applications where position resolution and/or imaging are important. Tracking, by identifying the first interaction, is essential for the millimeter position resolution needed in a Compton imager, or any high-resolution camera application operating above a few 100 keV.

Tracking naturally provides the ability to produce high-efficiency Compton-camera images through determination of the first and second interactions: the first two interactions define the direction of the scattered γ ray, and the energy losses determine the angle of scatter between this direction and the initial γ-ray. The possible direction of the incoming γ ray is thus restricted to a cone (event cone). The superposition of many such cones from a number of events is processed to form an image. The principle of a Compton camera has been used in space by the COMPTEL instrument on NASA’s Compton Gamma Ray Observatory, as well as in laboratory imagers, which are discussed in the published literature. A Compton camera can be used for imaging the distant sky, but also for producing full three-dimensional images of radioactive sources in the near field.

Astrophysical tracking also provides an important new capability to reject detector activation and other backgrounds. Space instrumentation becomes radioactive after exposure to the cosmic ray environment. This radioactivity typically dominates by several orders of magnitude over the much weaker signals from distant sources of scientific interest. Tracking readily rejects a large fraction of this background because the event cone is not consistent with a source location. Additional background may be rejected because tracking will reveal that one or more legs in a sequence of interactions are consistent with known radioactivities within the instrument. This is a new capability. It is by exploiting tracking in this way that the next generation of high-energy γ-ray astrophysics instruments will be realized. This mission, in its concept stage, is generally referred to as the Advanced Compton Telescope (ACT).

Tracking detectors under development for NASA include several detector technologies. Among these are, germanium strip detectors, segmented coaxial germanium detectors (now flying on a solar mission named RHESSI), thick lithium-drifted silicon strip detectors, liquid and high pressure

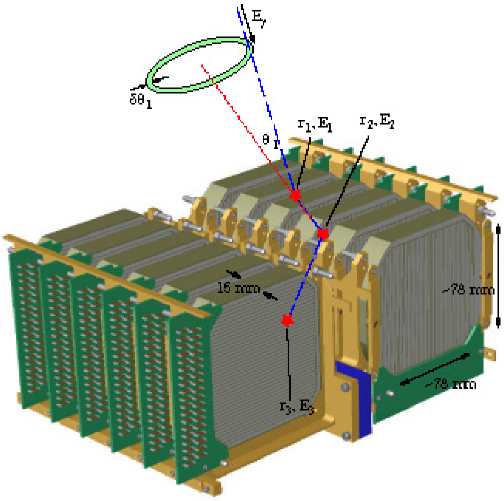


Fig 5.3.1 U. California, Berkeley concept using germanium strip detectors for a prototype balloon experiment. Each detector provides a full 3-dimensional position readout of each interaction. NRL is also working on a similar germanium-based concept.

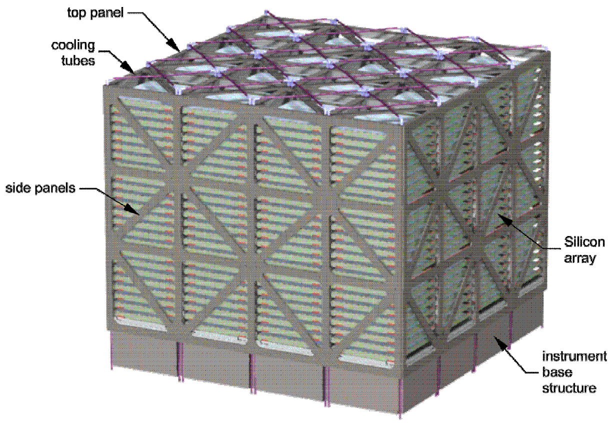


Figure 5.3.2 NRL concept using stacks of thick Si(Li) strip detectors assembled in towers. Cooling to –40C is accomplished by a fluid loop minimizing passive materials, with electronics along the outer wall of the instrument.

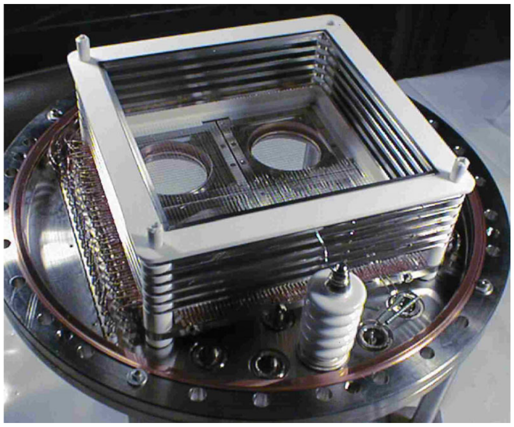


Figure 5.3.3: Liquid xenon time projection chamber developed at Columbia University. Crossed wires read out the x-y position of each interaction. The depth is determined by timing the charge collection relative to the initial scintillation light produced by the first interaction.

xenon time projection chambers, and thin silicon recoil-electron tracking detectors. Examples of several instrument concepts based on these are shown in Figures 5.3.1–3. One of these will become the future ACT. Besides technology development, the NASA program entails Monte Carlo simulations and tracking development distributed between various institutions.

In addition to space and nuclear physics, tracking applications reflect a diverse range of other interests ranging from sensitive imaging detectors to identify and map distributions of radioactivities for environmental remediation, processing of radioactive materials, developing sensitive detectors for detecting higher energy lines at large distances, surveys to find radioactivity, security through improved monitoring at ports of entry, and new techniques for medical imaging. One example is that the instruments shown in Figure 5.3.1 and 2 for spaceflight also are ideal for detection of the 2.6 MeV line from ^{232}U decays, typically found in trace amounts within enriched ^{235}U. Such an instrument could provide detection capability of ^{235}U at large distances on the order of 200 m, where lower energy lines would be attenuated by the atmosphere. This is a new capability, not provided by any existing detector system. Unlike the stronger 185 keV line, the 2.6 MeV line is difficult to shield and is an important component of a system to safeguard against nuclear terrorism.

Tracking promises to provide a major improvement in spatial resolution of γ-ray detectors through its unique ability to identify the location of the first interaction. This capability should find many applications. Among them, a tracking detector can efficiently and accurately identify and quantify the distribution of isotopes in a "plutonium button," a byproduct of reprocessing nuclear materials. This is important because of the need to keep a precise accounting of ^{239}Pu that is present throughout reprocessing steps. This application lends itself to a collimator configuration, or a Compton imager that can provide much higher γ-ray throughput, and therefore shorter exposure times. The techniques for this now in use are either slow, or prone to errors depending on the spatial distribution of materials.

Compton imaging can map the distribution of radioactivity in a waste barrel, suitcase, person or other object, or to map a physical site in a shorter time than traditional imaging techniques. Compton imaging is currently an underdeveloped technique due to the historical challenge of building adequate detectors. Recent progress in developing tracking detectors is certain to change this. The Compton imaging advantage is the ability to image without the use of a crude collimator, which has a low γ-ray throughput. Thus, Compton imaging potentially provides much high efficiency and requires shorter measurement interval.

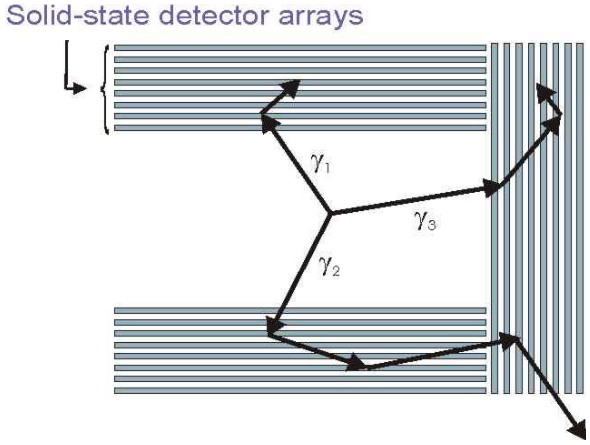


Figure 5.3.4 Medical Compton tracking concept. Decay site determined from Compton image of three simultaneous gamma rays.

Tracking is finding new applications in medical radiology, funded largely by NIH. Several groups have been developing Compton imagers over the last several decades with less sophisticated detectors. Modern tracking detectors provide the performance necessary to make Compton imaging useful in medicine. The advantages of tracking include an imaging capability for new isotopes and higher energies, higher throughput than is possible with a collimated imaging systems, and improvements in spatial resolution for PET imaging. Another novel application is the ability to use a new class of radioisotopes with multiple γ-ray decays (Fig. 5.3.4). A Compton image of a three-γ decay, for example, provides the precise three-dimensional position of the decay site on an event-by-event basis. It is not surprising that a large array of germanium tracking detectors (*e.g.* GRETA-like or planar strip detectors) would be a powerful new tool in nuclear medicine.

6 National R&D Plan for Tracking Detectors

The proposed national research and development plan for γ-ray tracking detectors is based on implementation of the recommendations of this committee as listed in the Executive Summary and chapter 7.

The Committee recommends highest priority to construction of GRETA, a 4π γ-ray tracking facility utilizing an array of closely packed coaxial Ge detectors. The R&D required for achieving this goal is summarized in the following table. Note that the proposed R&D on digital electronics, signal analysis and tracking development is applicable to all types of γ-ray tracking detectors.

GRETA 4π Array	Cost K$	FTE
Prototype cluster module [Funded]	750	1.0
2 cluster modules	1,000	2.0
Mechanical support	30	0.3
Digital electronics	225	2.5
Signal analysis	0	6.5
Tracking [Common]	0	5.5

Although the mechanical, digital electronics and some software development will require engineering support, performing measurements and developing algorithms can be done by physicists at universities and national laboratories.

The Committee supports further R&D on planar tracking detectors for complementary applications to nuclear physics. The R&D required for achieving this goal, assuming parallel development of digital electronics, signal analysis and tracking techniques, is:

Planar tracking detectors	Cost K$	FTE
Optimization of wafer and packaging	125	0.25
Stack of 4 planar detectors	500	0.75
Signal analysis	0	2.5
Tracking [See above]	0	0

A more detailed description of the proposed R&D is outlined for coaxial detectors in 6.1, planar detectors in 6.2, data processing in 6.3, digital electronics in 6.4, signal analysis in 6.5, and tracking algorithms in 6.6.

6.1 Coaxial Ge detectors

Further research and development is necessary to refine the design of the proposed national 4π γ-ray tracking detector array. The success in establishing the "proof of principle" with the 36-segment prototype has led to the next stage R&D, identified as the construction and full characterization of a GRETA cluster module, which consists of three crystals housed in a single cryostat. This will be followed by the final stage R&D necessary prior to construction of the national 4π γ-ray tracking detector array which is to prove full functionality of tracking across two or more tightly-packed cluster modules.

6.1.1 Three-crystal cluster module

The goal for testing of a cluster module is to confirm that it meets or exceeds the expected performance (based on the results obtained with the 36-segment prototype single Ge detector) both using radioactive sources and in-beam tests. Of particular importance in these tests is the tracking across adjacent detectors in a single cryostat.

The specifications for the cluster module require three tapered irregular, or regular, hexagonal crystals in a closely packed geometry. Based on the experience obtained with the prototype, each detector will have 36-fold segmentation and the following characteristics:

Characteristics of a single crystal central contact:

High Purity N-type Ge detector	
Minimum length of the crystal:	9 cm
Minimum diameter at back	8 cm
Operating temperature of the crystal:	90 K
Energy resolution: FWHM (keV):	1.2 @ 60 keV
	2.2 @ 1332 keV
Timing resolution: (FWHM) (ns):	5 @ 1332 keV

Characteristics of the segments:

Energy resolution: FWHM (keV):	1.2 @ 60 keV
	2.2 @ 1332keV
Timing resolution: FWHM (ns):	5 @ 1332 keV
Energy threshold:	<10 keV
Noise (for a bandwidth of 35 MHz):	~5 keV
Cross talk:	0.1%
3-dimensional position resolution:	~2 mm

An estimate (based on a quote from Eurisys Mesures) for the cost of a single cluster module is $750K for a cluster of regular hexagons. After delivery and successful acceptance tests, the first R&D milestone requires a full characterization of the module and detailed comparison with simulations. The performance for a single-interaction per segment at E_γ=0.662 MeV should be comparable to that obtained with the single GRETA prototype; i.e. a position resolution of ≤2 mm with an efficiency of about 85%. The module should be thoroughly tested in "realistic" in-beam conditions, and the Doppler reconstruction studied in detail. The module will be ordered in CY 2002.

It is estimated that the manpower required to test the cluster module will be 1 physicist-year based on experience gained in testing the prototype. The detectors will be fully instrumented on all channels, permitting performance studies in greater detail over the full volume of the detector. Variations

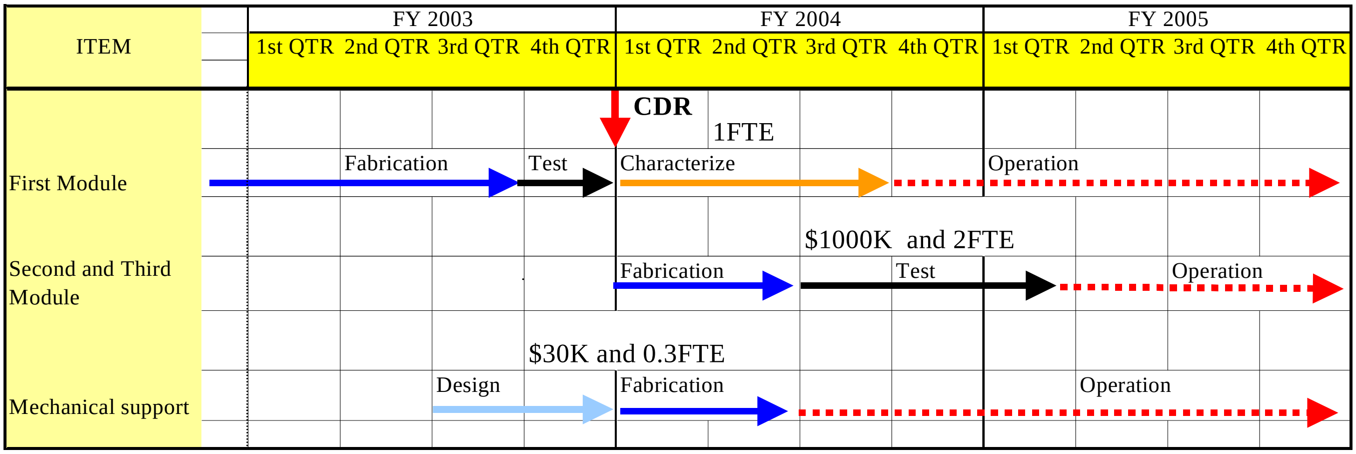


Figure 6.1: Research and development plan for coaxial tracking detectors

in pulse shape and calibration of the segments will be investigated. Questions of the variation in position and energy resolution within the detector volume, resolution of two nearby interactions, and detection threshold will be studied. These detectors will provide segment pulse-shape data similar to that which will be produced by the full GRETA array. These data will serve to develop deconvolution and tracking algorithms (discussed in sections 6.5 and 6.6), and provide direct confirmation of the over-all efficiency of the GRETA tracking modules.

6.1.2 Array of three cluster modules

The final R&D critical detector milestone is to prove the full functionality of an array of two and three tightly-packed cluster modules. The second and third cluster modules should have the irregular hexagonally shaped crystals plus vacuum envelope required for use in the final GRETA array. Extensive source and in-beam tests should confirm that the predicted performance is achieved, even when tracking between two separate cluster modules. Such an array will be, in itself, a powerful system for on-line experiments and can be used to benefit the nuclear physics research programs while developing the techniques for effective use of such tracking arrays in experimental programs.

Single vendor estimates place the cost of each cluster module at $500K. Following successful demonstration of the full functionality of the first cluster module, and after the geometry of the array is finalized, it is planned to purchase the second module in FY2003 and the third in FY2004. Testing of these two new detector clusters will require 1 physicist-year spread over two years.

It seems clear that the availability of a second vendor should both help to reduce this cost, but also to reduce the uncertainty in the delivery of the product. This could become an issue because of the large number of detectors required, and the possibility of a similar number of segmented coaxial detectors procured in Europe for AGATA or other programs. Negotiations with another vendor to develop and construct a GRETA cluster module should be a high priority.

Figure 6.1 summarizes the road map, costs and effort required for research and development of coaxial tracking detectors.

6.2 Planar detectors

The development roadmap and key milestones necessary to develop planar detectors described here are based on use of planar tracking detectors for applications to nuclear science, such as the Gamma Ray Box (GARBO) concept. Key issues, costs, and timeline questions addressed here are generally common to any application of planar detectors.

Most of the planar detector development prior to 1998 has been done by the NRL group in collaboration with Eurisys Mesures, in Europe. In the last three years the ANL group has worked with ORTEC, in the USA, to develop larger crystals (in area and thickness) and to work towards good energy resolution and position interpolation from image charges. Much has been learned from the first prototypes, with the ORTEC effort reaching maturity. Good detectors are now being produced. However, several technical issues still need to be addressed in order to realize a stacked planar detector. New funding is needed to address the following two R&D issues for planar detectors.

1) Continue to improve the performance and mechanical packaging of wafers

An important technical issue is replacement of the Li-implanted n-type contacts. This is the junction contact, so its characteristics are critical to the detector functionality. Lithium is mobile, so the inter-strip gaps need to be large, ~1 mm, and there are concerns that after annealing the strips may lose integrity. Lithium diffusion also produces significant dead layer over the contact surface with a thickness on the order 300-800 microns. Many new contact technologies are being explored to replace lithium, including amorphous

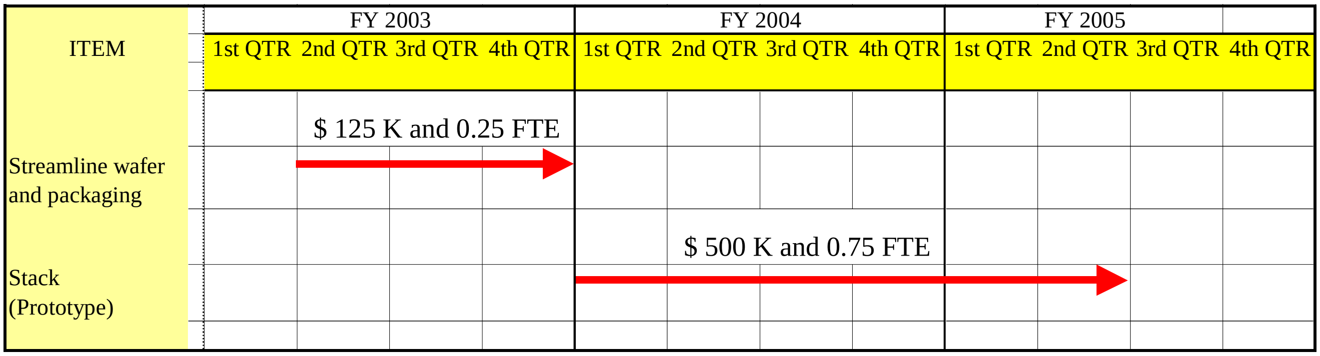


Figure 6.2: Research and development plan for planar tracking detectors

germanium, amorphous silicon, and phosphorus implantation. None of these alternative contacts are sufficiently established for commercial production, nor have they demonstrated sufficient durability to be deemed as reliable at this point. It is, furthermore, very important that future wafers have little or no passive material due to guard rings.

To date, all efforts at ANL and elsewhere have focused on studying the wafer performance. Cryostats have been much larger than needed, to minimize capacitive and cooling effects and to allow detector changes to be made without a cryostat rebuild. However, as the design becomes more refined, an efficiently packaged, streamlined detector needs to be procured. Funding is necessary to develop a new counter with non-lithium contacts, minimal passive material due to guard rings and compact packaging. This detector will constitute the building block for the future single-wafer or stacked planar detectors.

2) Stack of Planar Wafers.

A considerable thickness, ~8 cm of germanium is needed in order to efficiently detect γ-rays of >1 MeV. A stack of four 20 mm-thick wafers provides this stopping power, while providing accurate information on the location of the individual photon interactions. This detector would be a 90 mm x 90 mm x 80 mm active stack (with physical dimensions of roughly 90 mm x 90 mm x 95 mm, including 5 mm gaps between wafers). The plan would be to build a cryostat for a “4-stack” but initially load it with just two active wafers, to appraise performance, then reload with the second two wafers later. This detector would be enormously powerful for many applications. It would be a standalone Compton Camera, and would allow excellent imaging and tracking. It would have good position sensitivity with analog electronics, and exceptional possibilities with digital electronics. Monte Carlo simulations show that this detector would have an efficiency of 150%, compared to a 3”x3” NaI(Tl).

The optimal time to order is after a thin-contact alternative to the Li-contact has been perfected, and passive material due to guard ring is eliminated or significantly reduced. NRL is pursuing the contact issue with both ORTEC and LBNL, each using a different approach. ANL would expedite the ORTEC technology development through consultations and characterization of small test devices. A promising alternative is to commercialize the LBNL contact, possibly at ORTEC. A decision on how to proceed will become clear in the next several months. Figure 6.2 summarizes the roadmap, costs and manpower for R&D of planar detectors for nuclear science.

3) Large area planar detectors

The development of larger area planar detectors is another highly desirable task that would cost about $225K. Large area detectors are important for non-nuclear tracking applications, such as medical positron emission tomography (PET) scanners or Compton Cameras for environmental cleanup and for national security. However, bigger detectors would benefit nuclear applications too. As the dead material around the edge is fixed, so the active/passive ratio improves with size. If bigger wafers work well and are cost effective, they would be the optimum choice in most detector systems.

Scientists within the nuclear structure community are encouraged to reach out with their tracking technology and innovation to find applications outside of their traditional community. Cross-fertilization of ideas and disciplines has the promise of opening new lines of research, and with it new discoveries. Equally important, funding sources for tracking development outside of DOE exist, and these may provide valuable assistance in meeting our goals, containing costs, and assuring success.

6.3 Data processing for a 4π γ-ray tracking array

The concept of γ-ray tracking in a shell of closely packed Ge detectors requires processing schemes that can be implemented only by using a digital processing system. Figure 6.3 illustrates the envisioned data flow with data rates and processing requirements at different levels. This example is based on the GRETA implementation of a tracking array.

The first level (after analog filtering, gain and offset adjustment) consists of the waveform digitizers, which continu-

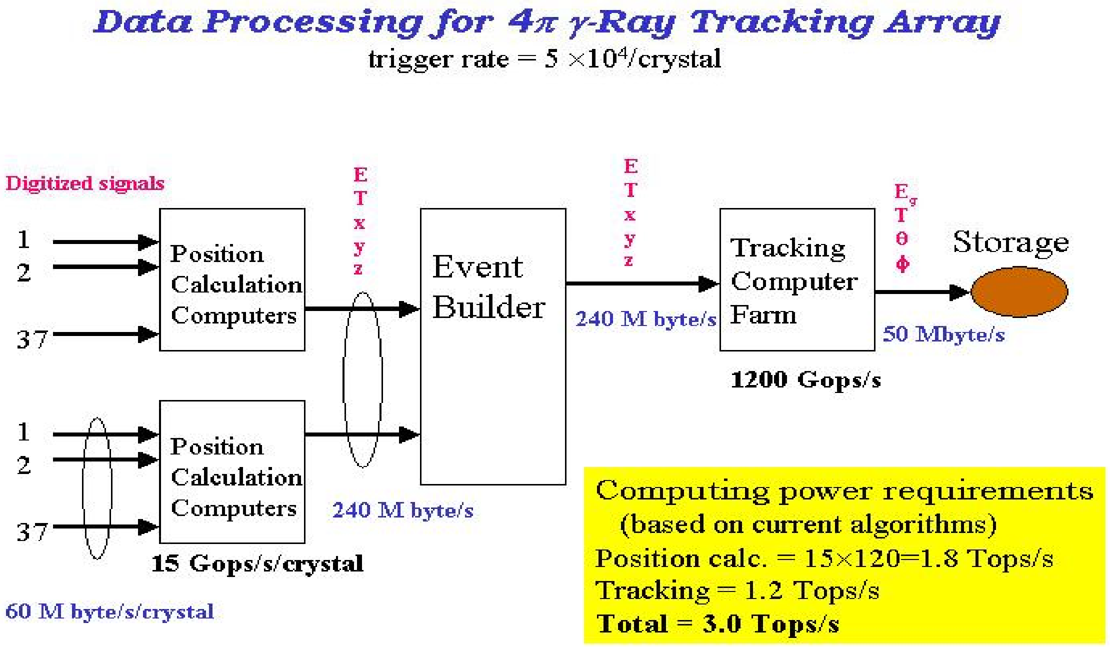


Figure 6.3: Schematics of data flow envisioned for a 4π gamma-ray tracking array.

ously digitize segment signals. The digitizer boards that are under development now have a 12bit resolution and a sampling rate of 100MHz, as described in 6.4. Assuming 200 samples (2μs) to determine the energy of the interactions in one segment, one obtains 300 Bytes per event per segment to be processed. Furthermore, assuming (i) a trigger rate of 50kHz for each detector,[*] (ii) that γ rays deposit their energies on the average in two segments, and (iii) that it is necessary to process transient signals of adjacent segments and the central channel of the crystal, results in processing 13 segments at a data rate of 195 MB/s per crystal (the total data rate at this point is 120x195MB/s=23.5TB/s). The second stage consists of processing units (such as FPGAs to provide sufficient I/O capability) for trigger implementations but also to determine parameters such as energy, time, and easily accessible position parameters.

The next stage in the processing chain consists of the signal decomposition calculations. Only 50 samples per segment are needed to cover the maximum rise time of the charge signals. Therefore, after determining the energy, time and simple position information and adding these parameters to the data flow one ends up with about 60MB/s per crystal. The main part of the decomposition calculation represents the determination of the χ^2 for each iteration step of the minimization procedure. Assuming two segments hit, both containing two interactions, one can estimate about 3x10^{5} floating point operations based on the currently used SQP technique. For an event rate of 50kHz per crystal one needs 15x10^{9} ops or 15Gops. The data rate after the decomposition calculation can be estimated to be 2.2MB/s per crystal (assuming the energy and time are from the central channel, plus energy, time, and x, y, z positions from two segments each with two interaction points.). 120 crystals result in a total data rate of about 240MB/s at this stage.

The “locally” running decomposition calculations are running in parallel, with a total processing power of 120 x 15Gops = 1.8Tops. The event builder combines the distributed information of the interactions according to time and feeds it into the tracking processor. Based on the currently used tracking algorithm 4 Mops is required to process one event. Assuming a maximum rate of 300 kHz for M=25 events, 1200 Gops of processing power is required for tracking. At this stage one can envision a farm of computers to handle the tracking task. Finally, one can estimate a data rate of 50-60MB/s, which has to be stored externally. These data contain energy, time, position, and potentially other information such as polarization of the identified γ rays.

6.4 Digital electronics

Development of digital electronics must occur in parallel with the detector development. The first critical milestone is completion and successful use of an 8-channel digital signal-processing unit with a tracking detector. The second and

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[*] A count rate of 50kHz can be expected assuming an event rate of 3x10^{5}/s (beam current of 3pnA, target thickness of 1mg/cm^{2}, and reaction cross section of 1b), a γ-ray multiplicity of 25 and an efficiency of 80% (300x10^{5}/s x 25 x 0.8 / 120 det = 50kHz/det).

final critical digital electronics milestone will be the construction of a 40-channel board and full integration tests with the array of 3 cluster modules, as well as with a planar stack.

While some of these developments are being pursued, new funding is vital for rapid progress to be made. Plans are outlined for keeping electronic developments in phase with detector progress.

6.4.1 ANL Analog/Digital commercial setup

The ANL group currently is developing a system of 64 high-resolution analog channels to instrument two HpGeDSSDs for “tracking”, Compton Camera, and “PET-scanner” modes. This phase is mostly funded, and should be in place before the second quarter of FY2003.

The addition of 32 channels of 100MHz flash ADCs (e.g. SIS3300 digital processor) for digital capture of preamplifier pulses will result in a very useful and portable “analog-digital’ setup than can be shared among several institutions interested in developing tracking techniques. Comparison of analog and digital reconstruction can be of importance to give directly the reconstruction efficiency, and the improvement in position resolution. This part of the project is not yet completely funded. Funds should be allocated to purchase a set of 5 SIS VME boards, (total cost of ~$25K) to implement the project by the end of CY2002. This will be a powerful system available immediately for work on coaxial and planar detector development in addition to system programming development at LBNL, ANL, MSU, ORNL, and SUNY-Stony Brook.

6.4.2 LBNL 8 channel card

The first phase of digital signal processing electronics development will be the design and construction of an 8 channel, 12-bit, 100 MHz flash-ADC board suitable to instrument the GRETA module array. This board was designed to meet the more general requirements for signal processing for the low-energy nuclear physics community, and in particular it can be used to instrument the planar setup at ANL. In addition to simple waveform digitization, this board will be capable of digital signal processing using a large FPGA with functionality comparable to standard analog electronics.

The following functions will be included on the phase 1 card:

1) Leading edge discriminator
2) Constant fraction discriminator
3) Energy algorithm

Three trigger modes will be provided to allow for internal triggering using the digital leading edge discriminator, external triggering (10 μsec maximum latency) and internal triggering with external validation. Each channel will be individually gated and the internal leading edge discriminator for each channel will be accessible to allow for integration with external detectors.

The board will be implemented using VME, to make it compatible with existing instrumentation and data acquisition systems. The individual board readout rate will be 8 MB/s using the VME back plane that allows for a sustained counting rate of 10 kHz with all channels firing.

Design of the phase-1 board began in Jan. 2002 and testing of the first prototype will begin in July 2002. Testing of the second prototype card with all digital processing in place will begin in September 2002 with completion expected December 2002. This effort of 1.5 FTE currently is supported by Berkeley LDRD funds.

Following the successful tests of the second 8-channel prototype, 5 units will be fabricated and distributed to the community for further tests with other types of detectors. DOE money for this fabrication is already available ($30K). In order to instrument the array of three cluster modules, 360 channels (3x(3x40)) are needed. At a cost of ~$600 per channel, this will require ~$200K plus 1FTE to oversee the project.

While, as mentioned above, some commercial options are already available, they are not as flexible as one would desire, in particular with regards to the trigger of the board. Moreover, the experience gained in the design and fabrication of this 8-channel board will be very important in the development of the next phase.

6.4.3 40 channel card

The second phase of the project will involve the design and construction of a 40-channel board. These boards will be equally valuable for HpGeDSSD development as well as for coaxial tracking detectors. In particular, this development is required once more than three GRETA detector modules are acquired. This board differs from the 8-channel board in both channel density and by the amount of on-board processing. As all channels from a given detector are on a single board, triggering decisions involving the detector as a whole (as opposed to individual segments) can be made on the board reducing the data forwarded to the data acquisition system.

Partial signal decomposition and event filtering will be performed on the card requiring processing resources beyond that of the FPGAs employed on the phase-I board. The level of this processing and its implementation will be determined by the tests to be carried out in the next two years, both with the GRETA module and the planar detectors. Given the high data output of these cards, readout will be performed by one of the emerging commercial high-speed serial link standards for I/O rather then a bus-based architecture used for the phase I board.

Design and construction of the phase-II boards could begin in FY 2003 and should involve collaboration between the electronic groups at Argonne and Berkeley. Informal discussions indicate this development may take 1.5 FTE over a

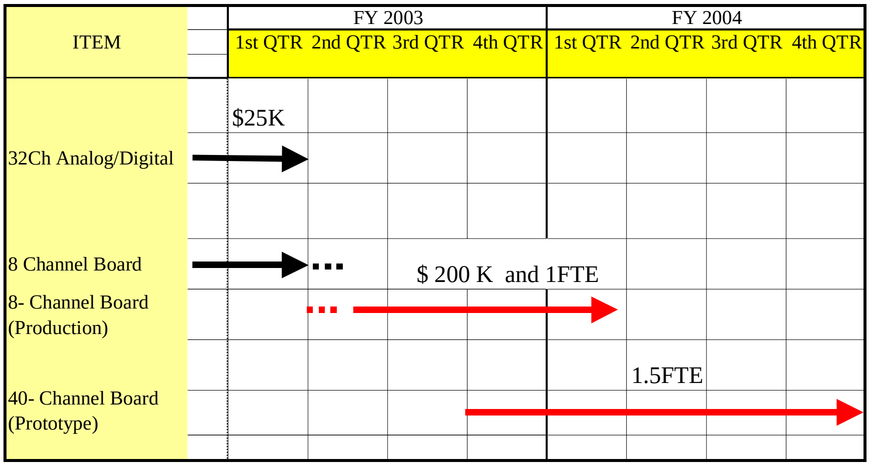

Figure 6.4: Research and development plan for the digital electronic boards

period of approximately one year, so if funded in FY2004, the first units could be operational by the end of 2004. The schedule, cost and manpower are shown in Fig. 6.4.

6.5 Signal analysis

The energies and three-dimensional positions of individual γ-ray interactions in two-dimensionally segmented HPGe detectors can be determined by using digital signal processing with a high sampling rate and high resolution. This signal decomposition principle applies both to two-dimensionally segmented coaxial detectors as well as to segmented planar DSSD detectors. Pulse shape analysis is required to determine the radial position for the coaxial geometry and the depth position for the planar geometry. In addition to the radial or depth information, pulse-shape analysis of transient charge signals can significantly increase the position resolution beyond the segment dimensions in the two complementary segmented directions. This improved position resolution from signal analysis allows use of fewer segments that reduces electronics channels, and concomitant heat load at the preamplifier stage. However, the number of segments has to be optimized in that use of fewer segments results in an increased number of interactions per segment, which increases the complexity in decomposing the measured signals to extract the information on these multiple interactions.

Advances have been made over the last several years in use of pulse-shape analysis for two-dimensionally segmented HPGe detectors both for the coaxial geometry (GRETA, MARS, MINIBALL and EXOGAM) as well as for the planar geometry (LBNL, ANL, XIA, NRL). For the planar DSSD geometry, the combination of segmentation and pulse-shape analysis has been used to extract the depth (z) information of the γ-ray interactions. The complementary x,y coordinates have been extracted by strip identification, as well as by using the image charges on adjacent strips, providing sub-strip resolution.

The signal analysis discussed here deals with necessary R&D efforts which should be addressed during the pre-conceptual and during the conceptual design phase. The main objective is the availability and the implementation of stable algorithms, which can be used for physics experiments with the array of three GRETA cluster modules. Algorithms and implementations should be open to improvements during the design and the construction phase of the full array.

6.5.1 Coaxial Detectors:

For the coaxial geometry, the pulse-shape analysis has been used to extract all three dimensions for location of γ ray interactions. A full analysis procedure has been developed to simulate signal shapes and to process both simulated and measured signal shapes. The analysis of radioactive source data (^{137}Cs, ^{60}Co ^{152}Eu) to determine energy spectra of the 36-fold segmented GRETA prototype detector is nearly complete. Comparison between the calculated and measured spectra obtained with, and without, tracking shows the degree of understanding of the measured signals that allows reliable determination of the performance of the current decomposition and tracking algorithms. Furthermore, it allows study of failure modes that is crucial for improving and refining the signal processing algorithms. Data have been acquired for different source locations to show the imaging capability of the prototype GRETA detector. In addition to radioactive source data, in-beam data were measured to investigate both the tracking capability and the first-hit recognition capability of the signal decomposition and tracking concept. The analysis of these data is in progress.

While the results so far look very promising, some issues still remain to be addressed using the single GRETA prototype detector to show full functionality of the proposed γ-ray tracking concept.

- It is crucial that the analyses of the currently available radioactive source and in-beam data, in terms of energy spectra and image generation, be pursued with highest priority. Failure modes will have to be addressed and improvements implemented if full functionality is not achieved.
- The current parameterization of signal shapes is based on "coincidence"-calibration measurements of only 3 segments. More segments have to be measured to increase the accuracy of decomposition procedure. Perform "key"-imaging experiments to measure collimator profiles such as keys or simply holes throughout the detector
- Crystal orientation effects, which change the direction of the charge carrier, have to be implemented to optimize the signal-shape parameterization. An analytical description for the transport for electrons can be derived but it is more complicated for transport of holes.
- Study the impact of neutron damage on signal shapes.
- Perform additional in-beam experiments with better beam spot definition than used for the previous in-beam experiments. Also run the prototype detector as an auxiliary detector in coincidence with one hemisphere of Gammasphere.
- Develop more accurate and faster minimization schemes for signal decomposition.
- Finalize segmentation layout, which optimizes trade-off between complexity of processing and number of channels.

In the following we summarize the manpower requirements for the decomposition of signals of the GRETA efforts to provide reliable position and energy information of individual γ-ray interactions potentially in real time. These efforts include measurements and calculations regarding the available GRETA prototype detector as well as the development of new and faster minimization procedures and their implementation:

Roadmap and required manpower for coaxial detectors:

Based on the above discussion the following needs and manpower requirements are identified for the signal decomposition procedure for the GRETA coaxial detector concept:

Analyze source and in-beam data	*1.5 FTE*
Develop improved and fast minimization procedures	*2 FTE*
Complete signal-shape parameterization including crystal orientation effects	*1 FTE*
Implementation of decomposition algorithm into hardware	*2 FTE*

6.5.2 Planar detectors

The focus of the Argonne effort has been the production of large area DSSD detectors suitable for the GARBO instrument. These detectors have a 5 mm pitch, thus the energy and position information of each individual interaction requires signal shape analysis, similar to what is done for the-coaxial GRETA design. Signal shape analysis from the GARBO prototype detector look very promising, as indicated in chapter 5.2. These measurements should be pursued with highest priority due to the importance of the signal-shape analysis in the GARBO detectors. In addition, effects on charge collection properties due to segmentation of the Li-contact or the use of a guard ring have to be studied. It should be possible to eliminate lithium contacts and the guard ring with further detector development. Radioactive source measurements as well as in-beam measurements have to be performed to obtain energy spectra, with and without employing signal decomposition, tracking, and imaging. A prerequisite for these measurements is the ability to digitize potentially all channels. Experiments employing analog electronics to obtain timing and energy for individual strips can be used for nuclear physics experiments. However γ-ray tracking will not be efficient employing 5x5x20 mm^3 voxels, and thus signal decomposition is necessary to fully exploit the tracking capabilities of planar detectors.

Remaining issues for planar detectors:

- Position resolution and its variation with depth for one and multiple interactions.
- Effect of segmentation on charge collection properties
- Effect of guard ring on charge collection properties
- Source measurements to determine efficiency and peak-to-total ratio as a function of energy, with and without tracking
- Image measurements
- In-beam measurements

Roadmap and required manpower for planar detectors:

The following issues have to be addressed:

Position resolution measurements	*1 FTE*
Charge collection properties	*0.5 FTE*
Radioactive source measurements for spectrum generation and imaging as well as in-beam measurements	*1 FTE*

The remaining issues regarding the signals analysis and optimization should be part of the common γ-ray tracking effort for all detector types.

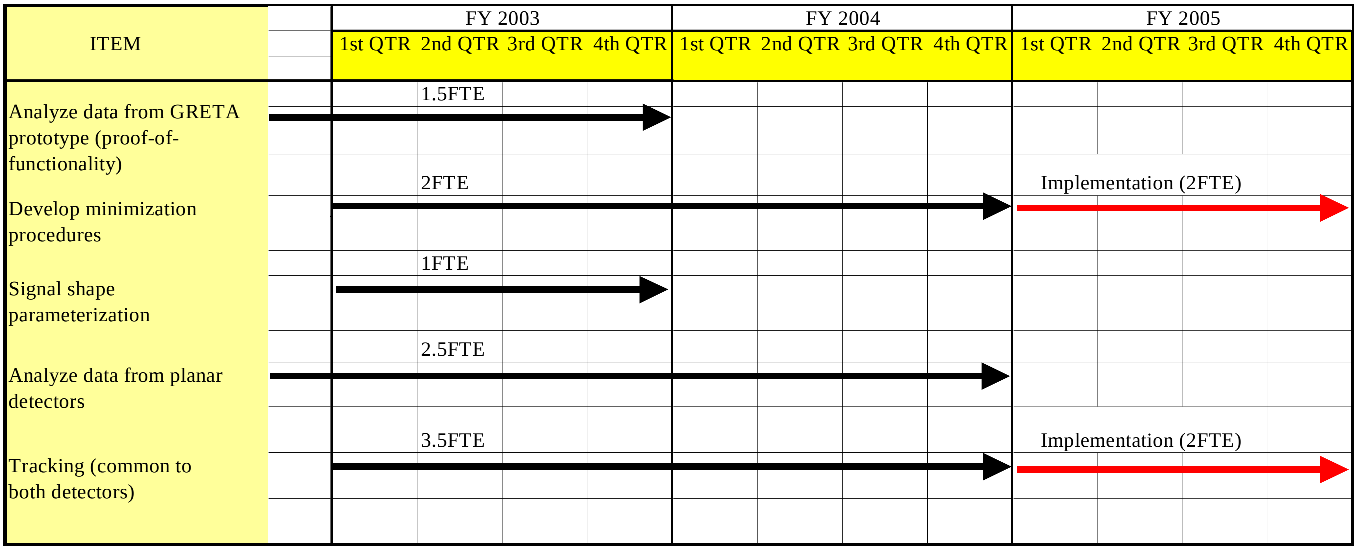

Figure 6.5: Research and development plan for signal processing and tracking

6.6 Tracking

Tracking algorithms convert the position and energy information, determined by the signal decomposition procedure, into energy and angle information for the incident γ ray. Not only can γ rays be identified and separated but also the γ-ray scattering sequence can be determined. Using the positions of the first interactions it is possible to correct the Doppler shift, to determine the linear polarization, and to determine the incident angle of the γ ray for point sources.

Roadmap and required manpower:

While there still are important milestones to be achieved in the development of faster and more accurate signal decomposition procedures, the available tracking algorithm is already reliable and can be implemented for real-time applications, although only using powerful computer hardware that currently is expensive. However, several options can be explored in more detail:

Extend and improve current “forward” Compton tracking algorithm	*2 FTE*
Evaluate pair-tracking algorithm in more detail	*1 FTE*

For example, implement different ordering schemes of individual interactions such as use of minimum spanning trees. So far, ordering, as well as clustering, is performed based on the angle coordinates. It will be useful to incorporate the likelihood of the traveled distance into the figure-of-merit for cluster evaluation.

Study and evaluate back-tracking algorithm, in particular as a function of noise	*0.5 FTE*
Implementation of tracking algorithm into hardware	*2 FTE*

Figure 6.5 summarizes the road map, costs and effort required for research and development of signal processing and tracking.

7 Committee Recommendations and Observations

The charge to the Gamma-ray Tracking Coordinating Committee includes three elements, namely:

- *Develop the various physics justifications for γ-ray tracking and establish the performance goals that are required in each area.*
- *Formulate a national R&D plan for γ-ray tracking detectors.*
- *Examine the currents efforts in γ-ray tracking that are underway in the United States and provide the Department of Energy with advice about how they should proceed.*

The first charge was answered in chapters 3 and 4 of this report. Chapter 5 examines current efforts in γ ray tracking underway in the United States. The Committee recommendations are described in the Executive Summary while the proposed national R&D plan based on these recommendations was given in chapter 6. A summary of the five recommendations and two observations is as follows:

Recommendations:

1 **A 4π Gamma-Ray tracking facility is an important new initiative within the 2002 NSAC Long Range Plan. This committee unanimously recommends a shell of closely packed coaxial Ge-detectors as outlined in the GRETA conceptual design for this 4π γ-ray tracking facility. We strongly recommend that DOE support this effort with highest priority**

2 **R&D necessary to demonstrate the full functionality of this detector was identified and has to be addressed immediately. We note that a substantial fraction of this R&D effort is manpower that must be supported.**

3 **The R&D phase, the subsequent final design, and the construction of GRETA should continue to be a community effort; in particular, it should involve significant participation by the low energy nuclear physics national laboratories and universities.**

4 **Tracking with planar detectors is of interest to the nuclear science community and has a wide range of applications outside of nuclear physics. R&D efforts in this direction should be supported as part of the drive to develop tracking, as most of the electronics and software challenges are common to all tracking detectors.**

5 **Gammasphere continues to be the premier national γ-ray facility until GRETA becomes operational. This research facility must be supported to sustain the vitality of the field.**

Observations:

1 GRETA construction costs

The GRTCC finds that there are compelling scientific arguments for GRETA, and strongly recommends rapid implementation of this project. It is important to proceed with procurement of the GRETA module and subsequent testing in order to better identify program cost and risk analysis. In addition the GRTCC encourages the GRETA Steering Committee to continue to study ways to reduce the projected cost.

2 Other applications of Gamma-ray Tracking

Tracking has important applications for science, technology, medicine, and societal issues such as homeland security. This report has focused on coordination for applications of tracking detectors in nuclear physics. However, it will be useful to coordinate development of γ-ray tracking in this much broader venue.

Appendix A: Committee Membership

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kvetter@llnl.gov

Appendix B: Appointment Letter

21 January 2002

Dear XXXXXX,

We would like to ask you to be a member of the Gamma-Ray Tracking Coordinating Committee. This committee is being set up by our three laboratories at the request of the DOE Division of Nuclear Physics to promote the development of gamma-ray tracking detector technology in nuclear structure research. We would like you to help organize the gamma-ray tracking community to provide widespread support and an effective plan for the future. The DOE Division of Nuclear Physics would also like to use this committee to obtain timely advice on issues and proposals in gamma-ray tracking. The full membership of the committee will be:

Cyrus Baktash	Oak Ridge National Laboratory
Doug Cline (chair)	University of Rochester
Teng Lek Khoo	Argonne National Laboratory
Richard Kroeger	Naval Research Laboratory
Augusto Macchiavelli	Lawrence Berkeley National Laboratory
Mark Riley	Florida State University
Michael Thoennessen	Michigan State University
Kai Vetter	Lawrence Livermore National Laboratory

A draft charge for the committee is attached. We expect this committee to take a broad role in the development of gamma-ray tracking detectors in this country. In particular there are three elements of the charge that should be addressed in a timely manner.

- Develop the various physics justifications for gamma-ray tracking and establish the performance goals that are required in each area.
- Formulate a national R&D plan for gamma-ray tracking detectors.
- Examine the currents efforts in gamma-ray tracking that are underway in the United States and provide the Department of Energy with advice about how they should proceed.

Your charge is focused on gamma-ray tracking detector technology in nuclear structure research. However the committee should take into account progress in other areas of science.

We would like to have preliminary answers to the first set of issues by 1 May 2002. DOE may ask you for advice on a shorter time scale.

We appreciate your willingness to serve on this important committee. Gamma-ray tracking has broad support in the community as evidenced by its significant place in the 2001 NSAC Long Range Planning deliberations. We believe it will have a major impact on progress in nuclear structure research and want to do everything we can to support it.

Sincerely,

Fred E. Bertrand, Jr	Donald F. Geesaman	Lee S. Schroeder
Director, Physics Division	Director, Physics Division	Director, Nuclear Science Division
Oak Ridge National Laboratory	Argonne National Laboratory	Lawrence Berkeley National Laboratory

Appendix C: The Charge

Mission: Promote development of gamma-ray tracking detector technology in nuclear structure.

1) PROMOTE DEVELOPMENT OF GAMMA-RAY TRACKING TECHNOLOGY BOTH WITHIN AND OUTSIDE THE NUCLEAR STRUCTURE COMMUNITY
The primary goal of the Coordinating Committee is to coordinate and promote the development, and use, of gamma-ray tracking detector technology for the benefit of nuclear scientific research, and to identify other potential applications. This requires the Coordinating Committee to promote vigorously development of gamma-ray tracking technology within the nuclear structure community, to the wider nuclear science community, NSAC, NSF, and DOE. To achieve this goal the Coordinating Committee will help organize the gamma-ray tracking user community to provide widespread support.

2) DEFINE PHYSICS JUSTIFICATION AND GOALS. DETERMINE PERFORMANCE GOALS
The physics justification for use of gamma-ray tracking detectors will be updated when scientific and technical developments in nuclear science, or the Long Range Plan for Nuclear Science, justify a revision. The participation in scientific updates should involve a broad and large representation of the projected user base including theoretical support. The justification should include physics opportunities at stable beam facilities, present radioactive beam facilities based on ISOL and fragmentation methods as well as the future RIA facility. Based on the physics justification, the Coordinating Committee should work with the community to define the performance goals of required gamma-ray tracking detectors. It is important that the whole community feel that it has participated fully in the physics justification and development of the performance goals.

3) PROVIDE OVERVIEW AND ADVICE ON GAMMA-RAY TRACKING DETECTOR DEVELOPMENT PROJECTS TO THE NUCLEAR STRUCTURE COMMUNITY AND FUNDING AGENCIES.
The Coordinating Committee will work with the nuclear community, individual development projects, and the funding agencies, to provide advice and assistance in development of gamma-ray tracking detectors in nuclear science. The Coordinating Committee will organize workshops and reviews that address the science and technical issues associated with development and use of gamma-ray tracking detectors.

4) ASSEMBLE AND COORDINATE A R&D PLAN
The Coordinating Committee shall formulate an R&D plan for gamma-ray tracking detectors. In coordination with specific detector groups and R&D groups, it shall facilitate formation of technical committees of engineers and scientists, as needed, to develop and design general technical capabilities required for gamma-ray tracking detectors. It will encourage and enlist participation of the community at every level.

5) PROMOTE AND COORDINATE DEVELOPMENT OF SPECIFIC DETECTORS.
The Coordinating Committee shall monitor development of individual detector projects exploiting the gamma-ray tracking principle. . The Committee also will coordinate, and provide advice to these detector development projects. The Committee shall facilitate the sharing of information and technology among the individual detector projects.

6) COORDINATING COMMITTEE COMPOSITION.
The Coordinating Committee shall include a balanced representation from national laboratories and universities, and groups involved in major gamma-ray tracking detector projects exploiting gamma ray tracking technology. Promoting this development of tracking technology requires representation throughout the community by well established and respected members of the nuclear community who can effectively communicate the importance of this technology both to their colleagues, review committees and agencies. Appointments to the Gamma-ray Tracking Coordinating Committee will be for three years, staggered to ensure continuity. The Coordinating Committee, with input from the DOE, NSF, and the community, will nominate prospective Committee members to the Selection Committee comprising Divisional Directors of the appropriate nuclear science divisions at Argonne, Oak Ridge and LBNL National Laboratories.

Appendix D: Agenda for GRTCC Fact-Finding Meeting

Argonne National Laboratory, PHY/203, R-150

Friday, 29 March 2002

8:30 - 8:40	Introduction (Doug Cline)

1) **Fact-Finding for Gamma-Ray Tracking Detector Initiatives** (Cyrus Baktash)
Status, performance goals, road map, major milestones, R&D needs, cost profile and total cost.

1a) Coaxial Detector Projects:

8:40 - 9:40	GRETA (I.-Y. Lee, *et al.*)
9:40 -10:30	AGATA (Dino Bazzacco)
10:30 -11:00	Break
11:00 -11:30	MSU Array (Michael Thoennessen)

1b) Planar Detector Projects:

11:30 -12:30	GARBO (Kim Lister, *et al.*)
12:30 - 1:30	Lunch – ANL Cafeteria
1:30 - 2:00	NRL (Richard Kroeger)
2:00 - 2:30	Auxiliary detector requirements (Demetrios Sarantites)

2) **Performance Goals** (Teng Lek Khoo)

2:30 - 3:15	Scientific and technical performance goals. Define requirements.
3:15 - 3:45	Break

3) **Technical** (Augusto Macchiavelli)
R&D needs, milestones, collaboration opportunities, manufacturing capability, etc.

3:45 - 4:30	Ge Detectors (Richard Kroeger)
4:30 - 5:15	Deconvolution (Kai Vetter)
5:15 - 6:00	Tracking (Kai Vetter)
6:00 - 6:45	Electronics (Dave Radford)
7:30	Dinner – ANL Guest House

Saturday, 30 March 2002

4) **National Tracking Detector Program** (Mark Riley)

8:30 -10:00	Formulate a national gamma-ray tracking program with roadmap, milestones, and cost profile. Discuss maintaining current major gamma-ray detector arrays such as Gammasphere for the nuclear research program during development of tracking arrays. Strategies and balance between national and smaller dedicated facilities.
10:00 -10:30	Break
10:30 -Noon	**Open Discussion and Conclusions** (Doug Cline) Cyrus Baktash, Teng Lek Khoo, Augusto Macchiavelli, and Mark Riley
Noon	End of General Meeting
12:15 - 3:00	GRTCC Closed Meeting Develop committee recommendations, and assign writing responsibilities.

Appendix E: Attendees of GRTCC Fact-finding Meeting

Baktash, Cyrus	ORNL	Oak Ridge, TN 37831-6371
Bazzaco, Dino	INFN	I-35131 Padova, Italy
Beausang, Con	Yale	New Haven, CT 06520-8124
Carpenter, Mike	ANL	Argonne, IL 60439
Cline, Doug	Univ. of Rochester	Rochester, NY 14627
Fallon, Paul	LBNL	Berkeley, CA 94720
Khoo, Teng Lek	ANL	Argonne, IL 60439
Kroeger, Richard	Naval Research Lab.	Washington, DC 20375
Lee, I-Yang	LBNL	Berkeley, CA 94720
Lister, Kim	ANL	Argonne, IL 60439
Macchiavelli, Augusto	LBNL	Berkeley, CA 94720
Moore, Frank	ANL	Argonne, IL 60439
Radford, David	ORNL	Oak Ridge, TN 37831-6371
Reviol, Walter	Washington Univ.	St. Louis, MO 63130
Riley, Mark	Florida State Univ.	Tallahassee, FL 32306
Sarantites, Demetrios	Washington Univ.	St. Louis, MO 63130
Tabor, Sam	Florida State Univ.	Tallahassee, FL 32306
Thoennessen, Michael	MSU/NSCL	East Lansing, MI 48824
Vetter, Kai	LLNL	Livermore, CA 94550

Appendix F: Acknowledgments

The Gamma-Ray Tracking Coordinating Committee acknowledges the contributions provided by Drs. Dino Bazzacco, Con Beausang, Mike Carpenter, Mario Cromaz, Paul Fallon, Thomas Glasmacher, I-Yang Lee, Kim Lister, Frank Moore, David Radford, Walter Reviol, Demetrios Sarantites, Michael Smith, Sam Tabor, and Paul Vetter.

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