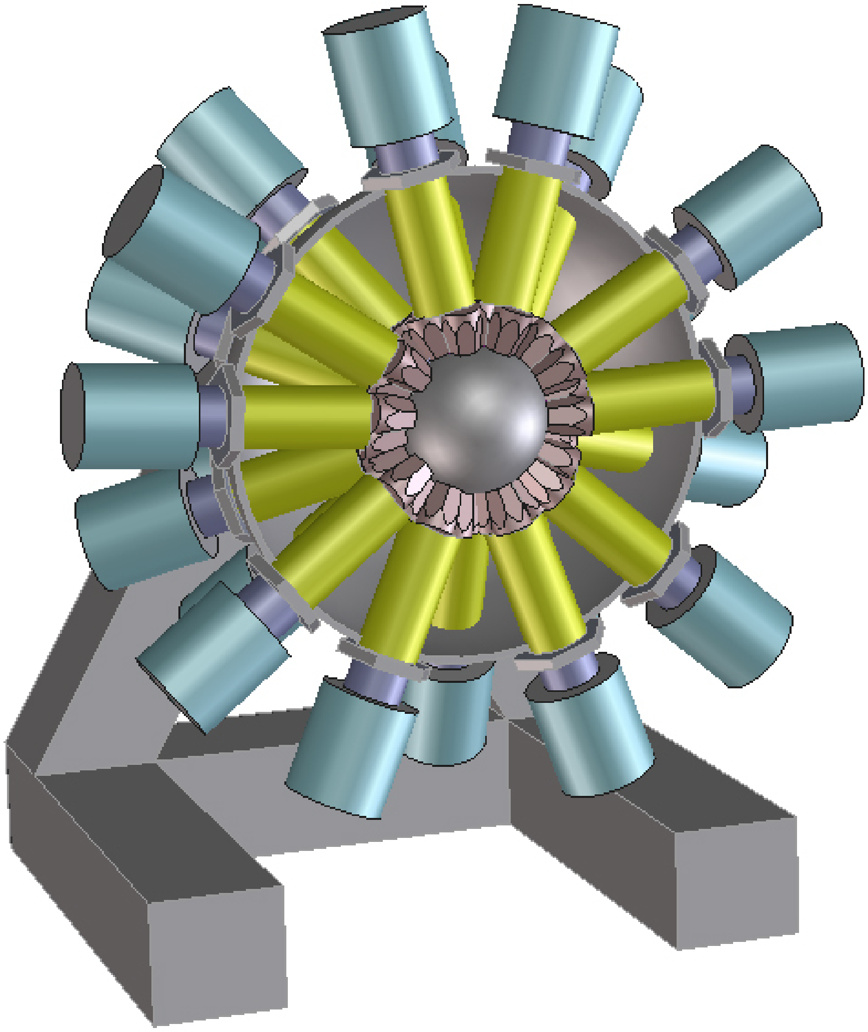
The Gamma-Ray Energy Tracking Array
(GRETA)



Material for the February 15, 2003, Meeting of the NSAC Subcommittee on Science and Technical Readiness

Prepared by the GRETA Steering Committee

The Gamma-Ray Energy Tracking Array (GRETA)

Material for the February 15, 2003, meeting of the NSAC Subcommittee on Science and Technical Readiness

The 2002 Long Range Plan for Nuclear Science [1] recognizes that "the detection of gamma-ray emission from excited states in nuclei plays a vital and ubiquitous role in nuclear science" and that a "4π detector shell consisting of electrically segmented germanium crystals […] promises to revolutionize gamma-ray detector design and will enable a new class of high-resolution gamma-ray experiments at several existing stable- and radioactive beam facilities, as well as at RIA."

The Gamma-Ray Energy Tracking Array (GRETA) [2,3] is the most advanced proposed detector to implement this new concept for photon detection. GRETA's sensitivity will exceed that of the best operating photon detector arrays by a factor of 100-1000. GRETA has evolved from a conceptual design study–initiated almost a decade ago–to a state where the pre-construction review can be initiated.

The Science of GRETA

Experiments with GRETA will address with unprecedented sensitivity crucial questions identified in the 2002 Long Range Plan in several areas of nuclear science:

- "How do weak binding and extreme proton-to-neutron asymmetries affect nuclear properties?" [4]
- "How do the properties of nuclei evolve with changes in proton and neutron number, excitation energy and angular momentum?" [4]
- "What are the origins of the elements necessary for life?" [5]

In the following we give a few illustrations of the major impact GRETA will have towards answering these crucial questions at existing stable and exotic beam facilities as well as planned facilities such as RIA.

Nuclei far from stability

Understanding the structure of marginally bound nuclear systems near the nuclear driplines will focus on obtaining a detailed picture of the wave functions of low-lying states, and the ground states themselves. The most interesting nuclei are usually those furthest from stability, which are most difficult to produce and have the smallest yields. Experiments must be as efficient and selective as possible, to differentiate between the states of interest and copious decays from other sources.

Do dramatic changes in shell structure occur far from stability?

Single-particle and pairing degrees of freedom play a pivotal role in nuclear structure. Nuclear shell structure is expected to change dramatically when approaching the extremes of isospin. Such alterations 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 behavior in the tail of the nuclear wavefunction that will lead to nuclear Josephson effects such as strongly enhanced pair transfer cross sections and diabolical pair transfer. GRETA 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.

What is the detailed wavefunction for exotic nuclei?

For the most exotic nuclei, direct reactions with fast beams and gamma-ray detection are a powerful tool that allows the determination of orbital angular momentum quantum numbers and spectroscopic factors for reactions leading to individual excited states. Nucleon-knockout reactions can be used to study states that are reached by removing a nucleon from any projectile produced by in-beam fragmentation. High-resolution in-beam γ-ray spectroscopy is possible with GRETA where 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. Experiments employing γ-ray detection to indicate decays of bound excited 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.

How do collective shapes evolve in nuclei?

States with very different collectivity can coexist in individual nuclei, and collective correlations evolve as a function of isospin and temperature. Detailed studies of such effects 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 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. In-beam γ-ray spectroscopy using GRETA with both intermediate-energy and re-accelerated radioactive beams will measure the energy and quadrupole (E2) transition strength to the first excited 2^+ states along long isotopic chains elucidating the evolution of collectivity with isospin.

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. The high efficiency and granularity of GRETA makes such measurement possible by comparing two experimental probes (for example, hadronic and electromagnetic probes) with different sensitivities to proton and neutron contributions.

Nuclei at the limits of angular momentum and excitation energy

What are the new symmetries, shapes and excitation modes at the limits of angular momentum and excitation energy?

Other fundamental questions in nuclear physics involve the limits of nuclear existence as spin and excitation energy are increased, and identifying the symmetries that are responsible for shell effects that add to nuclear stability. 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. GRETA is needed to discover and characterize such important but very weak ultra-high spin signals among a large fission background.

Does proton-neutron pairing 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. GRETA 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 to break 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 unclear. 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.

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.

The origin of the elements

Nuclear astrophysics is concerned with the impact of the microscopic aspects of nuclear structure and reactions on the macroscopic phenomena we observe in our universe and the synthesis of the elements in the cosmos. There are a number of measurements in the area of nuclear astrophysics that will benefit greatly from GRETA.

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.

Direct measurements of reactions such as $^{12}C(\alpha,\gamma)^{16}O$ or $^{14}N(p,\gamma)^{15}O$ at very low energies are crucial, 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 GRETA could reject the majority of the background γ rays, while giving a very high efficiency for detecting the capture γ rays of interest. There are probably more than 30 measurements that could benefit from this approach.

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. GRETA can help reduce the background 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. Of the order of 20 measurements can benefit from this technology.

Nuclear Structure measurements of astrophysical relevance

This category of experiments includes specific measurements for the indirect determination of important reaction rates where direct measurements are impossible. 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-driplines, where structure information is both greatly lacking and is very important for studies of stellar explosions. The high efficiency of GRETA will extend the scientific reach of any exotic beam facility several mass units closer to the drip line than possible with current detectors. There are hundreds of studies that can benefit from this technology, utilizing both stable and radioactive beams.

Fundamental Interactions and Rare Processes

The recent confirmation of neutrino flavor oscillations brings renewed interest to the study of the Weak Interaction in nuclei as a probe for physics beyond the Standard Model. Experiments on Weak nuclear decays and reactions search for new physics by exploiting fundamental symmetries and probing beyond leading order calculations of Weak processes. A γ-ray tracking array like GRETA with high efficiency, high segmentation, and excellent background rejection could be used to perform important Weak Interaction experiments at unprecedented precision.

Is the CKM matrix unitary? Are there undiscovered weak couplings or quarks?

One 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} matrix element of the Cabbibo-Kobayashi-Maskawa (CKM) matrix, which describes mixing among quark flavors. It is a well-known issue in the Weak Interactions and High Energy community that this unitarity test fails by roughly 2.3σ. The dominant contribution to the “first row” unitarity test is $V_{UD} \sim 0.974$, as measured in beta decays. Crucial issues in extracting V_{UD} from superallowed decays include the quality of the data across nine well-studied decays, and the estimation of isospin-breaking corrections to the nuclear matrix elements between parent and daughter nuclei. 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 into the main signal peak, which occurs at 1022 keV. Very high spatial resolution and pileup rejection in GRETA could remove this error from the current measurements, allowing an improvement in the precision of the branching ratio of a factor of 10 or more.

Beta delayed gamma emission: are there additional weak couplings?

Measurements of β–γ correlations could also be improved in an array with good spatial resolution and high photopeak efficiency. Several cases would be interesting as tests of recoil-order weak interaction form factors. These nuclei include ^{22}Na, ^{14}O, ^{20}Na-^{20}F, ^{12}B-^{12}N, ^{24}Na-^{24}Al, and ^{28}Al-^{28}P. Weak recoil-order form factors arise from radiative corrections to the charged weak current coupling, and from the momentum-dependence of weak couplings in β decay. Such terms in β decay are not well understood, and clean extraction of weak parameters of interest depends on shell model calculations. Comparisons within isospin multiplets can allow clean extraction of recoil-order terms. Disagreement with predictions of the "vector minus axial vector" form of the Standard Model would suggest new weak currents mediated by new massive bosons. Such new particles and couplings are suggested by supersymmetric theories. Past β–γ correlation measurements have been limited by poor angular resolution in both β and γ detectors, and GRETA would easily improve these measurements.

Parity violating weak intranuclear forces

A pressing field of interest in Weak Interactions is the description of weak nucleon-nucleon interactions. Several cases of large parity-symmetry forbidden nuclear decay amplitudes are known (including ^{180}Hf*(8-)→^{180}Hf decay). Such effects are currently described by weak parity-violating effective meson couplings between nucleons, yet the data on the extraction of these coupling constants is in very poor agreement. The ^{19}Ne-^{19}F/^{19}F* system has the least systematic uncertainty in extracting these coupling constants. The parity mixing of the $1/2^+$(g.s.) and $1/2^-$(110 keV) levels in ^{19}F can be studied with the GRETA array. ^{14}N*, ^{18}F*, ^{19}F*, and ^{21}Ne* are all anticipated to have strong Parity-odd effects as well in γ-ray emissions.

Identifying deformed nuclei impacts the search for atomic electric dipole moments

Nuclear structure studies also impact the field of fundamental symmetries through the search for permanent electric dipole moments in atoms – a Time Reversal violation probe. The sensitivity to a nonzero EDM in an atom is greatly enhanced by nuclear structure effects. Nuclei with large octupole deformation or large parity mixing between states can provide cases of unique sensitivity for atomic EDM searches. Search for large nuclear deformations could identify useful candidate nuclei.

Are the symmetries C, P, and T conserved in positronium annihilation?

GRETA would also be useful in studies of positronium annihilation. An experiment with only one week of data acquisition in a GRETA-like array could improve existing measurements of positronium annihilation to four and five photons, which test QED predictions at high orders of the coupling constant (α^8). This experiment would also significantly improve existing limits on Charge Conjugation Symmetry violating interactions. Such interactions are a natural but tiny consequence of superstring and "brane" theories. The decay of polarized positronium in a highly segmented detector could provide a sensitive test of the combined symmetry CPT (Charge conjugation, Parity reversal, and Time reversal), which is also predicted to be violated at a small level by superstring theories. Measurements of the linear polarization of the γ-rays (again using a highly segmented detector as a polarization sensitive detector as has been demonstrated with Gammasphere) emitted in positronium annihilation would allow detection of several correlations sensitive to various combinations of the fundamental symmetry operations C, P, and T, as well as interesting quantum mechanical three-body correlations which could provide a uniquely sensitive test of Bell's inequalities.

Functional Requirements

The breadth of the scientific goals requires a universal 4π gamma-ray detector that simultaneously satisfies a set of challenging requirements including large photopeak efficiency, high peak-to-total ratio, good position resolution, and excellent energy resolution, in the energy range of a few tens of keV to 20 MeV. A detailed description of the required functionality and performance goals are given in chapter 4 of reference [6]. The new concepts incorporated into GRETA provide the ultimate solution to these functional requirements.

Impact of GRETA

GRETA's impact on nuclear science and the education of the next generation of scientists proficient in the science of atomic nuclei can be extrapolated from the experience with Gammasphere–currently the nation's most advanced gamma-ray spectrometer. Gammasphere was commissioned as a national facility in 1995 and serves a scientific community of about 400 scientists from 94 institutions. As of April 2002, 386 refereed publications – 81 of which are high-impact Physical Review Letters or Physics Letters – have resulted from experiments with this detector. Users of Gammasphere include a large number of university-based investigators attracting emerging scientists into the field, training them, and producing 55 Ph.D. theses (as of Fall 2002).

The considerable advance in spatial resolution provided by the gamma-ray tracking technology developed for GRETA has far-reaching applications to other fields of science such as double beta decay, and astrophysics (Compton telescopes, polarimetry). It also has important applications in medical diagnostics, industry, identification and mapping of radioactivity for environmental remediation, and homeland security in the detection of nuclear materials or nuclear surveillance.

GRETA Technical Readiness

The technical feasibility of GRETA was reviewed by the 'Gamma Ray Tracking Coordination Committee' which met at Argonne (March, 2002) [6] and by the earlier DOE review of the 3-cluster module. A series of workshops and planning meetings were held (Berkeley 1998 [7], East Lansing 1999, Lowell 2001 [8], Argonne 2001, Oakland 2001 [9]) at which GRETA was discussed. These meetings helped develop the specifications for the array, endorsed the scientific goals, and showed that there is widespread support for the GRETA project from the nuclear science community.

In the following we will demonstrate that GRETA is technically and organizationally ready to move forward and has a realistic cost and schedule. GRETA research and development efforts have shown: 1) highly segmented coaxial germanium (Ge) detectors can be reliably produced; 2) fast digitization of segment signals can be performed; 3) we have the ability to locate and resolve charge deposition points within a Ge crystal based on pulse shape analysis of direct and induced segment signals; 4) we can disentangle and order interaction points, thereby enabling tracking of multiple gamma rays through the array. From these technical efforts a realistic cost estimate and possible schedule has been determined for GRETA by the GRETA Steering Committee (formally the GRETA Advisory Committee). This committee coordinates the GRETA effort.

Below we summarize the design concept and expected performance of GRETA. We then describe the development efforts that have demonstrated the technological feasibility of this project including the current status of detector prototypes, electronics, signals analysis techniques, and performance tests. An estimate of cost and construction time for GRETA is included.

Design Concept and Expected Performance

The current generation of 4π gamma-ray detector arrays, for example Gammasphere, are based on modules of Compton suppressed Ge detectors. They use high-purity Ge crystals, which have intrinsically good energy resolution. Although the largest available crystals are used, most of the gamma rays do not deposit all their energy in a single crystal. Such partial-energy events contribute to a background, which can be rejected by detecting the gamma rays that scatter out of the Ge crystal into a “Compton shield” (made with a high-density scintillator such as BGO) surrounding the Ge detector. While this improves the peak-to-total ratio, it does not improve the efficiency. Furthermore, the suppressors occupy a large fraction of the solid angle, which limits Gammasphere’s full-energy peak efficiency to 10% (at 1 MeV) with a peak-to-total ratio of 60%. To explore new scientific regions, as identified in the Long Range Plan and discussed in the first section of this report, new technology beyond arrays of Compton-suppressed detectors is required.

The efficiency limit can be overcome by eliminating the Compton shields and by closely packing the Ge crystals. Rather than suppressing events that scatter out of individual crystals, the gamma rays can be tracked across crystal boundaries by determining the location of the scattering points (a 1 MeV gamma ray has typically 3 to 4 interactions within the Ge before depositing its full energy). This can be achieved by using the new technology of highly segmented Ge detectors. These detectors have their outer electrical contact divided into a number of individual segments. By analyzing the direct and induced charges from these segments the scattering points of gamma-rays can be determined to better than a few millimeters. The pathways through the crystals can be followed and the gamma-ray energies reconstructed by using suitable algorithms. This is the concept underpinning GRETA.

For roughly the same volume of Ge used in Gammasphere, GRETA will give a much higher efficiency (60% at 1 MeV), a better peak-to-total ratio (80%), and a position resolution of about 1mm. When compared to Gammasphere, conservative estimates indicate that GRETA will be hundreds to thousands of times more sensitive for typical applications.

State of Development

Detector design and prototyping

The design of GRETA is based on a geodesic configuration, consisting of 120 hexagons plus 12 pentagons. Two types of slightly irregular hexagons are required for the packing (60 hexagons of each type). Tapered hexagonal Ge crystals will occupy these positions. Some of the 12 pentagon positions will be left unoccupied for beam entrance, beam exit, target ladder, and space for auxiliary devices. The tapered crystals will leave an inner radius of 15 cm, matching the minimum space requirements for accommodating auxiliary devices. Three or four crystals will be mounted in a common cryostat.

Two prototype high purity Ge detectors have been built by Eurisys Mesures and tested at LBNL. Both detectors have a regular hexagonal shape. They are 9 cm long with a maximum diameter of 7cm at the back with a tapering angle of 10^{o}. The first prototype was 12-fold segmented (6 azimuthal and 2 longitudinal segments) and the second prototype was 36-fold segmented (6 azimuthal and 6 longitudinal segments).

A triple-crystal detector module [10] was ordered in September 2002, and delivery is expected in October 2003. The design of this prototype integrates all the technology needed for a complete GRETA detector module. Such a module consists of three encapsulated Ge detectors, each with 36 segments, placed in a single cryostat. Each crystal has a partially tapered shape, which maximizes the distance from the source to the detector allowing more space for auxiliary detectors in the target chamber, and optimizing the Ge coverage. Each crystal gives 37 signals (from the 36 segments and one central electrode) amplified with cold FETs mounted in the cryostat. Since such a module may be regarded as the ‘fundamental unit’ from which GRETA will be constructed, by accepting the order the manufacturer has indicated that there are no fundamental fabrication issues for the full array.

Electronics

There are two challenges to be addressed in the electronics development for GRETA. The first is the production of high-bandwidth, low-noise preamplifiers that are capable of preserving the position information in the transient current signal from each detector segment. These units must be low power and highly miniaturized as 111 such preamplifiers are to be mounted on each 3-crystal cryostat. Such a preamplifier was designed and built at LBNL for the 36-fold segmented prototype detector. Measurements of noise characteristics, position sensitivity, and position resolution were performed with an 8-bit 500 MHz digitizers (Tektronix RTD720, on loan from LLNL) and a 12-bit 50 MHz digitizers (XIA DGF-4C, on loan from ORNL). It was found these preamplifiers meet the bandwidth, noise and power requirements and improve the energy resolution by 0.1 keV when compared to standard preamplifiers.

The second challenge is to develop fast, inexpensive digitizers capable of performing real-time data reduction, analysis, and triggering. Sampling rates of 100 MHz are required to preserve the position and time resolution required for the ~5000 channels in a 40-module array. To demonstrate the feasibility of such a system an 8-channel, 100 MHz, 12-bit ADC board was designed and constructed in 2002. Unlike most commercially available ADC boards, which perform only waveform digitization, the GRETA prototype board is capable of performing real-time digital signal processing (which encompasses all the standard functions of analog electronic systems). Additionally, the board implements a user-defined window to extract relevant parts of the pulse shape for subsequent signal decomposition. On the board there are also three trigger modes (internal, external, combined) for each channel allowing maximum testing flexibility. Readout of the prototype ADC board is carried out over a VME bus to simplify integration into current data acquisition systems. The readout for the final system, which will have a higher channel density, will use a much faster data transfer system..

As discussed above, the design and construction of the 8-channel board (including full simulations of the complex VHDL code required to implement the above functions) has been successful. The ability to carry out the required signal processing on a single large FPGA without the need for a dedicated on-board CPU or DSP has considerably reduced the cost and development time for this project. More 8-channel boards will be fabricated and fifteen of them will be integrated in a 120-channel acquisition system required for the three-crystal GRETA module prototype.

Signal Decomposition

Extensive measurements have been performed on the 36-fold segmented prototype to determine basic properties, such as energy resolution, noise characteristics, crystal orientation effects, and three-dimensional position sensitivity. 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 [11]. 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 gamma-ray tracking system [12]. In addition, electric field and pulse-shape calculations, as well as Monte-Carlo simulations, have been performed. The agreement between the calculated and measured signals is very impressive, indicating that we have an excellent understanding of the behavior of segmented detectors.

By employing an event-by-event analysis of measured signals in terms of calculated signals, a position resolution of better than 1mm at 374 keV was obtained for single interaction events. For multiple interactions in one segment, the measured segment signals have to be decomposed to obtain the positions of the individual interactions. All signal decomposition approaches studied are based on fitting the measured signals with a linear combination of calculated basis 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. The different algorithms achieve position resolutions of the order of a few millimeters. This proves that pulse-shape analysis techniques can provide the necessary position and energy information for tracking gamma rays scattering within a segmented tracking detector.

Signal decomposition is the most computationally intensive part of GRETA data reduction and analysis. Employing currently developed algorithms, it is expected that one Teraflop of processing power will be required. Given the explicit parallel nature of this procedure and the advent of inexpensive Linux-based computer clusters, the cost of this processing is expected to be a small fraction of the total project cost.

Tracking

Tracking procedures convert the position and energy information of the interactions into the pathway of a gamma ray as it scatters in the array. These procedures are based on the known physics of gamma ray interactions with matter. In a Ge detector, a 1 MeV gamma ray typically makes three Compton interactions and one photoelectric interaction before it is fully absorbed. Knowing the position and energy of the interactions, and using the angle-energy relation of the Compton scattering process, we can determine the correct sequence of the scattering points. The position of the first interaction provides the direction of the gamma ray for Doppler correction. Furthermore, tracking can also reject escaped Compton events and gamma rays that do not originate from the target.

Significant effort went into the development of a γ-ray tracking algorithm [13,14] based on the Compton effect, the photoelectric effect, and pair production. Simulations with this algorithm used a position resolution of 2 mm (which we have shown is reasonable from our pulse shape analysis of signals from the prototype detectors) and realistic assumptions for the final GRETA geometry (such as gaps and cryostat thickness). For events involving 25 emitted gamma rays, an efficiency of about 25% was achieved. This should be compared with Gammasphere, which has an efficiency of about 8% under the same conditions. Together with the improved position-sensitivity this implies a gain of 100-1000 in sensitivity depending on experimental conditions and requirements.

Performance

Additional end-to-end tests of the 36-fold segmented prototype have been performed using radioactive sources of ^{60}Co, ^{137}Cs and ^{152}Eu. These tests were used to demonstrate that by combining all the separate elements of GRETA the resulting system performs as simulated. In these measurements, most of the segments were instrumented with digital electronics and the full analysis procedure of signal decomposition and tracking was applied to the data. The measured data were treated with exactly the same analysis procedures as the simulations discussed above, and similar gamma-ray spectra were obtained. The measured and simulated efficiency and the peak-to-total ratio agree with each other for both the raw spectra and the spectra after the tracking. Currently, the efficiency of locating a single interaction in one segment to within 1 mm is 85%. As expected for a single crystal, the tracking improves the peak-to-total ratio but does not increase the efficiency. These results indicate that we have an accurate understanding of the entire system [15,16].

On-going R&D

This prototype single-crystal module is scheduled for in-beam test in March 2003. The order of the 3-crystal module has confirmed vendor capability and cost. We will use this module to track gamma rays across crystal boundaries to confirm the full functionality of this GRETA building block. After off-line testing, the performance of this module will be studied in a number of experiments including high spin, high-energy gamma ray, and high recoil-velocity measurements. From the good agreement between simulations and the performance of the one-crystal detector, we expect that this module will function as simulated. Experience gained from the production of this module could lead to performance improvements and cost reductions.

Following the successful tests of the 8-channel digitizer board, more boards will be fabricated and 15 of them will be integrated in a 120-channel acquisition system required for the three-crystal GRETA module prototype. Additional boards will be distributed to the other collaborative institutions (e.g. ORNL, ANL, and MSU) for tests and software developments. Based on the experience gained from this module, we will design a 40-channel module capable of processing all the signals and providing positions and energies of all interactions in one crystal. This board will constitute the final design of the GRETA digitizer.

Cost and Schedule

The GRETA Steering Committee suggests that a realistic cost estimate, given a 5-year construction period for GRETA, is $55.6 million FY02 dollars including escalation and a 30% contingency.

Conclusion

GRETA is required to address a broad range of scientific issues and can be used at existing and planned U.S. laboratories. The scientific goals have been endorsed and GRETA enjoys widespread support among the nuclear physics community. R&D efforts have provided a proof-of-principle in that tracking detectors have been built and perform as calculations and simulations suggest. The successful fabrication of highly segmented detectors and state-of-the-art electronicsindicate that there are no known manufacturing issues. The R&D in progress on the prototype cluster module will confirm full functionality, vendor capability, and program cost. In summary, GRETA is ready to proceed as outlined in *A National Plan for the Development of Gamma-Ray Tracking Detectors in Nuclear Science* [6].

References

[1] *Opportunities in Nuclear Science, A Long-range Plan for the Next Decade*, J. Symons *et al.*(eds.), April 2002. www.sc.doe.gov/production/henp/np/nsac/LRP_5547_FINAL.pdf
[2] greta.lbl.gov
[3] M.A. Deleplanque *et al*., Nucl. Instr. Meth. Phys. Res. **A 430** (1999) 292
[4] Opportunities in Nuclear Science, A Long-range Plan for the Next Decade, Ed. J. Symons *et al.* April 2002. www.sc.doe.gov/production/henp/np/nsac/LRP_5547_FINAL.pdf, page 22
[5] page 55, ibid.
[6] *A National Plan for the Development of Gamma-Ray Tracking Detectors in Nuclear Science*, Report by the Gamma-Ray Tracking Coordination Committee greta.lbl.gov/greta_docs/GRTCC-report.pdf
[7] *Proceedings of the Workshop on GRETA Physics: A Slide Report*, P. Fallon (ed.), LBNL-41700
[8] *Report of the Workshop on Gamma-Ray Tracking Detectors for Nuclear Science*, University of Massachusetts, Lowell, June 22-23, 2001
[9] *Contribution to the NSAC Long Range Plan: The Gamma-Ray Energy Tracking Array, GRETA* greta.lbl.gov/greta_docs/ps/greta_white.ps
[10] *Proposal for a GRETA Module*, greta.lbl.gov/greta_docs/ps/proposal.ps
[11] K.Vetter *et al.*, Nucl. Instr. Meth. Phys. Res.Nucl. Instr. Meth. Phys. Res. **A 452** (2000) 105
[12] K.Vetter *et al.*, Nucl. Instr. Meth. Phys. Res. **A 452** (2000) 223
[13] G.J. Schmid *et al.*, Nucl. Instr. Meth. Phys. Res. **A 430** (1999) 69
[14] T. Teranishi *et al.*, LBNL NSD Annual Report, 1999
[15] K.Vetter *et al.*, Nucl. Phys. **A 582** (2001) 286c
[16] A. Kuhn, Ph.D. Thesis U.C. Berkeley, 2002.