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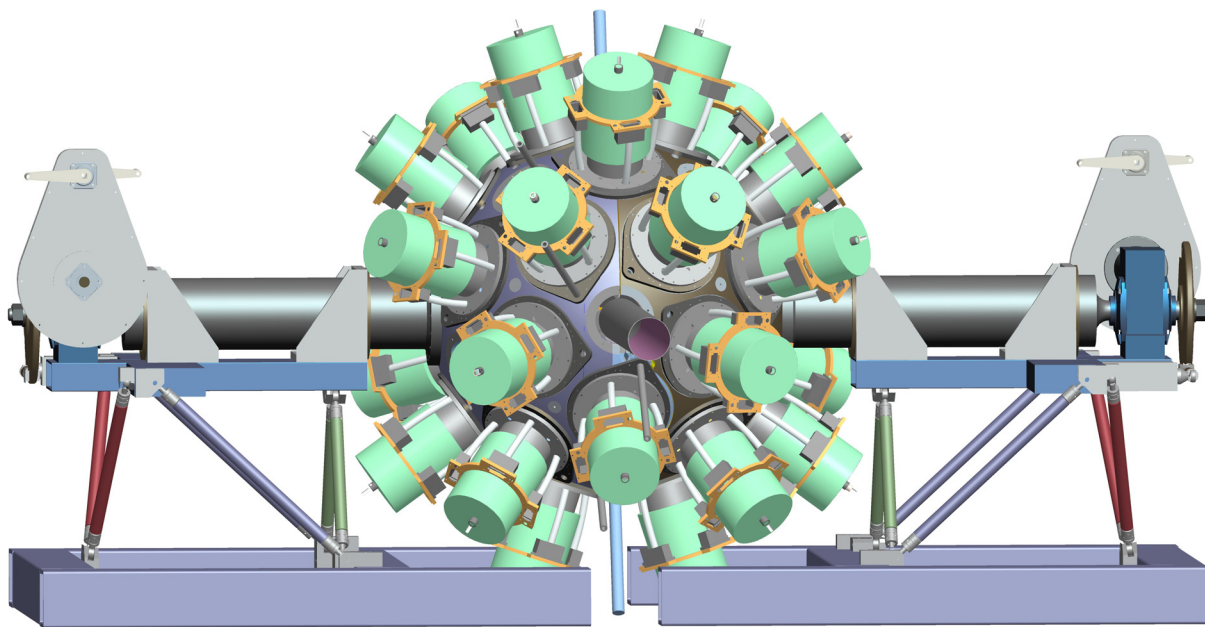
GRETINA Physics Working Group, the GRETINA Advisor

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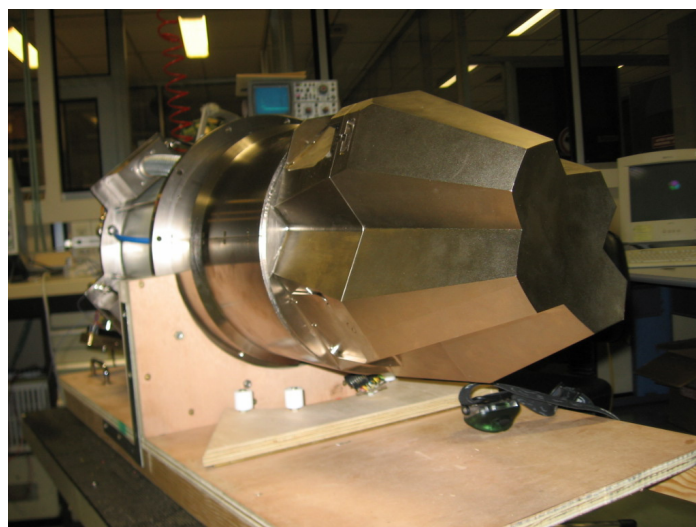
**THE FUTURE OF GAMMA-RAY SPECTROSCOPY:
GRETA,
THE GAMMA-RAY ENERGY TRACKING ARRAY**



December 2006

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Photograph of the first quad-cluster Ge detector module which forms the basic building block of GRETINA and GRETA. (October 2006)

1. Executive Summary

This is a time of great opportunity in nuclear spectroscopy. The development of radioactive beam capabilities around the world is opening a new landscape for discovery, and the connections between nuclear structure studies and astrophysics, neutrino physics, and physics beyond the standard model are stronger than ever. New detector technologies are evolving which can meet the challenges of the new generation of experiments. Leading these is the technology of “ γ -ray tracking” which can revolutionize γ -ray spectroscopy in a way that large arrays of γ detectors did a decade ago. During the last few years this technology has been shown feasible and GRETINA a 1π detector is under construction. However, the momentum in developing this technology to its full potential must continue towards GRETA, a full 4π calorimeter. GRETA will carry γ -ray spectroscopy into the next generation where it will be needed to fully exploit the science opportunities at radioactive beam facilities and increase the reach of stable beam facilities. In addition, γ -ray tracking technology will have important applications for science, medicine, and homeland security.

GRETA was first mentioned in the 1996 Long Range Plan (LRP) and became a recommendation in the subsequent LRP of 2002. In the 2003 NSAC report entitled “The Nuclear Physics Science Horizon: Projects for the Next Twenty Years” GRETA obtained the highest rank of “1” in both science and readiness categories. The physics justification and technical performance for a 4π γ -ray tracking detector were also well documented in the extensive report submitted by the National Gamma-Ray Tracking Coordinating Committee setup by the DOE Office of Nuclear Physics in 2002. A selection of physics highlights along with an up to date status of technical issues are contained in the present document.

As a first step towards GRETA, a physics-rich pilot program was devised to allow technical development to advance at full speed. This led to the proposal of GRETINA, a detector with 25% coverage of solid angle. The GRETINA project is moving forward according to schedule with a start of operation date of 2010. Our intention is to keep moving forward with γ -ray tracking in this country and to complete our original proposal to build the full 4π array GRETA, in order to fully optimize the physics potential of this new technology.

For most experiments, GRETA will improve the power of GRETINA by a factor of 10 -100. This will greatly extend the reach of the physics and allow advances in the study of nuclear structure, nuclear astrophysics, and fundamental interactions. For example, the alteration of shell structure and new collective phenomena at the two extremes of isotopic number can be studied with fast beams from ^{48}Ni to ^{80}Ni . The structure of heavy elements with Z larger than that of Sg ($Z=106$) can be studied with enough detail to help constrain and refine the theoretical calculations needed to make a more accurate prediction of the stability of super heavy elements. The search for hyperdeformed nuclei with 3:1 axis ratio at the very limits of angular momentum will be within reach with GRETA’s 100 fold increase in sensitivity. Crucial capture reactions in element synthesis in nuclear astrophysics have extremely low cross sections which require detectors with the highest possible efficiency and ability to reject background. In the area of fundamental interactions GRETA’s high spatial resolution and efficiency will bring a large increase in sensitivity to many measurements; including tests of QED and CPT from studies of positronium annihilation, and measurements of V_{ud} obtained from the superallowed β -decay of ^{10}C .

The GRETINA construction project has developed all the advanced technology needed for GRETA. The first detector module with 4 highly segmented irregularly shaped crystals closely packed in a single cryostat has been produced. Signal digitizers with the required resolution and sampling rate have been fabricated and are in use. Signal decomposition and tracking software has already demonstrated the required position resolution and speed. The data acquisition system with sufficient computing power and storage capability has been designed and prototyped.

In Europe a competitive γ -ray tracking germanium shell detector, AGATA, is advancing. It will be used at the European radioactive and stable beam facilities. At present, the collaboration between GRETINA and AGATA scientists in technology R&D is very strong. Similar to the US, the nuclear physics community in Europe realizes the vast range of opportunities offered by this device and the demand for its use is expected to be very large. Clearly, continuing development toward GRETA is essential to our competitive position in the field of γ -ray spectroscopy.

Detailed GRETA cost projections have been based on the current GRETINA project. As GRETINA contains all the key technologies, the cost scaling should be reliable and have very little uncertainty. Following the DOE project scheme for escalation and contingency, we estimate a total project cost of \$42M beyond the GRETINA phase and a project completion date in 2016. The development would steadily lead to ever-increasing physics reach and flexibility as the device grows from 1π to 4π . However, many key physics goals require the complete shell for success.

In summary we would like to quote from the 2002 NSAC Long Range Plan Overview and Recommendations section (page 9),

“The detection of gamma-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array 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 several existing stable and radioactive beam facilities, as well as at RIA.”

With GRETINA now under construction we are moving towards this goal. We strongly urge the timely completion of the full 4π system GRETA.

2. Introduction

The unique strongly interacting aggregation of fermions that we call the atomic nucleus displays a remarkable diversity of phenomena and symmetries. Its behavior and structure continues to surprise and fascinate as unexpected properties are revealed by fresh experimental opportunities 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's resolution, granularity, efficiency, and ability to be used in conjunction with a powerful suite of auxiliary detector systems, have made it an unsurpassed device for studying rare and exotic nuclear properties. (Over 600 refereed publications and 100 PhD theses have been written utilizing data from this detector so far.) It is therefore extremely exciting that at the same time as a major new radioactive beam accelerator facility initiative is on the horizon that huge advances in our γ -ray detection capabilities are also possible. Such a next generation detector system would allow us to capitalize on the science opportunities prior to and when the new accelerator facility was completed. Indeed, as stated in the 2002 NSAC Long Range Plan (Overview and Recommendations, page 9),

“The detection of gamma-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array 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 several existing stable and radioactive beam facilities, as well as at RIA.”

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 paradigm utilizing the concept of γ -ray energy tracking in electrically segmented Ge crystals. These new opportunities have arisen from technical innovations first realized by the US γ -ray spectroscopy community. The new 4π detector design mentioned above which was already discussed in the 1996 Long Range Plan is called GRETA (Gamma-Ray Energy Tracking

Array). It would contain about 120 (30 quad-cluster modules) co-axial Ge crystals each segmented into 36 portions and arranged in a highly efficient 4π geometry. GRETA would have about 100 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 the previous generation of detector systems.

The improved sensitivity or resolving power is due to the new technique of “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 (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 MSU SeGA array) 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 (a factor of ~ 5 over Gammasphere), good position resolution (1.4 degrees versus 6 degrees 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 γ -ray measurements possible. The modularity of the detector design makes it extremely versatile and flexible for use in many different configurations.

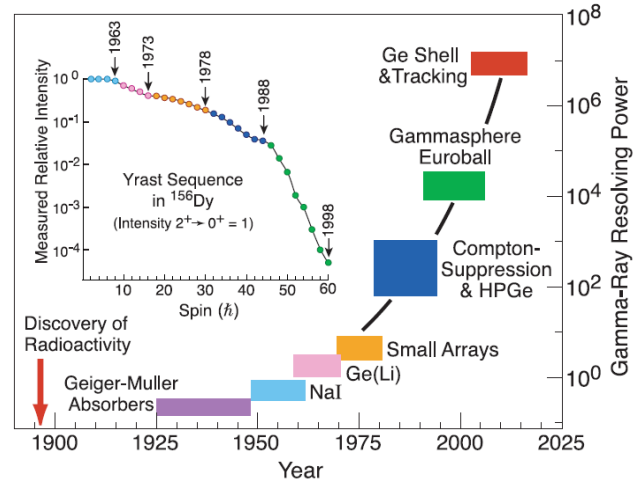
In 2003, after major R&D efforts had validated the GRETA concept to show that building a tracking detector array was feasible, and that a first class physics case existed, the DOE gave the go ahead for a mission need decision on GRETINA (CD0). GRETINA, which comprises $\frac{1}{4}$ of GRETA, is a logical first phase for a staged approach to GRETA. GRETINA itself will provide a large gain in sensitivity compared to existing systems for addressing an important range of scientific questions and especially for studying nuclei far from stability at existing rare isotope accelerator facilities.

The gains in performance are most significant for fast beam experiments such as fragmentation reactions, and quasi-elastic processes such as Coulomb excitation and transfer reactions. Progress on all the essential components of GRETA, which will comprise of 28 36-fold segmented Ge crystals in 7 cryostats, is proceeding extremely well and is on track for a start of operation date in 2010.

The aim of this document is to keep the momentum going with regard to γ -ray tracking in this country and to argue that we should complete our original intention from 1996, namely to build the complete 4π array GRETA, in order to fully optimize the physics potential of this new technology. This is supported by the recommendation contained in the 2002 Long Range Plan and the major report from NSAC in 2003 entitled “The Nuclear Physics Science Horizon: Projects for the Next Twenty Years” in which GRETA obtained the highest rank of “1” in both science and readiness categories. In addition there is a major effort in Europe to build a 4π highly-segmented germanium shell, called AGATA, similar in concept to GRETA. The US nuclear structure community, which conceived of this next revolutionary step in γ -ray detection capability, is therefore poised and eager to complete a next generation 4π γ -ray spectrometer with unsurpassed sensitivity and discovery potential, GRETA.

The present document is arranged as follows. In the next section some key physics goals are presented where the capabilities of GRETA over existing detector systems are emphasized in each case. The technical accomplishments towards a 4π γ -ray tracking array are then documented. New auxiliary triggering detectors

which will play an essential role in the success of GRETA and GRETA are discussed followed by some applications of “ γ -ray tracking” technology. Next the cost estimates and timeline of GRETA are presented along with a brief summary of progress and milestones so far. In the appendix an outline of the management structure of the GRETA project is given.



Evolution of γ -ray detector technology. The large gain provided by a Ge shell and tracking is clearly shown. The calculated resolving power is a measure of the ability to observe faint emissions from rare and exotic nuclear states. This is illustrated in the left hand insert, which indicates the strong inverse relationship between resolving power and the experimental observational limit. Taken from the NSAC 2002 Long Range Plan document, page 132.

3. Physics Opportunities with Gamma-Ray Tracking

In the 2002 NSAC Long Range Plan for Nuclear Science a number of key physics themes and questions were selected for special discussion and which outlined future priorities of investigation for our field. They include,

- *What are the limits of nuclear existence?*
- *How do weak binding and extreme proton-to-neutron asymmetries affect nuclear properties?*
- *How do the properties of nuclei evolve with changes in proton and neutron number, excitation energy, and angular momentum?*

It is now accepted that a γ -ray energy tracking detector will be needed to address these questions. This is of course one of the reasons that GRETINA has been approved for construction. However to fully capitalize on the science opportunities at existing, and future facilities, a full 4π array is essential.

Of course the gains made possible with GRETA will be specific to the type of physics experiment being performed. For example, the previous figure refers to a high multiplicity experiment. In the following Table and Figure the improvement in resolving power or sensitivity of GRETA is calculated and compared to GRETINA, Gammasphere or SeGA for a variety of different experiments and reaction types.

The physics impact of GRETA will cover a broad range of topics and its use will be in high demand. For example, at the 2004 RIA Facility Workshop, GRETA was a critical device in a very large fraction of the proposed experiments. In fact much time was spent discussing how it would be moved from beam line to beam line. The experimental examples below offer only a brief sampling of the richness of questions that GRETA will ultimately touch upon.

3.1. How do extreme proton-to-neutron asymmetries affect nuclear properties, such as shell structure and collectivity?

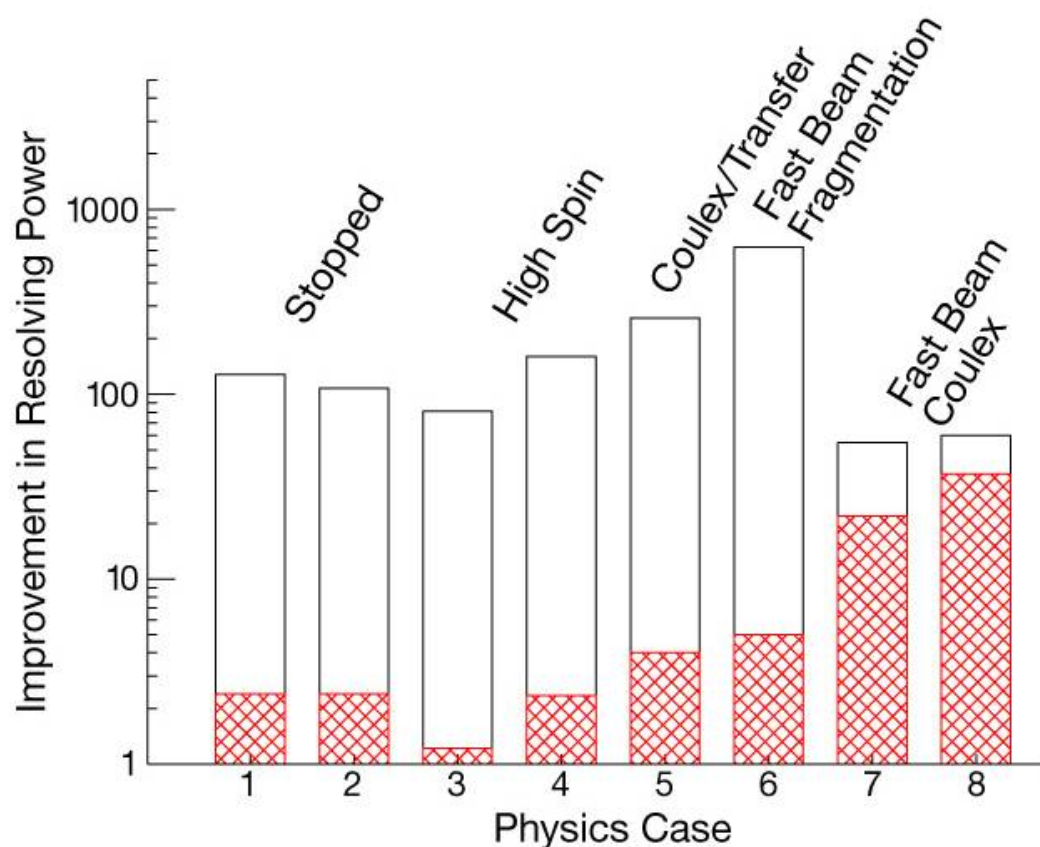
3.1.1. Doubly Magic Nuclei Far from Stability

Nuclear shell structure has been an underlying theme of nuclear structure physics for over 50 years, and earned the Nobel Prize for J. Hans D. Jensen and Maria Goeppart-Mayer in 1963. The “magic” nuclei, with a closed shell of protons or neutrons, serve as landmarks in the chart of the nuclides, analogous to the inert noble gases in the periodic table. Of special interest are “doubly magic” nuclei such as ^{40}Ca and ^{208}Pb , which together with their immediate neighbors have long been the focus of extensive study. Light neutron-rich nuclei, however, indicate that the shell structure of nuclei near stability cannot be reliably extrapolated to the drip lines. It is thus especially exciting that beams of new doubly magic nuclei are becoming available. Initial studies of the region around ^{132}Sn are already possible, but can be greatly improved at the next-generation facilities; the more exotic neutron-rich ^{78}Ni and proton-rich ^{100}Sn regions will need to await a facility like RIA. By employing GRETA at such a facility, it should be possible to make detailed studies of all three of these new doubly-magic regions. Such studies are great importance for both nuclear structure and astrophysics.

Measurements of Coulomb excitation of magic and doubly magic rare isotopes provides crucial information on the collectivity of low-lying excitations, on the underlying nuclear shape (through the reorientation effect), and on their magnetic moments (through transient field or recoil-in-vacuum techniques.) The superb energy resolution afforded by GRETA will be important for multi-step Coulomb excitation, but also for cases where low-energy (“safe”) Coulomb excitation is performed with cocktail beams and the excited levels of the various beam components lie close in energy.

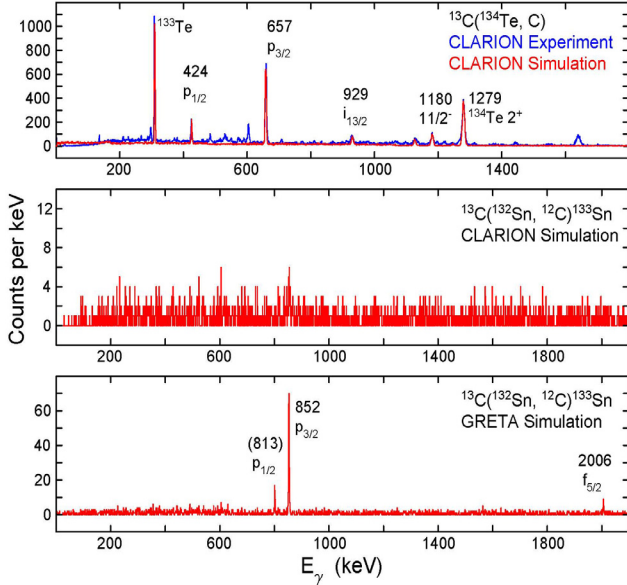
Single-particle transfer reactions such as (d, p) or (d, ^3He) in inverse kinematics, reveal the energy and strength of the single-particle and single-hole excitations relative to the closed shells. Studies with these reactions will not only identify new single-particle states, but also provide measurements of the spectroscopic factors, related to the single-particle purity of the observed levels. Inverse kinematics is required,

Experimental Technique or Reaction Type	$\langle E_\gamma \rangle$ MeV	v/c	M_γ
1. Stopped - Hi E_γ	5.0	0.0	4
2. Stopped - Low E_γ	1.5	0.0	4
3. Hi-spin - Normal Kinematics	1.0	0.04	20
4. Hi-spin - Inverse Kinematics	1.0	0.07	20
5. Coulex/Transfer	1.5	0.1	15
6. Fast Beam Fragmentation	1.5	0.5	6
7. Fast Beam Coulex - Hi E_γ	5.0	0.5	2
8. Fast Beam Coulex - Low E_γ	1.5	0.5	2



Top: Table showing the variety of different experimental techniques or reaction types along with characteristic γ -ray energies, recoil velocities and γ -ray multiplicities. Bottom: Improvement in resolving power or sensitivity of GRETA compared to Gammasphere or SeGA (whichever array was optimally suited) for a variety of different experimental cases given in the Table above. The red hatched bars correspond to the expected performance of GRETA. The calculations do not consider any contributions from auxiliary detectors.

however, which together with the energy loss of the heavy beam in the target limits the energy resolution available from detection of the light reaction products alone. Detecting the γ transitions from excited states not only allows the excitation energy to be determined precisely, but also provides additional data from angular correlations. Since GRETA comprises a highly efficient Ge shell, it can serve as a superb γ -ray calorimeter, determining the excitation energy of the excited beam with excellent specificity.



Simulation of GRETA performance for single-particle transfer reaction studies. The upper panel shows the spectrum (blue) from the $^{134}\text{Te} + ^{13}\text{C}$ reaction, obtained with CLARION at the HRIBF. Unless otherwise indicated, transitions are from excited states in ^{135}Te . The spectrum in red is the corresponding simulated spectrum for CLARION which overlaps the experimental spectrum extremely well. The middle panel is a simulation for CLARION for the $^{132}\text{Sn} + ^{13}\text{C}$ reaction, with a beam that is fifty times weaker than in the top panel. The bottom panel is the corresponding simulation for GRETA.

The sensitivity gain from using GRETA for such transfer studies is illustrated above by the case of an exotic ^{134}Te beam incident on a ^{13}C target. Single-particle states populated in ^{135}Te following neutron transfer were clearly seen in an experiment at the HRIBF, using the CLARION array of segmented clover detectors and the HyBall CsI array. The top panel in the figure shows the measured CLARION spectrum in blue, and a simulated spectrum in red. The second panel shows the

corresponding simulated spectrum for a similar experiment using a ^{132}Sn beam, available at the HRIBF but at a factor of fifty weaker in intensity. The third panel shows the simulated spectrum from GRETA, using the same weak ^{132}Sn beam. Clearly, GRETA will greatly extend the reach of transfer studies and open the way to a new generation of experiments exploring the evolution of nuclear shell structure far from stability. In addition to its high detection efficiency, the very high angular resolution is critically important for these experiments and for Coulomb excitation studies, both of which exhibit recoil velocities around 0.1c.

3.1.2. The Alteration of Shell Structure Far from Stability

The shell structure of atomic nuclei close to stability is well established. Pronounced shell closures define the effective degrees of freedom needed for a quantitative understanding of the atomic nucleus. The nuclear potential is well-parameterized and theoretical frameworks explain many experimental facts. For atomic nuclei away from stability decreasing nucleon binding energy and the large neutron-to-proton asymmetry lead to modifications in the nuclear potential and the spin-isospin component of the nucleon-nucleon interaction drives changes in the single-particle structure. This, together with the increased role of many-body correlations, leads to the disappearance of shell closures established close to stability and to the emergence of new magic numbers. For the lightest nuclei, such changes have already been observed experimentally at current facilities with present-day detectors. For example, established shell closures at $N=8$, $N=20$, $N=28$ have been observed to disappear for neutron-rich nuclei, while a new magic number has emerged at $N=16$.

Experimentally, the first indications for shell closures traditionally come from mass measurements. To establish that a magic number has vanished, it is necessary to measure effective single-particle energies or to determine experimentally that the ground state wave function of a presumed magic nucleus has a significant admixture from the shell expected to be above the shell closure. The quantitative determination of such admixtures can be accomplished in single-nucleon removal and single-nucleon addition reactions, both with fast exotic beams and with reaccelerated exotic beams. Such experiments depend crucially on the correct identification of the final states. In most applications these final states are particle-bound and can be tagged by coincidence measurements with γ -rays. Compared to

precisely measuring the momentum of the scattered particle in a spectrograph, γ -ray experiments have the advantage of allowing for much thicker reaction targets, thus extending the scientific reach of any facility. Gamma-rays traverse matter with known attenuation and multiple scattering of the projectile in a thick target does not affect their energy resolution. Complementary information on the strength of the coupling between ground-state and excited-state wave functions can be achieved by measuring the transition matrix elements between states. By comparing different probes (for example hadronic, electromagnetic, and isoscalar probes) one can begin to separate the proton- and neutron-contributions to the observed collectivity.

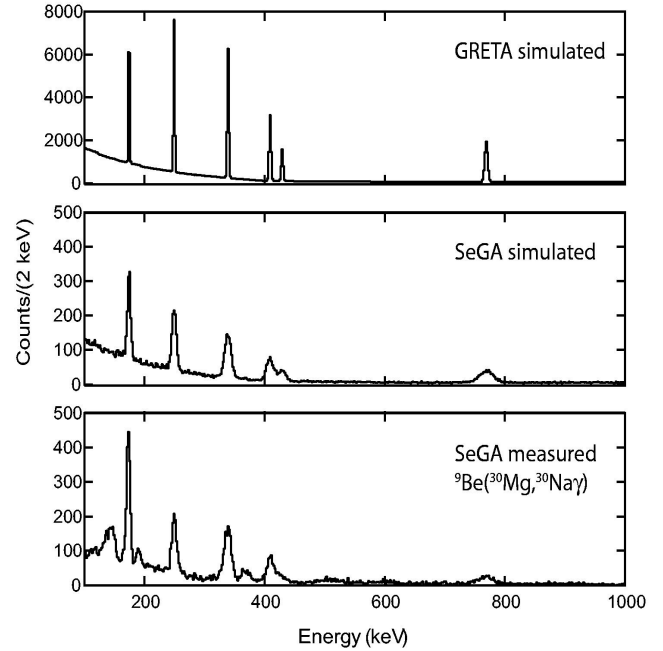
The sensitivity of any such measurement and the scientific reach of any facility depend directly on the resolving power of the γ -ray spectrometer used. GRETA will have superior resolving power for fast-beam experiment compared to any other γ -ray detector. This increased resolving power translates directly into added discovery potential.

For example, with GRETA it will be possible to characterize the shell structure of $Z=28$ nickel isotopes $^{52-76}\text{Ni}$ ($N=24-48$) at the NSCL Coupled Cyclotron Facility. GRETA will enable definitive measurements with fast beams from ^{48}Ni - ^{80}Ni ($N=20-52$) at facilities under discussion (200 MeV/nucleon heavy-ion driver, 400 kW beam power). The experimentally accessible nickel isotopic chain ^{48}Ni - ^{80}Ni covers three major shell closures ($N=20, 28, 50$) with the lightest and heaviest isotopes both very weakly bound, effectively amplifying shell-modifying effects. ^{48}Ni is located beyond the proton dripline and ^{80}Ni is expected to have a neutron-separation energy of less than 4 MeV. This unique scientific reach across three shell closures makes the nickel isotopes a key laboratory for studying the modification of shell structure in atomic nuclei.

Zirconium ($Z=40$) isotopes will provide complementary information to nickel, covering isotopes from the proton-dripline to close to the neutron-dripline. GRETA will enable definitive measurements of the wave functions with fast beams for ^{75}Zr - ^{115}Zr ($N=35-75$) at future facilities and ^{79}Zr - ^{108}Zr ($N=39-68$) at the NSCL CCF.

The doubly-magic nucleus ^{100}Sn ($Z=50, N=50$) as well as ^{99}Sn ($N=49$) will be accessible for in-beam γ -ray reaction studies with GRETA at future fast beam facilities, together with tin isotopes ranging to ^{139}Sn ($N=89$),

reaching into the astrophysically important r-process path.



Comparison of current data taken with the SeGA array with simulations of SeGA and GRETA. Note the significant increase in statistics and improved resolution with GRETA.

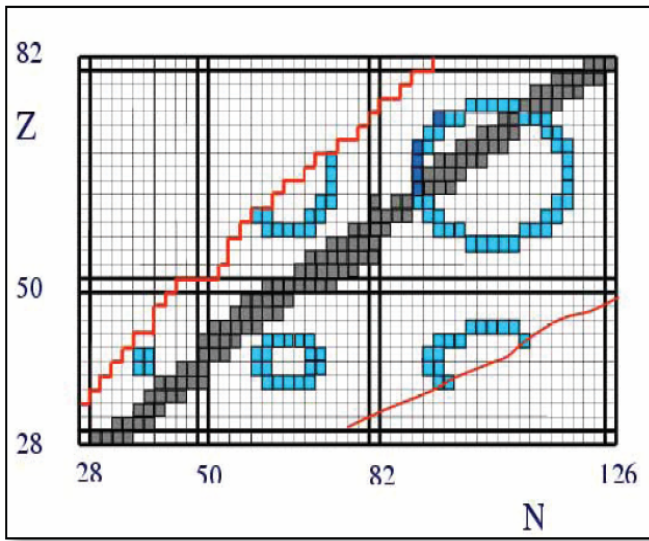
3.1.3. Symmetries and Excitation Modes in Exotic Nuclei

Critical Point Symmetries

A remarkable feature of heavy nuclei is the emergence of novel collective properties that are not apparent in few-body systems. Such regularities can often be described in terms of many-body symmetries, which simplify the interpretation by introducing simple degrees of freedom. One recent example of emergent collectivity focuses on rapid changes in structure that occur in mass regions where nuclear shapes suddenly switch with the addition of only one or two nucleons. The classical theory of phase transitions has been applied to describe these changes of nuclear shapes and has offered new insights into the transitional behavior of finite many-body systems in general.

A specific example is the case of the rapid change from spherical to ellipsoidal deformation. This can be understood in terms of a transition between coexisting spherical and deformed phases. When these phases have equal energies, a phase transition occurs. Nuclei which lie at this “critical point” (such as ^{152}Sm) have been successfully described in terms of new analytic

critical-point models, which predict a number of characteristic spectroscopic signatures. Understanding these phase transitions of nuclear shapes requires studying the evolution of structure across many nuclei. This is illustrated in the figure which shows the locus of expected shape transition regions over a large swath of the nuclear chart. Most of the regions of interest lie off the valley of stability (e.g. neutron-rich Mo-Zr or rare-earth nuclei). These can be reached by using deep-inelastic reactions with either intense stable beams or reaccelerated neutron-rich beams from radioactive beam facilities. Properties of ground-state sequences need to be measured and GRETA will be essential for these studies.

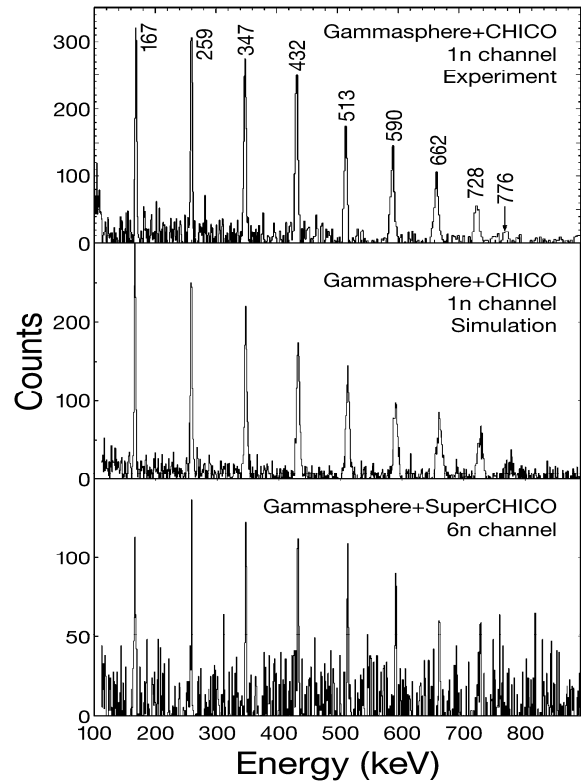


The expected locus (in blue) of nuclei showing the critical-point behavior of the rapid phase change from spherical to ellipsoidal deformation (taken from the RIA brochure “The Science of the Rare Isotope Accelerator (RIA) – A Brochure from the RIA Users Community”, February 2006).

The sensitivity gain from using GRETA for such deep-inelastic studies is illustrated by the case of a ^{238}U beam incident on a ^{170}Er target. The ground-state rotational structure, of the target-like fragment after a 1n-transfer channel, was clearly seen in an experiment using the Gammasphere+CHICO combination. The top panel in the figure shows the measured Gammasphere spectrum, while the second panel shows the corresponding simulated spectrum. The third panel shows the spectrum from GRETA, in combination with Super-CHICO, assuming the sequence is in a 6n-transfer channel (with a cross-section approximately 300 times less than the 1n-transfer). Clearly, GRETA will extend

the reach of deep-inelastic studies and open the way to a new generation of experiments exploring the evolution of nuclear structure and emergent collective properties far-from-stability.

Examples of experiments on symmetry properties of mass $A \sim 100$ nuclei made possible by GRETA include, (a) Using multi-nucleon transfer reactions with stable beam and target combinations, such as ^{96}Zr or ^{100}Mo and ^{238}U or ^{208}Pb to study ^{104}Zr , ^{106}Mo ; (b) Coulomb excitation of re-accelerated neutron-rich beams (to a limit of 10^4 beam pps) to measure transition rates in, for example, ^{108}Zr and ^{112}Mo .



The gain in experimental sensitivity using GRETA (together with a state-of-the-art heavy ion detector) for multi-nucleon transfer or Coulomb excitation reactions, compared with the present state of the art γ -ray detector Gammasphere. The upper panel shows data taken using Gammasphere and CHICO to study the 1n transfer channel from reactions of a ^{238}U beam on ^{170}Er target. The middle panel shows the corresponding simulated spectrum. The lower panel shows a simulation for a 6n transfer reaction (assumed to have a cross section 300 smaller than the 1n transfer channel) that would be possible using GRETA and SuperCHICO.

Dipole Resonances

Collective dipole excitations are a general phenomenon of finite fermion systems. In atomic nuclei they can, for instance, arise from out-of-phase oscillation of the proton and neutron “fluids” giving the well known Giant Dipole Resonance (GDR) at excitation energies of $\sim 15\text{--}20$ MeV. In metallic clusters, E1 modes have been observed corresponding to positive ions oscillating against the electron cloud, and more recently there have been predictions for dipole modes in quantum dots due to the motion of the confined electrons and holes.

While the GDR is the dominant E1 mode in nuclei there is evidence for an excess of E1 strength at significantly lower energies in the vicinity of the 1-neutron emission threshold. This strength is usually referred to as the Pygmy Dipole Resonance (PDR). In analogy to the GDR, the PDR has been interpreted as a collective oscillation of a core of equal numbers of neutrons and protons against a neutron excess. The occurrence of non-statistical low-lying E1 strength can influence (γ, n) reaction rates, for example, in hot stellar scenarios for nucleosynthesis.

So far, the majority of information on the PDR has come from Nuclear Resonance Fluorescence experiments on stable nuclei and Coulomb dissociation experiments on neutron-rich unstable nuclei. GRETA will provide a powerful new tool to study and characterize “resonant” states near to particle threshold using high-resolution γ -ray spectroscopy, and specifically γ -ray coincidences. In these experiments the PDR will be excited by heavy-ion Coulomb/inelastic scattering at ~ 20 MeV/A. With this method either stable or unstable nuclei (i.e. neutron-rich radioactive beams) can be studied. GRETA’s increased efficiency for high energy γ rays will give a factor of ~ 30 improvement for the detection of high- E_γ (6 MeV) – low- E_γ (1 MeV) coincidences, and the 4π coverage and high granularity will be needed to cleanly isolate the low γ -ray multiplicity events that will characterize the decays of these states.

3.1.4. The Nucleus as an Open Quantum System

A nucleus is not an isolated system; it interacts with its environment and communicates with other nuclei through decays and captures. If the continuum space is not considered, this communication is not allowed: the system is closed; such an approximation is often made in nuclear structure calculations. In exotic, weakly-bound nuclei, particle and cluster thresholds appear

particularly low; hence, their properties are strongly affected by open, or scattering, channels. The proximity of the scattering continuum in weakly bound and unbound nuclei, implies that these nuclei cannot be properly described without taking into account the coupling between discrete states and the continuum of positive energy states, thus one must treat bound, resonant and continuum states on an equal footing. In addition to the cases at the neutron and proton driplines, threshold phenomena are expected at higher excitation energy where new decay channels open up. Here, a good example is particle decay competing with γ decays in rotational bands. How GRETA can help us make significant progress in this exciting areas of current research is discussed below.

Decay studies of neutron-rich nuclei

Decay spectroscopy is the best method to discover and study the low energy levels in new neutron-rich nuclei. Such measurements charting the evolution of single-particle states and the deformation of very neutron-rich isotopes are likely to be first to observe the predicted changes in the shell structure. However, to achieve this goal, advances in the production of exotic isotopes as well as γ -ray detection are necessary.

Decay spectroscopy experiments rely on the efficient detection of γ rays and GRETA will offer an order of magnitude in efficiency compared to systems presently in use. In addition, the high granularity of each detector element in GRETA combined with digital signal processing will allow new opportunities in the selection of rare signals associated with β^- decays. In particular, shallow-penetrating β particles compared to deep-penetrating γ rays can easily be identified and separated. The identification of β -delayed γ radiation at rates below one ion per hour may become feasible. At present such limits are at about 100 ions/hour.

With production rates expected for a future major US radioactive beam facility it should become possible to study the decay properties of all r-process nuclei between $N=50$ and $N=82$, as well as significantly advance studies between the $N=82$ and $N=126$ shell closures.

Proton emitter studies

With the departure from the line of β stability the binding energy of constituent nucleons (protons on the proton-rich side and neutrons on the neutron-rich side) decreases until the nucleons become unbound at the driplines. Small binding energy can lead to halos, a larger diffuseness of the nuclear potential, and a mix-

ing of bound states with the continuum. In addition, unbound nucleons can be spontaneously emitted from a nucleus. At the neutron dripline profound changes in nuclear structure are expected. On the proton-rich side protons are confined temporally by the Coulomb barrier and new phenomena are expected to set in gradually. However, the proton dripline can be accessed experimentally now while the neutron dripline studies are limited to only a handful of light nuclei. New detection techniques, such as γ -ray tracking, will allow precise mapping out of the transition between well confined and open nuclei across the proton drip line.

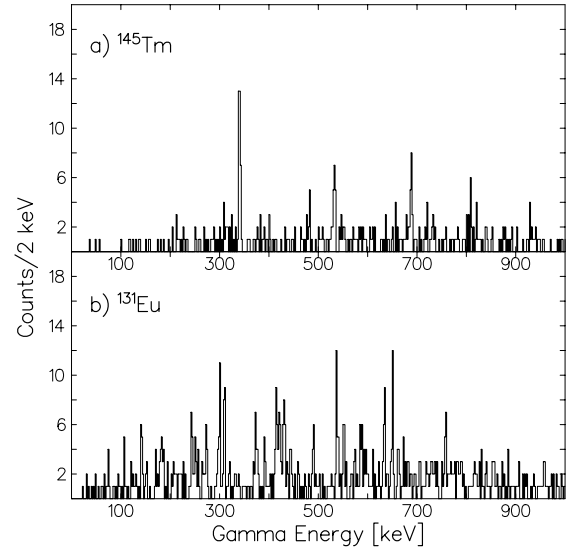
The limit of nuclear existence on the proton rich side of the line of β stability is delineated by nuclei spontaneously emitting protons. Proton emitters are a unique laboratory for studying quantum tunneling through a 3-dimensional Coulomb barrier. They are also a source of information on nuclear structure far from the line of stability as proton decay rates depend on the single particle content of proton decaying states, which depends on the shape of the nuclear potential, and on the strength of the pairing interaction. Proton decay studies can be also combined with in-beam γ -ray spectroscopic methods offering a glimpse at these loosely bound nuclei at high excitation energy and angular momentum.

Gammasphere coupled to the Argonne Fragment Mass Analyzer has successfully studied excited states in several deformed proton emitters along the island of deformation between $Z=50$ and $N=82$. (Similar studies have been performed at ORNL using the Recoil Mass Spectrometer and CLARION γ -ray array.) Figures a) and b) below contain γ -ray spectra obtained for the deformed proton emitters ^{145}Tm and ^{131}Eu , respectively.

Both proton emitters were produced with cross sections of about 300 nb and are representative of the current experimental limit. In panel a) of the following figure a regular sequence of γ rays can be easily seen and was interpreted as a $\pi h_{11/2}$ decoupled ground state rotational band. The spectrum in panel b) of the following figure is much more complex as several rotational bands are present close to the yrast line. In order to discern the ^{131}Eu decay level scheme γ - γ coincidences have to be measured. The γ - γ data obtained with Gammasphere are inconclusive. Thus to make progress in these studies better γ -ray detection capabilities are needed.

Using the fact that the efficiency of GRETA is 40% (4 times that of Gammasphere) and that GRETA crystals (which cover twice the solid angle compared to Gam-

masphere crystals) can count up to 50 kHz (5 times that of Gammasphere), resulting in an increase of the maximum beam current by 2.5, then a factor of $40 = 4^2 \times 2.5$ increase will be obtained in the number of detected γ - γ coincidences. This will certainly make the determination of the ^{131}Eu structure possible. Similar arguments apply to other well deformed proton emitters such as, ^{117}La . In addition, in-beam studies could now be extended to deformed odd-odd proton emitters such as, ^{130}Eu and ^{144}Tm , which are produced with cross sections of about 30 nb.



Current state-of-the-art prompt γ -ray spectra correlated with the deformed proton emitters a) ^{145}Tm and b) ^{131}Eu . These data were collected using Gammasphere. GRETA will allow an improvement factor in statistics of ~ 40 pushing dripline spectroscopy to new levels of sensitivity.

Discrete charged-particle decay in $A \sim 60$ nuclei

A challenging, “new” decay mode has been uncovered in the $A \sim 60$ mass region. Single and often multiple discrete-energy proton- and alpha-particle decays have been observed from the highly deformed to otherwise shell-model spherical structures. The cross sections for these decays are very small and their observation was only possible by combining the power of Gammasphere with auxiliary charged-particle arrays, first the Microball and then a Si wall coupled to the Microball. To further explore these exotic decays and to uncover the underlying physics behind these decays the power of GRETA coupled with new highly segmented charged-particle arrays will be needed. New areas of such decay will also be found in the proton rich nuclei up to around ^{100}Sn . A first example may be the recently reported ^{94}Ag proton-decay.

3.2. What are the properties of nuclei at the limits of mass and charge?

Heavy Element Research

The quest for superheavy nuclei and an understanding of their formation and stability has always been a defining challenge for nuclear structure physics. Their very existence depends on stabilization by quantal shell effects, at charge $Q > 100e$ the Coulomb energy is sufficient to destroy the stability of any conventional drop of nuclear matter. Studying the coalescence of nuclei which can form these systems, the fission barriers which inhibit their instant decay, and the modes of excitation they can sustain, all provide details of the delicate balance of forces which are in play. Thus, these studies deepen and generalize our understanding of all nuclei.

For many years the most fruitful avenue of research in this field has been synthesis of superheavy nuclei through heavy ion fusion. Their existence and relative stability can be determined by observation of the groundstate decay modes. This research has taken us from $Z=98$ to $Z=113$, by cold fusion of ^{208}Pb and ^{209}Bi and heavy ions, and recent research suggests progress to $Z=118$ using hotter fusion of a ^{48}Ca with actinide targets. This approach has been critical in defining the topology of the mass surface in very heavy systems. However, as production cross-sections are extremely low, at the parts-per-trillion level, addressing the issues underlying the causes of stability are difficult.

In this century, a new paradigm for understanding superheavy nuclei, through the detailed spectroscopy of slightly lighter elements has already made important contributions to our understanding of all heavy systems. A new field of γ -ray spectroscopy has started on nuclei with $Z > 100$. Already, the shapes of these very heavy systems have been conclusively determined, and the spin-dependence of the fission barriers studied. The location of critical states at the Fermi surface have been determined, both in studying spectroscopy of odd- A nuclei and by locating K-isomeric states. The latter results have directly challenged the issue of locating gaps in the single-particle sequence in the heaviest nuclei. These experiments have only become possible with recoil separators, to identify successful synthesis, and the γ detector arrays of the Gammasphere generation. Even in the best cases, fusion is at the parts-per-million level, and spectroscopy is at the very limit of what is feasible. We continue to refine our experiments and are approaching experiments at the

tens of parts-per-billion level. To make further real progress, to the parts-per billion level, a new generation of detectors is critical.

The GRETINA array will allow substantial progress to be made in this field when operated with recoil separators like the Fragment Mass Analyzer (FMA) at ANL or the Berkeley Gas-filled Separator (BGS) at LBNL. High intensity heavy ion beams, of hundreds of particle nanoamps, are needed to produce the nuclei of interest. The beams are sufficiently intense that large target wheels are needed to prevent melting. Prompt γ spectroscopy, the study of γ rays emitted during coalescence and cooling at the synthesis position, is limited by countrate as the dominant fission reaction process produces γ rays copiously. The new generation of detectors with digital pulse processing, can be tuned for high countrates, and can sustain rates 5-10 times higher than traditional systems. Further, the compact nature of the array will allow the residues to be more efficiently collected, and the beam-dump better shielded. In all, a factor of 100 improvement should be feasible, leading to experiments in the parts-per-billion regime. This should allow detailed spectroscopy above $Z=104$ to be started for the first time.

GRETA will allow even more sensitive studies. At the target position, another significant gain can be made in “high-fold” detection of more than one γ -ray, possibly increasing sensitivity by another order of magnitude. Perhaps more significant are the prospects of performing high resolution calorimetry; determining the spin dependence of the fission barrier by measuring the entry distribution of γ rays in nuclei which survive coalescence and determining if and how it falls at very high atomic numbers. These measurements provide unique insights into the coalescence mechanism, particularly determining which partial waves lead to fusion. Until very recently, the conventional assumption was that only very low partial waves can contribute. However, it is now clear that this is not so. Perhaps the biggest gain can be achieved in delayed isomer spectroscopy. Locating GRETA at the focal plane of a gas-filled spectrometer (which allows the most efficient collection of heavy residues) could provide an experimental environment in which isomers formed with cross-sections well below the part-per-billion level could be measured, in nuclei with $Z > 106$. In this case, the tracking capability will be essential in suppressing γ backgrounds, as at very low production levels, it becomes essential to understand the genesis of each photon detected.

3.3. What are the properties of nuclei at the limits of angular momentum?

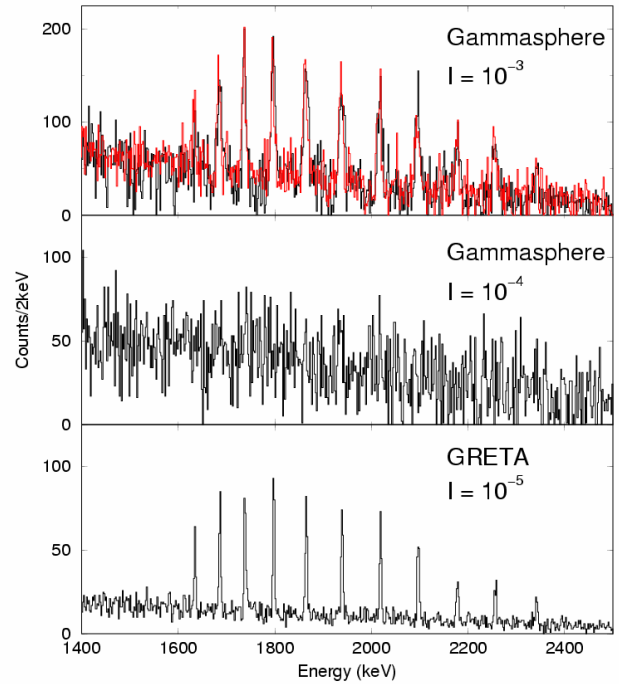
Nuclear Hyperdeformation

The shape of the atomic nucleus is governed by a delicate interplay between macroscopic liquid-drop properties and microscopic quantal effects. As discussed above, the heaviest elements survive only because of shell stabilization. Their ability to sustain rotational states above $20\hbar$ indicates that the fission barrier may be more robust than previously thought. A similar situation occurs for hyperdeformed (HD) nuclei, which are associated with a third minimum in the potential energy surface of rapidly rotating nuclei. The extreme deformation (approaching a 3:1 major-to-minor axis ratio) is predicted to occur at the very limits of sustainable angular momentum before the nucleus undergoes fission. The observation, and detailed spectroscopy, of HD structures will allow us to study the interplay between macroscopic shape effects (the role of the surface is of particular importance), shell stabilization, and angular momentum. There have been suggestions of the first glimpses of HD in the rare-earth and actinide regions but definitive identification of discrete-line HD sequences will be a major achievement for nuclear physics.

Understanding the conditions of formation, survival, and decay of these exotic nuclei will be extremely challenging. There is likely to be only a small entry window in the excitation energy-spin plane, close to the fission limit, through which to populate these states. Entrance channel effects (for instance, static and dynamical shape distortions) might determine the delicate balance required for their formation. The survival of HD structures is dependent on the fission barrier and shape relaxation effects. We will learn a great deal on these topics by studying HD nuclei which lie at the extremes of nuclear deformation and angular momentum. In order to address all these issues GRETA will be an absolute necessity.

The sensitivity gain from using GRETA for this type of high-angular-momentum experiment is illustrated by the case of ^{108}Cd . A weak rotational structure, with an intensity of $\sim 10^{-3}$ of the total fusion cross-section has been seen at high angular momentum in an experiment with Gammasphere. This structure corresponds to a very deformed prolate shape, possibly exceeding a 2:1 major-to-minor axis ratio. The top panel shows the measured Gammasphere spectrum (black) together with the corresponding simulated spectrum (red). This

is the observational limit for current detector arrays - a band with intensity of 10^{-4} would not be seen today (middle panel). The bottom panel shows a simulation from GRETA where we have assumed the band is 10 times weaker still (i.e. an intensity of 10^{-5}). This ~ 100 fold increase in resolving power will open the way to a new generation of experiments at high angular momentum and the detailed investigation of topics such as hyperdeformation using intense stable beams available today and re-accelerated neutron-rich beams from future radioactive beam facilities.



Simulation of GRETA performance for high multiplicity γ -ray data. The upper panel shows the spectrum (black) of the very deformed rotational band in ^{108}Cd obtained with Gammasphere using 4-fold data. This band carried $\sim 0.1\%$ of the reaction cross-section. The spectrum in red is the corresponding simulated spectrum for Gammasphere. The middle panel is a simulation for Gammasphere assuming the band carries 0.01% of the intensity. This intensity is at (beyond) the sensitivity limit for Gammasphere. The bottom panel is a simulation for GRETA assuming the band has an intensity of 0.001% (100 times weaker than the structure presently observed).

A specific example of a hyperdeformation experiment would be the reaction of a ^{48}Ca beam on a ^{64}Ni target to produce ^{108}Cd , where recent calculations predict hyperdeformed structures at a spin of $\sim 70\hbar$. This is beyond the reach of today's experimental sensitivity, but

within the reach of GRETA. In addition, reaccelerated radioactive beams of, e.g. ^{94}Kr , will give access to neutron-rich Cd isotopes up to ^{114}Cd , where hyperdeformed structures are predicted to be favored at even lower spins and where GRETA's 100 fold increase in sensitivity will be needed to compensate the lower beam intensity.

3.4. Nuclear astrophysics , fundamental interactions and rare processes

3.4.1. Nuclear Astrophysics

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. There are a number of measurements in the area of nuclear astrophysics that will benefit greatly from a highly efficient γ -ray tracking detector array such as GRETA. For example:

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 $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ or $^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ 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 are often detected in singles. These signals can be easily masked by backgrounds from cosmic rays and natural radioactivity in a typical experimental hall. Surrounding such a target with a tracking detector like 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 many (~ 30) important measurements of this type that would benefit from this approach. It should be noted that these experiments will require beam times of a month or more.

Many studies of stellar explosions involve inverse capture reactions of radioactive ion beams on gas targets. By the time of GRETA, it is highly likely that gas jet targets in which the high density gas is localized to ~ 2 mm coming out of a nozzle will have been developed for this class of experiment. The use of γ -ray tracking detectors like those in GRETA closely-packed around the target will help reduce the very high backgrounds from 511 keV annihilation radiation along with cosmic-ray induced events. GRETA will provide high efficiency for $\sim\text{MeV}$ γ rays, and high energy resolution to reconstruct the cascade γ -ray decays in cases where there is a reasonably high level density. Of the order of ~ 20 important measurements would benefit and be made possible using GRETA.

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 GRETA 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, utilizing both stable and radioactive beams.

3.4.2 Fundamental Interactions and Rare Processes

A γ -ray tracking array like GRETA 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 GRETA would essentially remove this error from current measurements, allowing an improvement in the precision of the branching ratio of a factor of 10 or more.

GRETA with its 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. Technical Accomplishments towards a 4π Gamma-Ray Tracking Array

The concept of a γ -ray tracking detector array was proposed in 1994, and after about ten years of R&D, the technology was in place to construct such a detector. The Department of Energy made the Critical Decision-0 (CD0) for GRETA in August 2003 to construct a tracking detector covering one-fourth of the total solid angle. Since then the project has proceeded according to schedule and is planned to be completed in 2010. In the following, we will give a short summary of technical accomplishments.

Detector

The critical detector technology is the manufacture of two-dimensionally segmented coaxial germanium detectors which provide signals with sensitivity for locating interaction points in three dimensions. In addition, the crystals should have large volume and be shaped into tapered irregular hexagon shapes for close packing into a spherical shell with high solid angle coverage. We have been working closely with a detector manufacturer to develop such detector. The final prototype has three tapered crystals in a cryostat, each segmented into 36 segments. Extensive tests have demonstrated that this detector will meet the requirements of γ -ray tracking. The geometric design of GRETA uses 120 crystals packed in 30 cryostats. The first production 4-crystal detector module was ordered and was delivered at the end of 2006.

Electronics

Determining the interaction position in three dimensions requires a detailed analysis of the pulse shapes. The pulse shape needs to be recorded at sampling rate about 10 MHz and a resolution of at least 12 bits. We have produced a prototype signal digitizer using commercially available parts. To reduce the amount of data to be stored, online processing in the electronic module generates energy, time, and trigger information, as well as capture of the relevant portion of the pulse shape for signal decomposition by a computer farm in real time. A trigger and timing system will carry out complex trigger decisions and distribution clock and trigger information to GRETA and auxiliary detectors. The design of the production version of both the digitizer and trigger modules is completed and the modules will be fabricated and be available for testing in early 2007.

Signal decomposition

In order to perform γ -ray tracking, the positions and energies of the γ -ray interactions in the Ge (usually several Compton scattering events, followed by photoelectric absorption) must be accurately determined from the signal waveforms. The procedure must handle cases where two or more interactions occur within one of the detector segments. An algorithm to perform this "signal decomposition" has been developed, by combining several methods such as Singular Value Decomposition, adaptive grid search, and constrained least-squares. It utilizes calculated signal waveforms, and incorporates such effects as the preamplifier response and two different types of cross talk. We have shown experimentally that this algorithm can achieve an average position resolution of at least 2 mm.

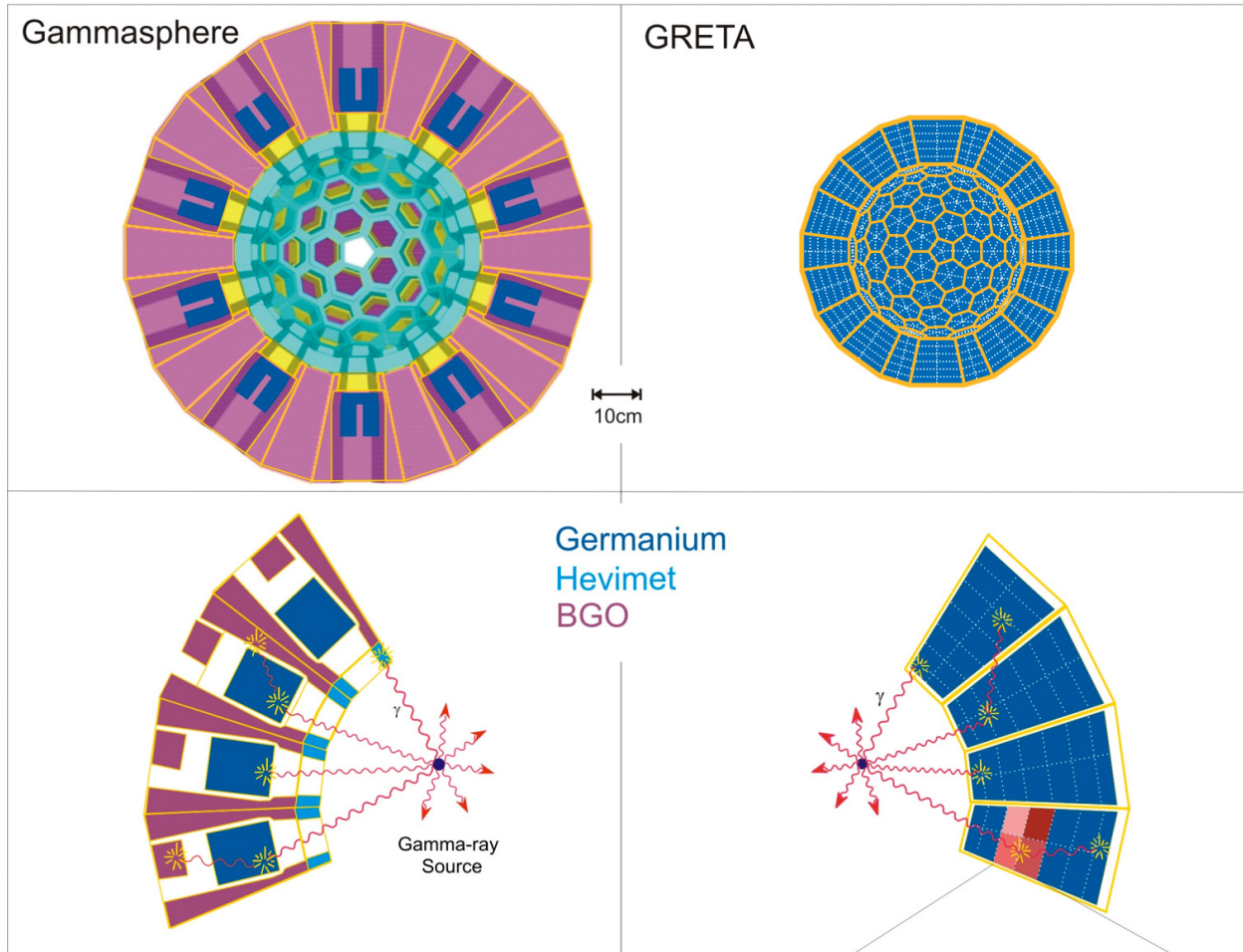
It is important that the signal decomposition be performed in real time, so that large quantities of waveform data need not be stored. However, this requirement means that the signal decomposition forms the data acquisition bottleneck; computational speed is therefore very important. On the current generation of 2 GHz processors, the algorithm requires less than 10 ms of CPU time per hit segment. With advances in processing power from multi-core CPUs, this performance will be sufficient to meet our requirements.

Tracking

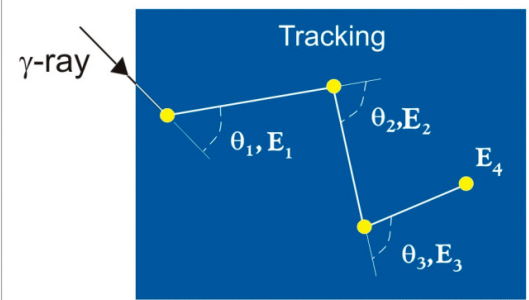
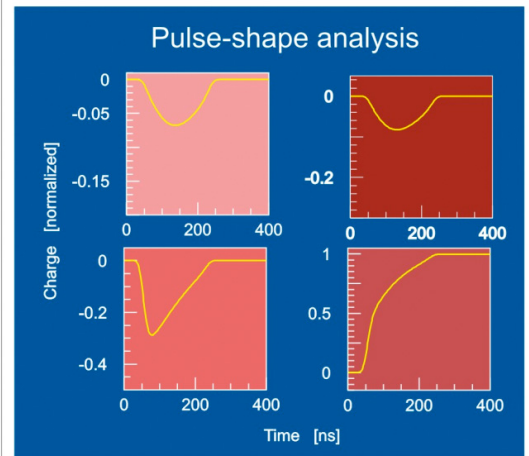
The tracking process uses the energies and positions of the interaction points produced by the signal decomposition to determine the scattering sequence for a particular γ -ray. Algorithms have been developed to track events based on Compton scattering, pair-production and photo electric interactions. Tracking efficiency achieved ranged from $\sim 100\%$ to 50% with γ -ray multiplicity changed from 1 to 25. The current tracking algorithm needs $\sim 10\%$ of the planned computing power.

End-to-End tests

The three-crystal prototype detector has been subject to several end-to-end tests with all of the 111 segments instrumented with signal digitizers. Measurements were carried out using γ -ray sources, and with γ rays produced in-beam at both the 88-Inch Cyclotron at LBL and the NSCL at MSU. At MSU, γ -particle coincidence data were taken with fragments detected in the S800 spectrograph. The full data analysis process, including event building, signal decomposition, and tracking, was performed. Results indicated that a position resolution of about 2 mm (RMS in all three dimensions) can be achieved with the prototype system.



This figure illustrates the basic principles of γ -ray tracking. 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 γ 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.



5. Auxiliary detectors for GRETA

Auxiliary detectors continue to play a very important role in γ -ray spectroscopy with Gammasphere where they augment tremendously the physics that can be achieved. With GRETA, a number of auxiliary detectors will play an even more important role. A major advantage of GRETA, in addition to its higher efficiency, is the energy resolution for in-beam studies, as emphasized in Section 3. This results from the considerably smaller opening angle ($\sim 2^\circ$ in θ and ϕ compared to 7° for Gammasphere). But in order to make good use of this angular resolution for Doppler corrections the angle of the recoiling nucleus must now also be determined with comparable angular resolution.

Thus a new generation of auxiliary detectors is needed with higher segmentation and higher counting rate capabilities than any of the existing devices which include, (i) **Microball**: a 95-element 4π -CsI(Tl) detection system for protons and alpha particles, (ii) **HERCULES**: a 64 element fast scintillator-system that can count and separate fusion evaporation residues with high efficiency in the presence a copious amounts of fission and elastic scattering, (iii) **CHICO**: a 4π parallel-plate avalanche counter that can identify deep inelastic and Coulomb excitation in nearly symmetric reactions, (iv) **Si-strip detectors**: highly segmented high resolution charged particle detection systems, and (v) a “**Neutron Shell**” consisting of 30 liquid scintillators for neutron counting.

Below we summarize some of the next generation auxiliary detectors along with examples of the physics opportunities where these devices are essential.

Nanoball

The Nanoball is a new highly segmented light charged particle system with 4π solid angle coverage. This detector will have the same segmentation as the current Microball but it will use much faster scintillators. This will allow the same exit channel selection and recoil direction determination, higher counting rates and preserve the ability to determine optimally the nuclear spin direction event by event. This device will often be coupled to a Si ΔE Wall and/or the Neutron Shell. One of the important areas of study where the Nanoball is essential is the structure of nuclei with $N=Z$, $Z-1$ and $Z-2$ for mass regions below $A\sim 100$, such as:

- Spectroscopy in $N=Z$ nuclei

- The “charge independence” of heavier isospin multiplets
- The discrete-energy charged particle decay from excited states

In these studies, the combination of the Nanoball, Si Wall, the Neutron Shell and GRETINA/GRETA will be unsurpassed in providing the necessary channel selection, recoil correction capability and high energy resolution for particle spectroscopy.

SuperHERCULES

SuperHERCULES is a highly segmented evaporation residue detection system. It will use fast plastic detectors coupled to phototubes with a segmented anode. It will have a higher segmentation than the current HERCULES detector. SuperHERCULES provides a way to study the structure of heavy nuclei that is complementary to the setups using a magnetic separator. It will provide a unique tool for studying fusion reactions induced by light projectiles where the recoil energies are too low for magnetic separators. In addition, many evaporation residues in the neighborhood of ^{254}No are beyond the reach of a separator acceptance because they require production by (HI, α xn) reactions.

The combined use of the Nanoball with the Neutron Shell and in some instances with SuperHERCULES will be crucial for both channel selection and high-resolution spectroscopy of the structure at high spins using fusion reactions near the barrier in the mass regions $A\sim 80$, 60 and $A\sim 40$. Here a few current topics of interest are:

- Discrete line proton and alpha decay of highly deformed structures around $A\sim 60$, and searches for such decays in the neighboring $A\sim 40$ and $A\sim 100$ mass regions.
- Multi-particle multi-hole excitations and “high-purity” terminating states in the $40 \leq A \leq 48$ region.

MicroWall (a phoswich detector system)

This detector is a fast plastic plus CsI(Tl) phoswich arrangement to provide Z resolution and sustain higher rates than the Microball. It will have a segmentation comparable to that of SuperHERCULES.

With the advent of the CARIBU and the future “RIA” facility it becomes necessary to explore all possible avenues to study the properties of the neutron rich nuclei for which only beams can be produced. Such reac-

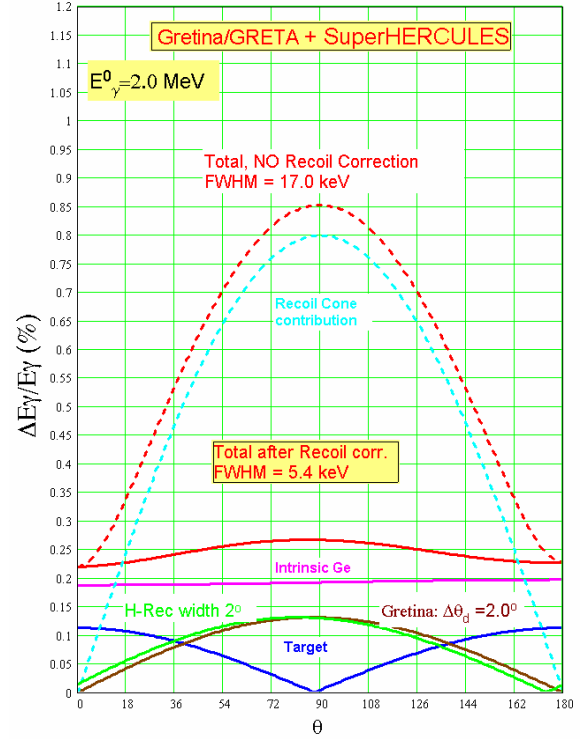
tions have been used at HRIBF to study neutron-transfer in reactions like $^{134}\text{Te}(^{13}\text{C}, ^{12}\text{C})^{135}\text{Te}$, see Section 3.1.1. In these reactions the projectile-like fragments are stopped in suitable absorbers while the target-like fragments (TLF) are emitted at larger angles with increasing cross sections and decreasing energies. This detector will detect the TLFs and provide the necessary angular resolution, Z identification, and time of flight information, as well as handling the high counting rates required for these studies.

SuperCHICO

SuperCHICO is a 4π position-sensitive heavy-ion detector with an angular resolution of $1^\circ \times 1^\circ$ for θ and ϕ respectively as compared to the $1^\circ \times 7^\circ$ for the current CHICO detector. Such a detector is required for the kinematic reconstruction of transfer, Coulomb excitation, and fission reactions and will lead to nearly an order of magnitude improvement in γ -ray energy resolution. This will greatly expand the opportunities for advancing nuclear structure studies to higher spin, heavier mass and to odd-Z nuclei. The physics opportunities provided include exploring the evolution of collective motion, single particle pairing correlations, and unusual isomeric configurations with increase in spin, isospin, or excitation energy.

In the figure below we show the contributions to the energy resolution for a typical fusion reaction $^{58}\text{Ni}(^{48}\text{Cr}, \alpha 2n)^{100}\text{Sn}$ at 170 MeV and a 0.5 mg/cm^2 thick target. They are: (a) intrinsic Ge resolution shown as magenta, (b) GRETINA/GRETA opening angle contribution in brown, (c) target thickness contribution in blue, (d) recoil cone contribution without recoil detection shown in dashed cyan, (e) recoil contribution after recoil detection with a device having 2° opening angle (SuperHERCULES), (f) Total resolution for a 2.0 MeV γ -ray without recoil correction (dashed-red curve) has a maximum FWHM of 17.0 keV, and (g) Total resolution with recoil correction with FWHM of

5.4 keV. For comparison with the same reaction, Gammasphere with HERCULES (4° opening angle) has uncorrected and corrected FWHM values of 20.3 and 11.3 keV, respectively.



Contributions of energy resolution from various sources for the reaction $^{58}\text{Ni}(^{48}\text{Cr}, \alpha 2n)^{100}\text{Sn}$. If uncorrected, the angular distribution of the recoil direction dominates the energy resolution. See text for details.

The above reaction is the best case scenario. For other reactions (transfer, deep inelastic reactions, etc.) with much larger recoil velocities the detection of the recoils is even more important.

6. Applications of Gamma-Ray Tracking Detectors

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 science, technology, medicine, and societal issues such as homeland security.

An important application to homeland security is 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 approximately 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 (PET, 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.

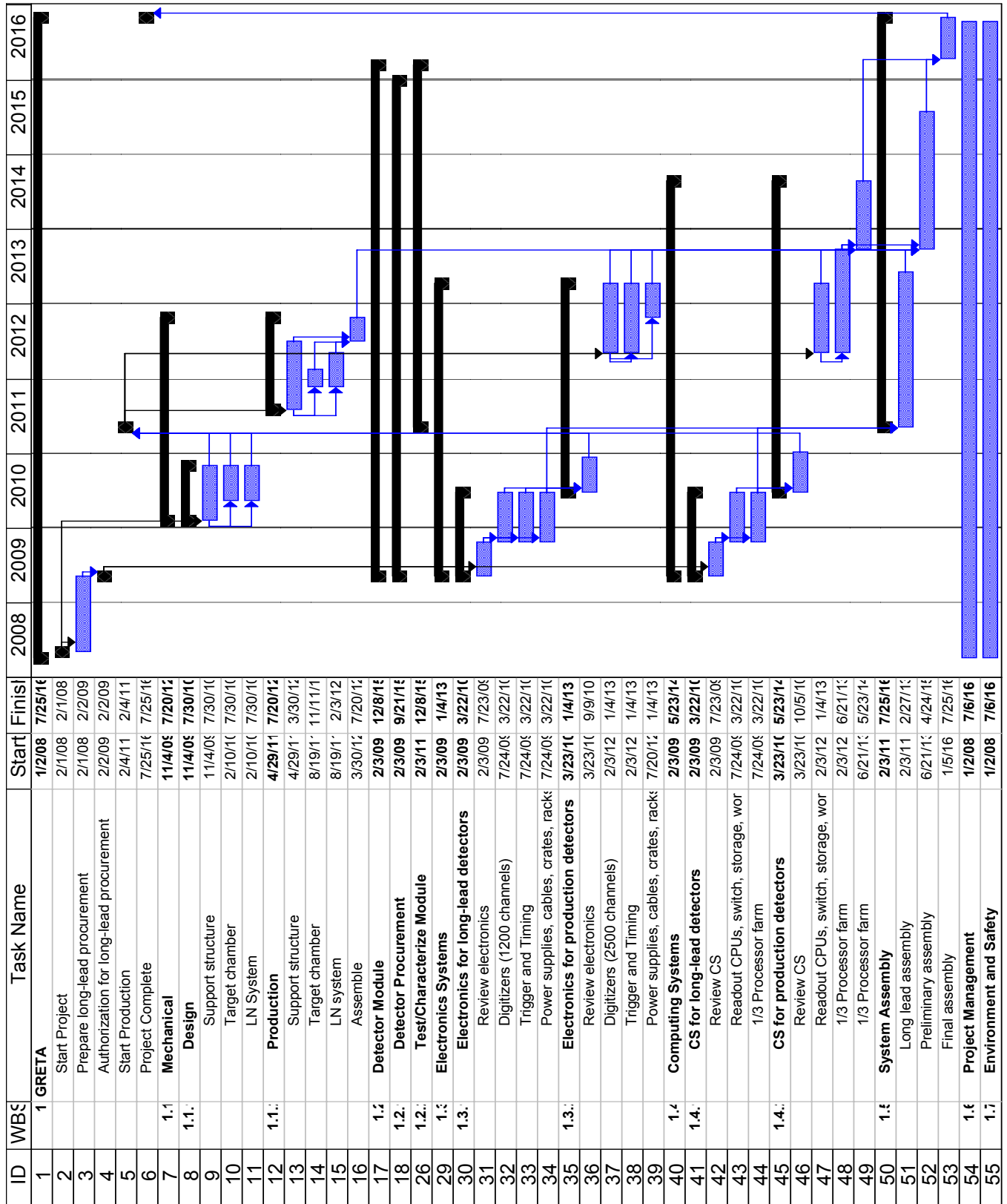
7. Cost Estimates for GRETA

In this section, we give a high level summary of the cost and schedule of GRETA. The estimated cost to complete GRETA, beyond the cost of GRETINA, is \$42M including escalation and contingency. The schedule is determined by the delivery of the germanium detector modules. We used the same delivery rate, 4 modules per year, as the GRETINA modules, and if funded the project could be completed in 2016.

Schedule

The figure on the following page shows the schedule of the high level WBS elements of GRETA. This schedule prevents conflict with GRETINA. The plan is to continue procuring detector modules after the final order for GRETINA modules has been placed. The project starts in FY08 with the preparation for the long-lead time procurement of the first four detector modules. The first order for detector modules is issued in FY09. In order to manage a continuing resolution scenario, all big orders are placed in early February. A new batch of electronics and computing systems is procured and assembled to instrument the detector modules delivered for the long lead procurement. The design of the 30 module detector support structure then starts. In parallel, preparations to place the contract for the remaining 19 detector modules will be underway. Production starts in FY11.

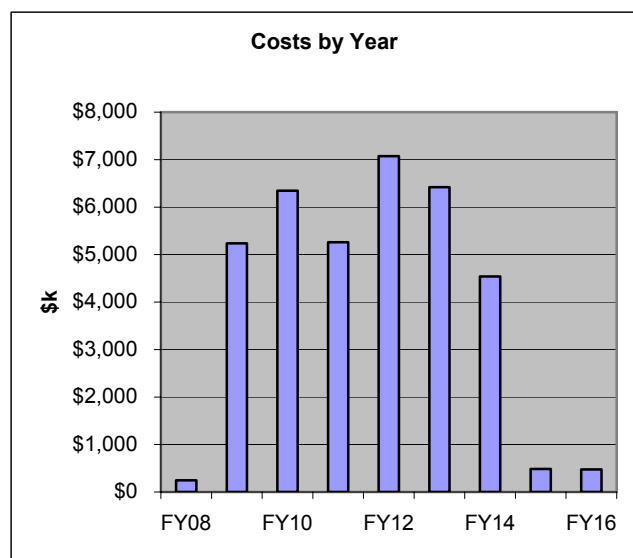
In FY10, after all GRETINA detector modules are received, we start receiving GRETA detector modules. We use the same approach used for GRETINA: the detectors are procured one year in advance, and they start being delivered one year after the order. We assume that the vendor will be able to deliver detectors at the same rate they are planning to deliver now: four modules per year. All detector modules are received by FY15, and FY16 is used to assemble all the systems and to perform the qualification tests. Project Management and Environment and Safety are on going activities during the duration of the project.



The detailed schedule for GRETA

Cost

Based on the schedule discussed above, we developed a funding profile in actual year dollars, as shown below. The table on the following page shows the breakdown cost summary for the GRETA in actual year dollars. All estimates have been inflated using escalation rates of 4% per year for material and labor assuming a funding profile that covers FY08 to FY16. This cost takes into account that GRETINA will be completed and its electronics, computing system and detector modules will be available to complete this 4π GRETA detector.



The funding profile for GRETA.

This cost estimate is based on the GRETINA cost estimate. It takes into account that most of the design is done during the GRETINA project, and that GRETA

will concentrate mainly in the procurement of more detector modules, and hardware for the Electronics and Computing System, as well as the testing and assembly into a system. However, the Mechanical Systems will require a new design of the support structure, to accommodate the additional 23 detector modules (a total of 30 modules).

The cost of the materials was projected to larger quantities (which includes savings). We have contacted Eurisy and we projected the price estimate of the detector modules to be \$1M per unit (in FY07 dollars). The detector price is derived by considering the unit price of €800k per module and an exchange rate Euro/Dollar of 1.25. In the current estimate, we applied escalation to this price. Although it is likely that we could obtain a fixed price contract in Euro, as we were able to do for GRETINA detectors.

Contingency allocation reflects the risk reduction due to knowledge and experience acquired with GRETINA. We have set the detector module contingency at 15%, which takes into account the risk of Dollar/Euro fluctuations in the exchange rate.

This cost estimate also assumes approximately the same level of redirected effort from Argonne National Laboratory, Lawrence Berkeley National Laboratory, the National Superconducting Cyclotron Laboratory at Michigan State University, Oak Ridge National Laboratory, and Washington University in St. Louis (for example, in the test and characterization of the detector modules, WBS 1.2.2 by MSU)

GRETA: The Future of Gamma-Ray Spectroscopy

WBS	Description	Cost (\$k)	Cont	Cont (\$k)	Total (\$k)
1	GRETA	\$36,235	17%	\$6,160	\$42,395
1.1	Mechanical	\$1,125	25%	\$280	\$1,406
1.1.1	Design	\$380			
	Support structure	\$325			
	Target chamber	\$0			
	LN System	\$55			
1.1.2	Production	\$745			
	Support structure	\$515			
	Target chamber	\$55			
	LN system	\$115			
	Assemble	\$60			
1.2	Detector Module	\$26,690	15%	\$4,005	\$30,694
1.2.1	Detector Procurement	\$26,690			
1.2.2	Test/Characterize Module	\$0			
1.3	Electronics Systems	\$3,280	25%	\$820	\$4,100
1.3.1	Electronics for long-lead detectors	\$1,100			
	Review electronics	\$195			
	Digitizers (1200 channels)	\$480			
	Trigger and Timing	\$105			
	Power supplies, cables, crates, racks	\$320			
1.3.2	Electronics for production detectors	\$2,180			
	Review electronics	\$270			
	Digitizers (2500 channels)	\$1,005			
	Trigger and Timing	\$240			
	Power supplies, cables, crates, racks	\$665			
1.4	Computing Systems	\$1,450	30%	\$435	\$1,885
1.4.1	CS for long-lead detectors	\$530			
	Review CS	\$155			
	Readout CPUs, switch, storage, workstations	\$160			
	1/3 Processor farm	\$215			
1.4.2	CS for production detectors	\$920			
	Review CS	\$160			
	Readout CPUs, switch, storage, workstations	\$210			
	1/3 Processor farm	\$300			
	1/3 Processor farm	\$250			
1.5	System Assembly	\$500	25%	\$125	\$625
	Long lead assembly	\$175			
	Preliminary assembly	\$190			
	Final assembly	\$135			
1.6	Project Management	\$2,955	15%	\$445	\$3,400
1.7	Environment and Safety	\$235	20%	\$50	\$285

Table: The Cost of GRETA

8. The Path to GRETA: Progress and Milestones So Far

1994 – First discussions at LBNL

1995 - Duke Town meeting

1996 - GRETA mentioned in Long Range Plan document

1997 - First prototype segmented detector received and tested

1998 - Workshop on GRETA physics (LBNL) - Workshop on experimental equipment for RIA (LBNL) - GRETA Advisory Committee formed

1999 - Second prototype segmented detector received and tested

2000 - Workshop on GRETA physics (MSU) - Proposal for a GRETA module cluster submitted to DOE

2001 - National Steering Committee for Gamma-ray tracking in Nuclear Structure Physics formed - Santa Fe meeting (2002 LRP) presentation and discussion - Workshop on Digital Electronics in Nuclear Physics (ANL) - Workshop on Gamma-ray Tracking Detectors for Nuclear Science (U. Mass. Lowell)

2002 - GRETA mentioned in Overview and Recommendations section of the 2002 LRP –Gamma-ray

Tracking Coordination Committee meeting (ANL) and report - Module cluster funded and ordered.

2003 - NSAC sub-Committee on Future Facilities presentation and report - Workshop on experimental equipment for RIA (ORNL) - GRETINA proposal written and submitted to DOE - CD-0 approval of GRETINA. Official start of project. - I.Y. Lee named as Contractor Project Manager and GRETINA Advisory Committee formed - Review of GRETINA project by LBNL -Review of GRETINA project by DOE

2004 - CD-1 approval for GRETINA - Facility Workshop for RIA at MSU - Workshop of GRETINA Detector Working Group at ORNL - Three Crystal Cluster prototype arrives in Berkeley - Workshop of GRETINA Software Working Group at LBNL - Workshop of GRETINA Electronic Working Group at ANL

2005 - CD-2A/3A approval for GRETINA -Workshop of GRETINA Software Working Group at FSU - First Quad-cluster module order sent out

2006 - Workshop of GRETINA Auxiliary Detector Working Group at St. Louis - Workshop of GRETINA Physics Working Group at FSU – Delivery of first Quad-cluster module (Dec)

For further information on the progress of GRETA/GRETINA over the past 4 years please see the annual newsletters which can be found at the official GRETA/GRETINA website <http://grfs1.lbl.gov/>

Appendix: The Management Structure of GRETINA

1. Management Advisory Committee

- James Symons (LBNL)
- Glenn Young (ORNL)
- Don Geesaman (ANL)
- Konrad Gelbke (MSU)

2. Contractor Project Manager

- I-Yang Lee (LBNL)

3. GRETINA Advisory Committee

- Con Beausang (Univ. of Richmond)
- Doug Cline (Univ. Of Rochester)
- Thomas Glasmacher (MSU)
- Kim Lister (ANL)
- Augusto Macchiavelli (LBNL)
- David Radford, **Chair** (ORNL)
- Mark Riley (FSU)
- Demetrios Sarantites (Washington Univ.)
- Kai Vetter (LLNL)

4. Working Groups and Chairs

- **Physics:** Mark Riley (FSU)
- **Auxiliary Detectors:** Demetrios Sarantites (Washington Univ.)
- **Electronics:** David Radford (ORNL)
- **Software:** Mario Cromaz (LBNL)
- **Detector Development:** Augusto Macchiavelli (LBNL)



This document was composed and edited by the GRETINA Physics Working Group, the GRETINA Advisory Committee and the Contractor Project Manager following a dedicated workshop entitled "The Future of Gamma-Ray Spectroscopy" held in Tallahassee FL, in August 2006. A list of participants along with presentations and a summary of the workshop can be found at <http://fsunuc.physics.fsu.edu/gretina>