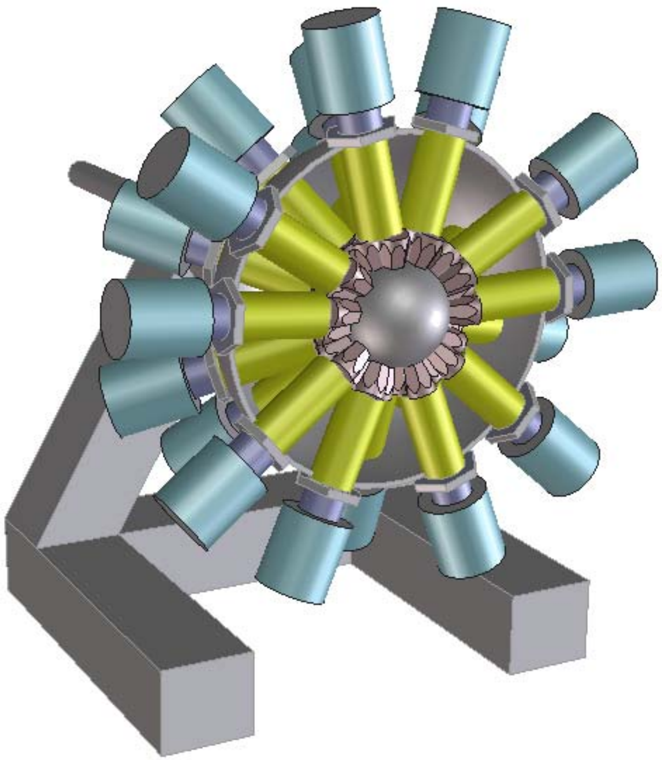
The Gamma-Ray Energy Tracking Array (GRETA): A key device for Nuclear Structure Physics



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

Thomas Glasmacher for the GRETA Steering Committee

GRETA addresses major science questions identified in the 2002 NSAC Long-Range Plan

- “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?”
- “What are the origins of the elements necessary for life?”

The science case for GRETA has evolved for almost a decade and has been made

- 1994 Conceptual design study
- 1998 Workshop on GRETA physics (LBNL)
- 2000 Workshop on GRETA physics (MSU)
- 2000 Proposal for a 3-crystal module cluster peer reviewed and funded
- 2001 Workshop on Gamma-ray tracking detectors for nuclear science (Lowell)
- 2002 Gamma Ray Tracking Coordination Committee meeting (ANL)
  ⇒ "*A National Plan for the Development of Gamma-Ray Tracking Detectors in Nuclear Science*"

2002 LRP

- "The detection of gamma-ray emission from excited states in nuclei plays a vital and ubiquitous role in nuclear science"
- "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."

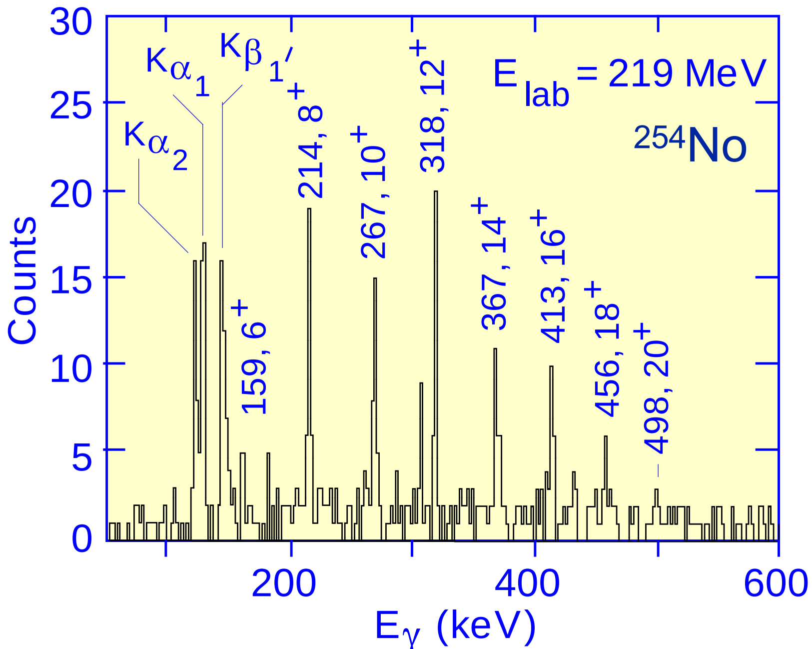
GRETA addresses questions in multiple areas of nuclear science

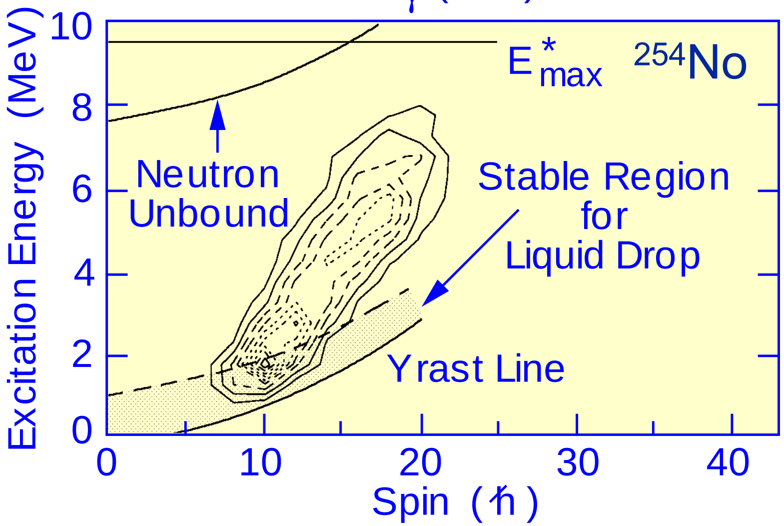
- GRETA is movable to address most important science questions at different accelerator facilities
- Choice between “breadth” and “depth” up to PACs
- Single-experiment device, but for some classes of experiments many exit channels yielding to many analyses

Science examples

- Examples
  - Nuclear Structure Physics
    - » Do dramatic changes in shell structure occur far from stability?
    - » What is the detailed wavefunction for exotic nuclei?
    - » How do collective shapes evolve in nuclei?
    - » Are the proton- and neutron fluids in nuclei deformed differently?
    - » What are the new symmetries, shapes and excitation modes at the limits of angular momentum and excitation energy?
    - » 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?
    - » When do shell effects melt away above the yrast line and how does chaos emerge out of order?
  - Astro-nuclear Physics
    - » Low-Energy Capture Reactions
    - » Nuclear Structure measurements of astrophysical relevance
  - Fundamental interactions
    - » Is the CKM matrix unitary? Are there undiscovered weak couplings or quarks?
    - » Beta delayed gamma emission: are there additional weak couplings?
    - » Parity violating weak intranuclear forces
    - » Identifying deformed nuclei impacts the search for atomic electric dipole moments
    - » Are the symmetries C, P, and T conserved in positronium annihilation?

Properties of super-heavy nuclei





What are the properties of super-heavy nuclei?
Why does a super-heavy nucleus not explode from Coulomb repulsion?

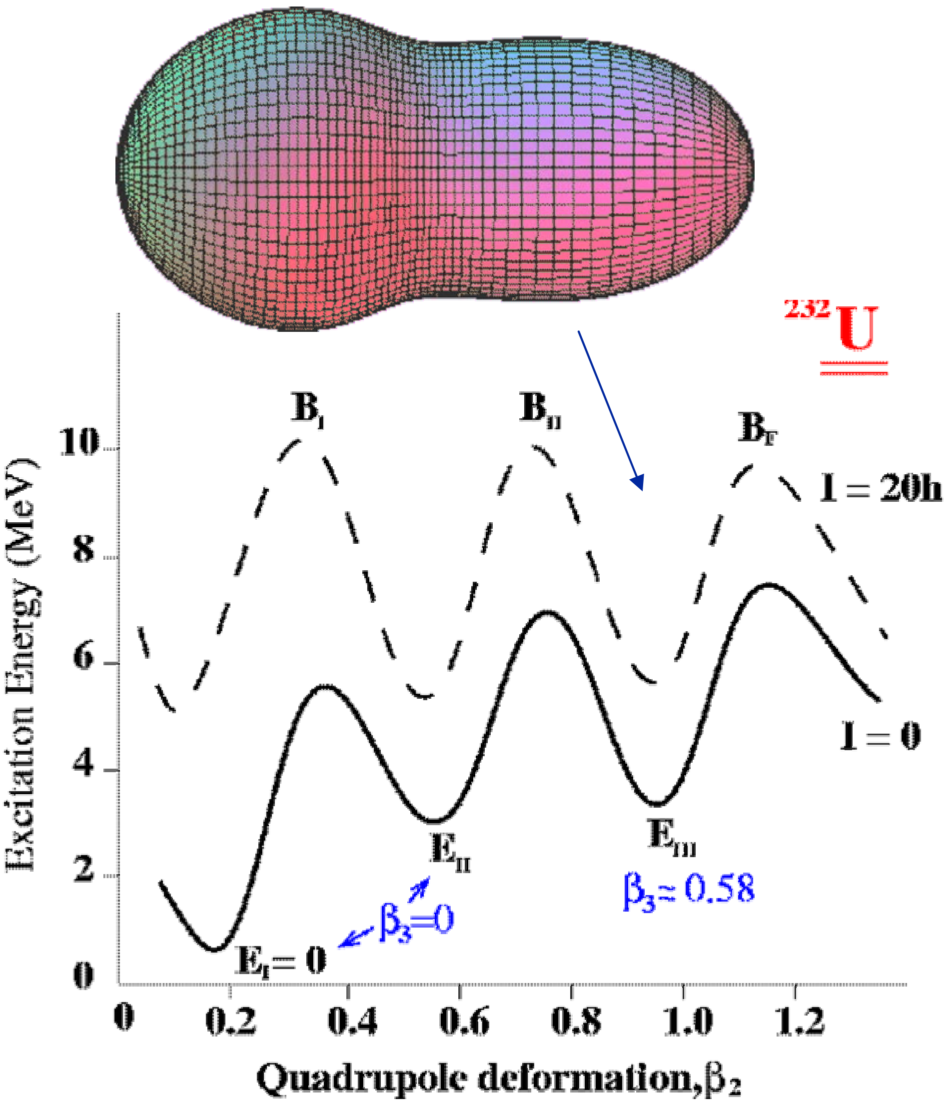
Experiment
- Fusion-evaporation with recoil-decay tagging trigger

Challenges
- Small cross section (1 μb – 10 nb)
- Fission background

The gamma-ray tracking advantage
- ☒ Resolving power
- ☒ Efficiency
- ☒ Count rate capability
- ☒ Linear polarization

P. Reiter *et al.*, Phys. Rev. Lett. **82** (1999) 509; **84** (2000) 3542.

Nuclei with extremely deformed shapes



How deformed can a nucleus become and what is its structure?

- Exotic shapes with 3:1 axis ratio
- Predicted to exist near fission limit: Very heavy nuclei or at high angular momentum

Challenges

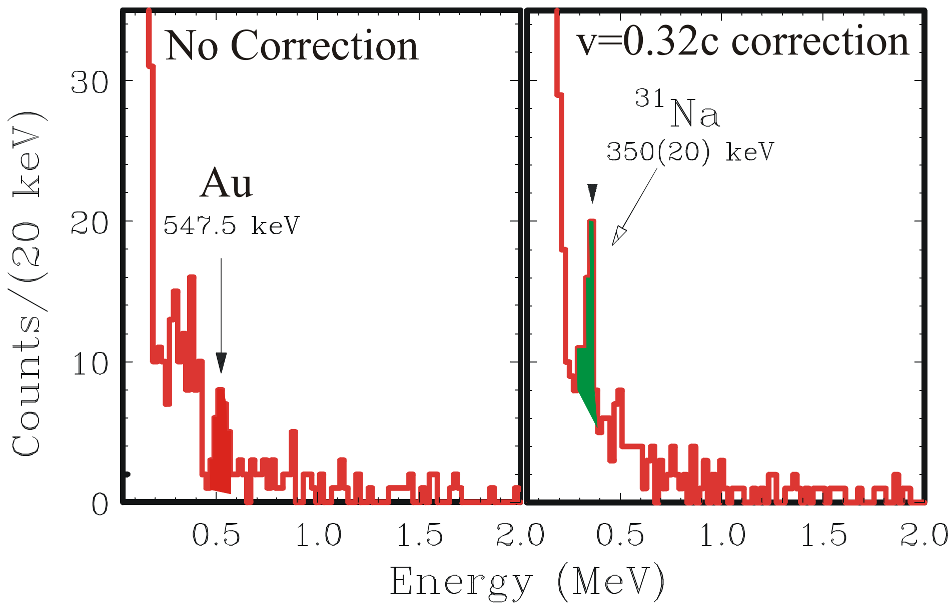
- Small cross section
- Weak channel
- Fission background

The gamma-ray tracking advantage

⌦Resolving power
⌦Efficiency
⌦Count rate capability
⌦Linear polarization

Measuring collective properties of neutron-rich nuclei with fast exotic beams

How do the structure and shapes of nuclei evolve when the drip lines are approached?



B.V. Pritychenko *et al.*, Phys. Rev. **C63** (2001) 011305(R).

Experiment

- Intermediate-energy inelastic scattering
- Thick secondary targets require γ-ray detection to indicate inelastic scattering

Challenges

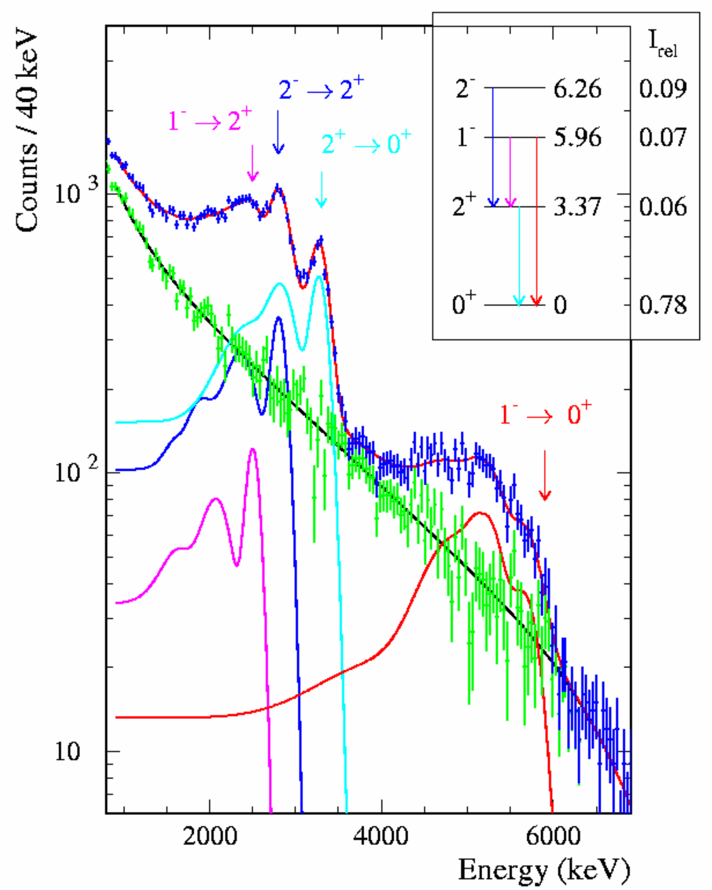
- Need γ-ray emission angle for Doppler-shift reconstruction
- Low beam rate (few/s)

The gamma-ray tracking advantage

⌦Efficiency
⌦Angular resolution
⌦Extends reach of NSCL CCF and RIA two neutrons further from stability

Mapping wave functions of exotic nuclei

What are the spectroscopic factors in the wave function of exotic nuclei?



T. Aumann *et al.*, Phys. Rev. Lett. **84** (2000) 35.

Experiment

- Intermediate-energy nucleon knockout
- Thick secondary targets require γ-ray detection to indicate inelastic scattering

Challenges

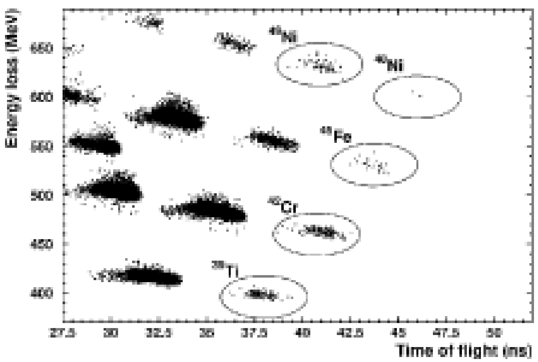
- Need γ-ray emission angle for Doppler-shift reconstruction
- Low beam rate (0.1/s)

The gamma-ray tracking advantage

☒ Efficiency
☒ Angular resolution
☒ Extends reach of NSCL CCF and RIA two neutrons further from stability

Beta-decay properties of the most exotic nuclei

What are the properties of the most exotic nuclei?



B. Blank *et al.*, Phys. Rev. Lett. **84** (2000) 1116.

Experiment

- Beta-decay after implantation
- Bound excited states of daughter
- Clean beta trigger, beta detection >98% efficient

Major challenge

- Minute cross section: 1 atom/week (fb)

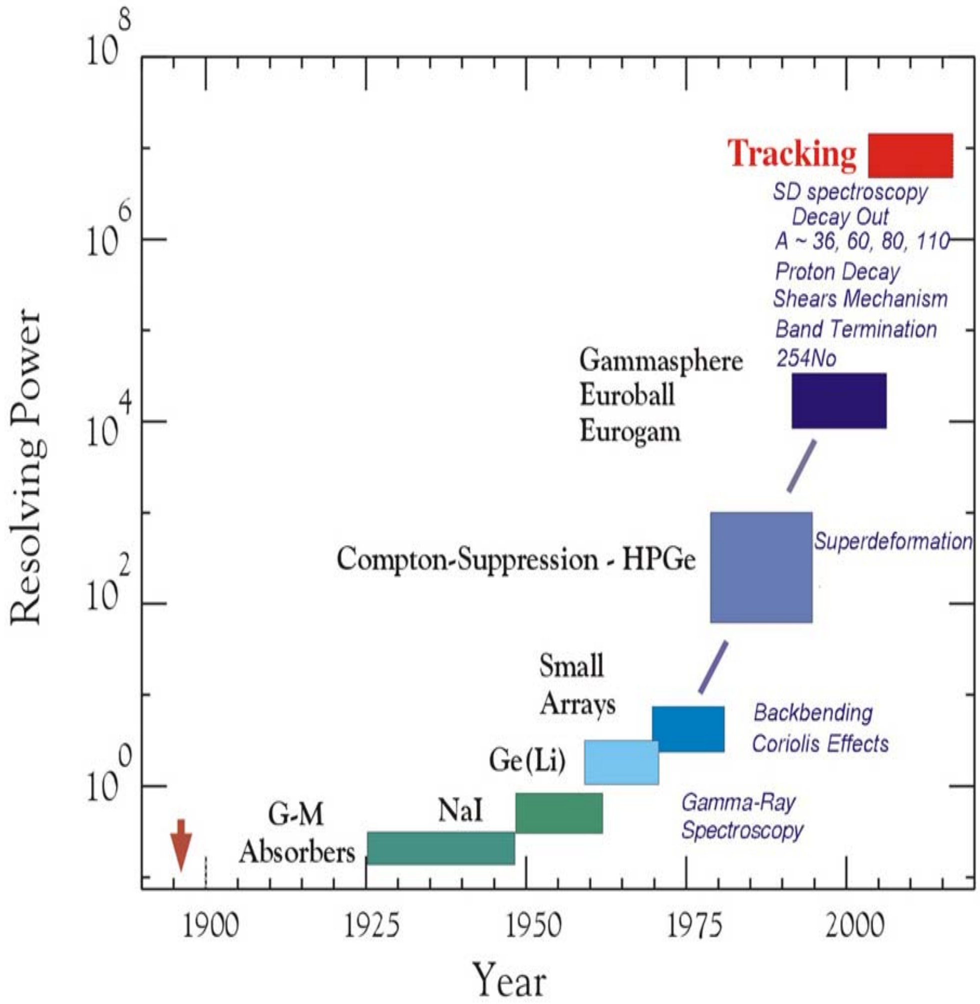
The gamma-ray tracking advantage

⌧ Efficiency

⌧ Background rejection by photon direction

Can other detectors address the same science questions?

Yes, certain aspects of them with much less sensitivity



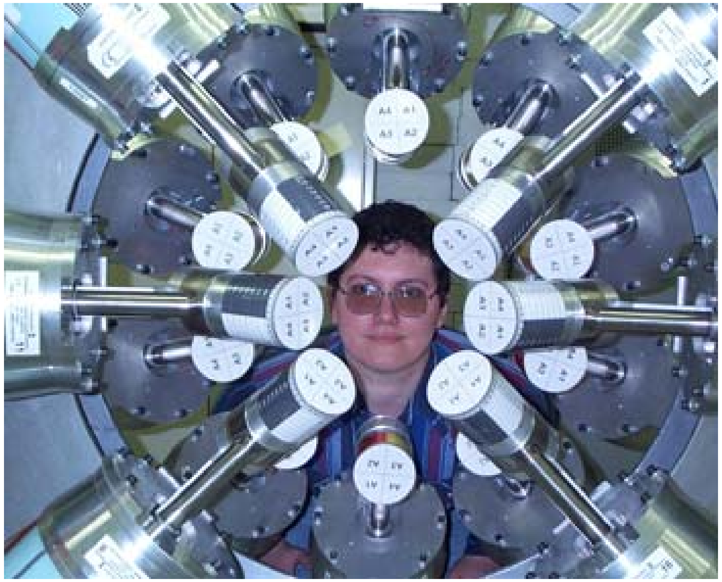
- GRETA will be world-unique in combining
  - Energy resolution
  - Efficiency
  - Peak-to-total ratio
  - Position resolution
  - Directional information
  - Polarization information
- Sensitivity gain of 100-1000 compared to best operating γ-ray arrays
  $\Rightarrow$ **Discovery potential**
  $\Rightarrow$ **Extended scientific reach**

Capabilities of a gamma-ray tracking array beyond current detector systems

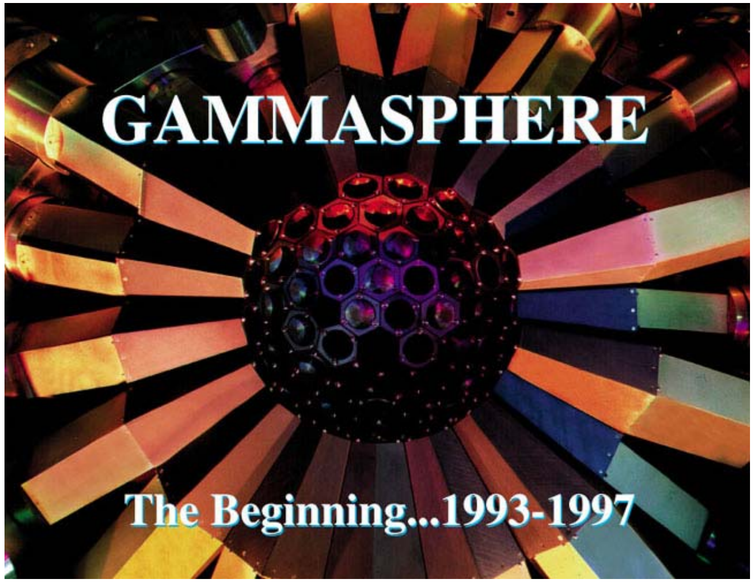
- Resolving power: 10^7 vs. 10^4
  - Cross sections down to ~1 nb
    - » Most exotic nuclei
    - » Heavy elements (e.g. ^{253,254}No)
    - » Drip-line physics
    - » High level densities (e.g. chaos)
- Efficiency (12% vs. 0.5% at E_γ=15 MeV)
  - Shape of GDR
  - Studies of hypernuclei
- Efficiency for slow beams (55% vs. 9% at E_γ=1.3 MeV)
  - Fusion evaporation reactions
- Efficiency for fast beams (55% vs. 0.5% at E_γ=1.3 MeV)
  - Fast-beam spectroscopy with low rates -> RIA
- Angular resolution (0.2º vs. 8º)
  - N-rich exotic beams
    - » Coulomb excitation
    - » Transfer reactions
  - Fragmentation-beam spectroscopy
    - » Halos
    - » Evolution of shell structure
- Count rate per crystal (50 kHz vs. 10 kHz)
  - More efficient use of available beam intensity
- Linear polarization
- Background rejection by direction

Other γ-ray detector

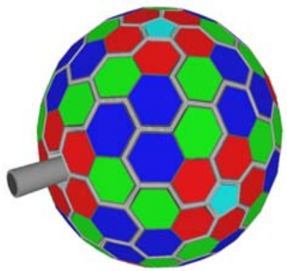
- Largest operational array of highly segmented germanium detectors (SeGA at MSU)
  - No tracking by pulse-shape analysis
  - 30 times less efficient than GRETA



- Gammasphere - A National Facility
  - No position sensitivity
  - 1000 times less resolving power than GRETA



- European idea
  AGATA (Advanced Gamma Tracking Array)
  - no finalized design or prototypes



Impact of GRETA

- Community overlap with Gammasphere community plus others, Gammasphere commissioned in 1995
  - Scientific community 400 scientists from 94 institutions. As of April 2002,
  - 386 refereed publications (April 2002), 81 of which Physical Review Letters or Physics Letters
  - Large number of university-based single investigators producing 55 PhDs (as of Fall 2002).
- Gamma-ray tracking technology has possible applications in other areas of human endeavors (as does any technology that advances sensitivity by orders of magnitude)
  - Medical imaging
  - Industrial imaging