γ-ray detectors for RIA-Summary

Douglas Cline

- **Major fraction of RIA experiments will utilize γ-ray detection.**
- **Most γ-ray detector usage will involve auxiliary detectors**
- **Effective use of rare and exotic nuclear species at RIA justifies a substantial investment for gamma-ray detection system to achieve the physics goals.**

Examples of auxiliary detectors using γ -ray detection.

Residue detectors: [Target and focal plane]

SuperFMA, Gas-filled spectrometer, Hercules, etc

Heavy-ion kinematic coincidence:

4π heavy-ion gas detector array, CHICO

Light ion detection:

Nanoball, DSSD, etc

Neutron detection:

BaF_2 neutron shell, sweeper magnets

Required γ-ray detector performance for RIA

Highest detection efficiency	**[Effective cost and beam time utilization]**
Highest energy resolution	**[Resolving power]**
Best peak-to-total ratio	**[Sensitivity]**
Wide dynamic energy range	**[X-rays to 20 MeV, large recoil velocity]**
Angular resolution [<1°]	**[Doppler correction for fast ions, Background suppression]**
Track interactions[~1mm]	**[Compton suppression, identify multiple gammas, polarization]**
Good Timing	**[Background suppression]**
High granularity	**[High count capability]**
Modular design	**[Flexibility and portability, accommodate range of beam profiles]**
Compatibility with auxiliary detector systems	**[High selectivity]**

Recommended γ-ray detectors for RIA

1: 4π Ge tracking array, GRETA

"Ultimate" detector system

2: Dedicated γ-ray detectors

Specialized and dedicated systems for use with auxiliary detectors

Additional coaxial and planar tracking Ge detectors,

Clover detectors, X-ray detectors, CdZnTe, HgI_2

BaF_2, BGO, NaI, calorimeter.

[Gamma Ray Tracking Coordination Committee (July 2002)
"A National Plan for the Development of γ-Ray Tracking Detectors in Nuclear Science"]

Current Generation Ge Detectors:

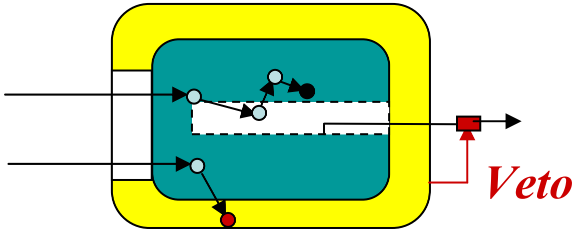
4π Arrays:

Gammasphere, EuroBall

Smaller arrays:

Clarion, Yrast, etc

- Compton Suppressed Ge



N_{det} = 100

Peak efficiency = 0.1

Efficiency limited

New Generation Tracking Ge Detectors:

4π Arrays:

GRETA, AGATA

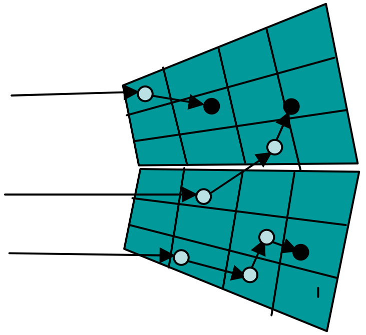
Smaller arrays:

SeGA, Tigress

Planar detectors:

CNS Array, Argonne, NRL

- Gamma Ray Tracking



N_{det} = 100

Peak efficiency = 0.6

Segmentation

New technology:

Segmented Ge ,

Digital signal processing,

Tracking algorithms

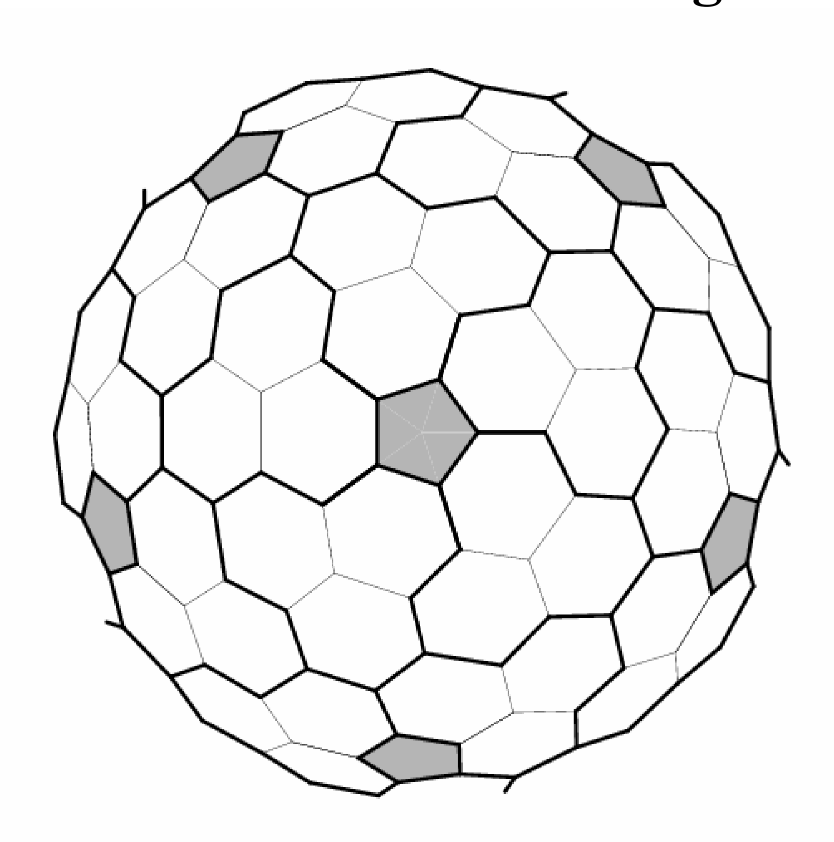
High-resolution γ-ray Tracking Ge Detectors

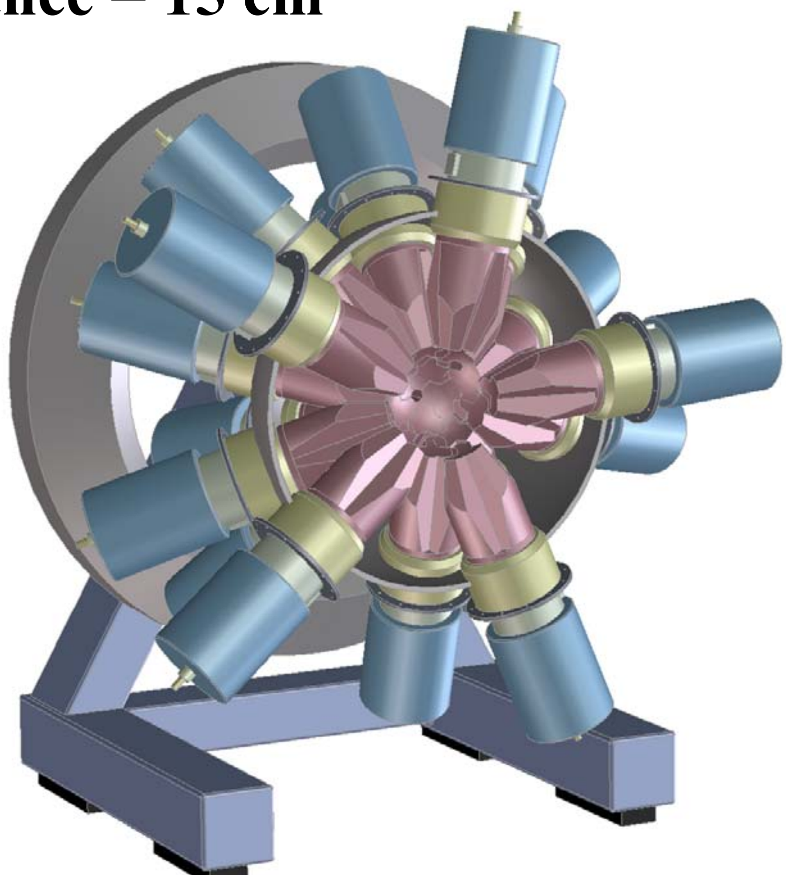
GRETA	I-Yang Lee	[LBNL]
GRETINA simulations	Martina Descovich	[LBNL]
AGATA	Dino Bazzacco	[INFN-Padova]
Detector characterization in Europe	Andy Boston	[U. Liverpool]
Tigress	Helen Scraggs	[Triumf]
CNS Ge Array	Susumu Shimoura	[CNS, Tokyo]
Position-sensitive planar detectors	Kim Lister & Sean Freeman	[ANL]
Segmented Ge detectors for Majorana	Craig Aalseth	[PNNL]
Auxiliary detectors for 4π gamma arrays	Demetrios Sarantites	[Washington U]
4π heavy-ion detector for γ-ray spectroscopy	Ching-Yen Wu	[U. Rochester]

GRETA Detector Configuration

I-Yang Lee [LBNL]

- **Two types of irregular hexagon, 60 each**
- **Pack three crystals per cryostat → 40 modules**
- **Detector – target distance = 15 cm**



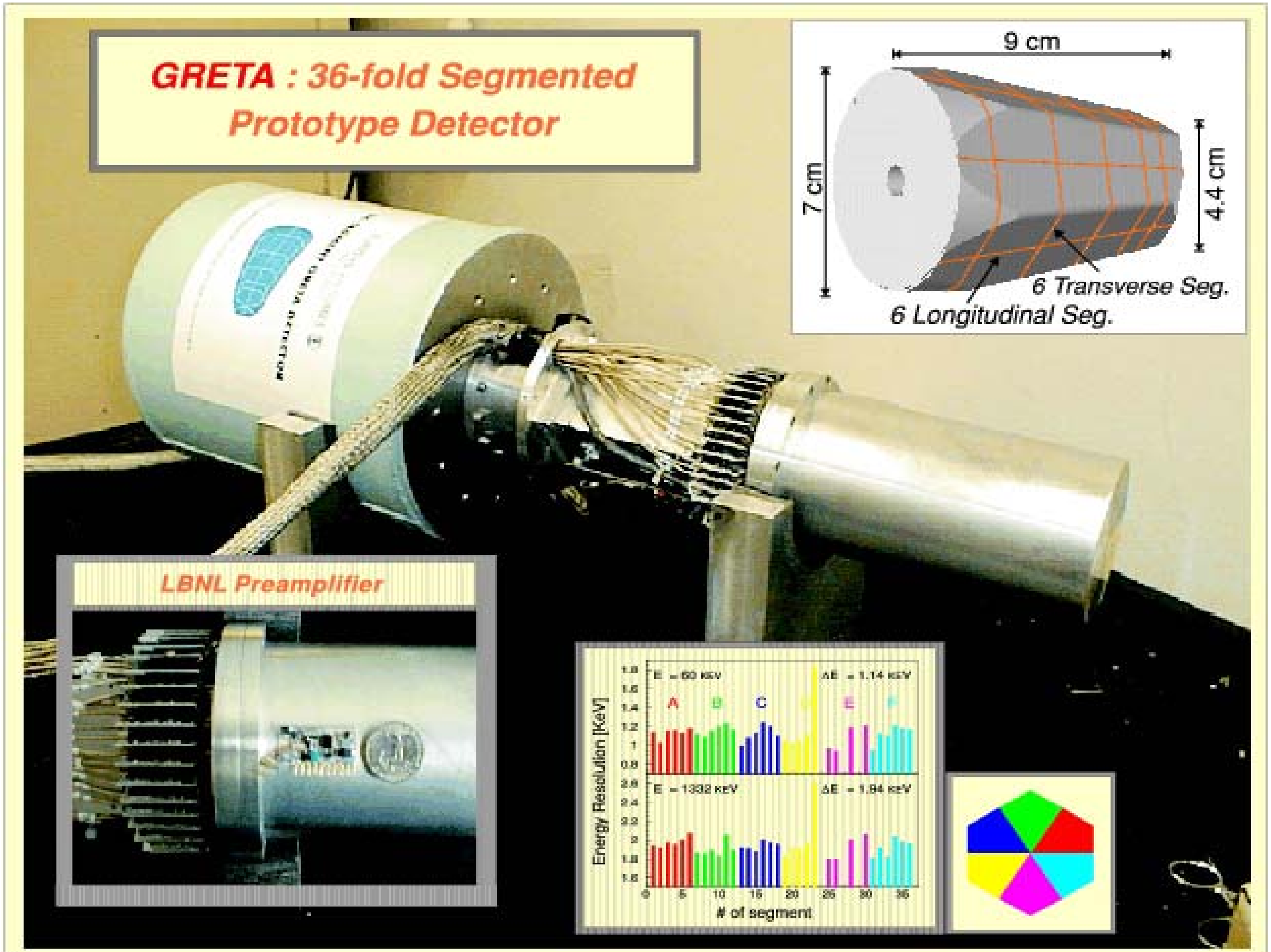


GRETA Resolving Power

Realistic : Ω=0.8, Δx=2 mm

Reaction	<Eγ> (MeV)	β	Mγ	Resolving Power	× Gammasphere
Stopped	5.0	0.0	4	2.1×10^7	270
High spin					
normal kine.	1.0	0.04	20	3.3×10^6	100
inverse kine.	1.0	0.07	20	3.0×10^6	230
Coulex/transfer	1.5	0.1	15	4.5×10^6	1000
Fragmentation					
in beam	1.5	0.5	6	6.3×10^6	29000
Coulex	5.0	0.5	2	2.7×10^3	213

Prototype detector II at LBNL



R&D Accomplishments

Proof of principle: No show stoppers

- **Segmented detectors**

  Energy resolution: 1.2 keV at 60 keV and 1.9 keV at 1332 keV

  Total integrated noise: < 5 keV (bandwidth 35 MHz)

  3-D position sensitivity: < 1 mm at 374 keV (single interaction)

- **Signal analysis**

  Adaptive grid search: 1-2 mm

  Least square: 1-2 mm

  Genetic algorithm: 2 mm

  Wavelet transformation: 5-6 mm

- **Tracking algorithms**

  Compton tracking (150 keV < E_γ < 5 MeV) : eff = 50%, for m= 25.

  Pair tracking (E_γ> 5 MeV) : eff = 50%

M. A. Deleplanque et al., Nucl. Instrum. Methods Phys. Res. A430, 292(1999).

G. J. Schmid et al., Nucl. Instrum. Methods Phys. Res. A430, 69 (1999).

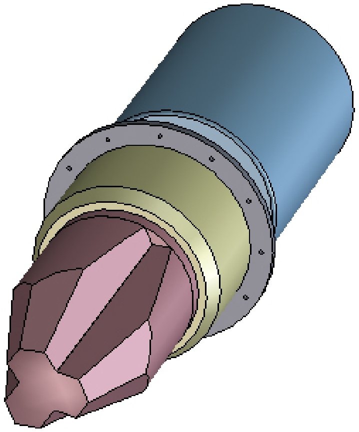
K. Vetter et al., Nucl. Instrum. Methods Phys. Res. A452, 105 (2000).

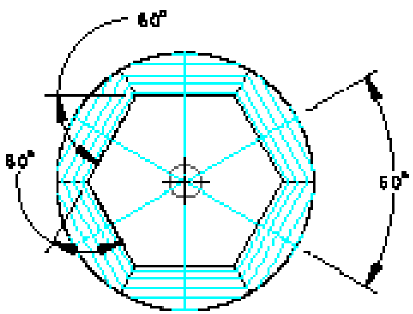
K. Vetter et al., Nucl. Instrum. Methods Phys. Res. A452, 223 (2000).

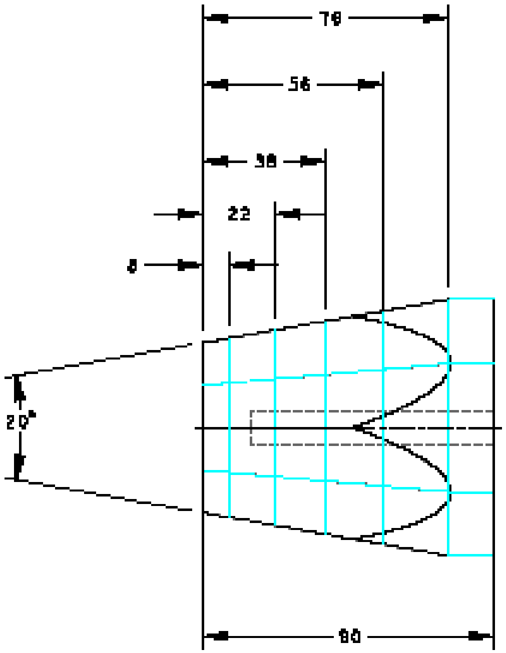
Three-crystal detector module

Building Block of GRETA

- Tapered regular hexagon shape.
- DIA= 8 cm, L= 9 cm, 36 segments.
- Close packing of crystals with gap= 3.5 mm.
- On order and expecting delivery in Oct. 2003.
- Cost = $750 k ($450k for 40 units)







Recent progress of GRETA

Conceptual design study (1994), leading to several workshops, prototyping, etc

April 2002 NSAC Long-Range Plan for the Next Decade

"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 both existing stable and unstable beam accelerators, as well as RIA"

July 2002 Gamma Ray Tracking Coordination Committee

"A National Plan for the Development of γ-Ray Tracking Detectors in Nuclear Science"

"...This committee unanimously recommends a shell of closely packed coaxial Ge detectors as outlined in the GRETA conceptual design.... We strongly recommend that DOE support this with highest priority"

March 2003 NSAC Ad-hoc Facilities Subcommittee

"The Nuclear Physics Scientific Horizon, Projects for the Next Twenty Years"

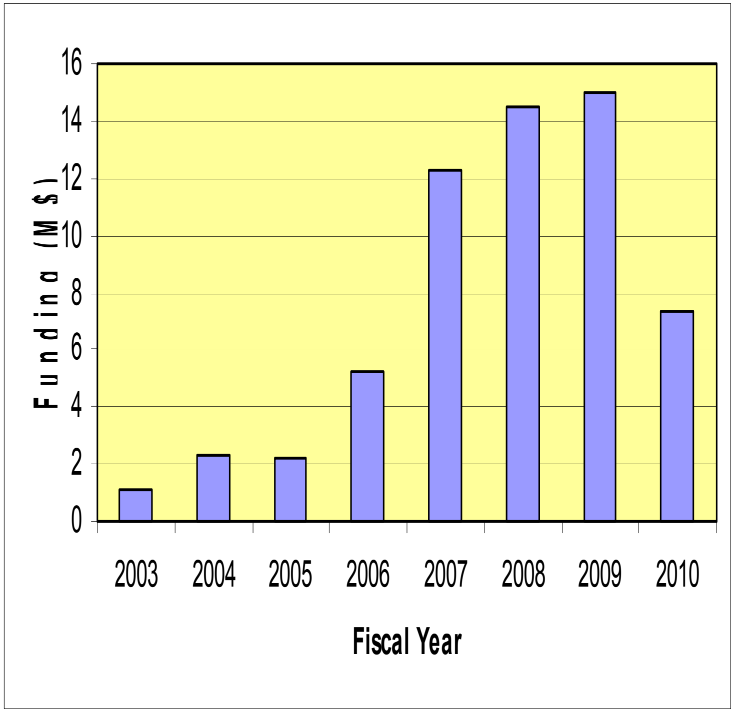
GRETA :	*Science:*	*Category 1; Absolutely central*
	Readiness:	*Category 1; Ready to initiate construction*

GRETA Total Cost and Cost Profile

FY02 Dollar, with overhead

Item	Purchase (M$)	Effort (FTE-yr)	
Mechanical	0.9	5	
LN	0.5	4	
Detector	18.0	7	
Electronics	3.4	10	
Computer	1.1	13	
Installation	0.0	6	
Management	0.0	15	
Safety	0.0	3	
		63	
TOTAL (M$)	**23.9**	**12.6**	**36.5**
+ escalation			**42.9**
+ contingency (27%)			**54.5 (TEC)**
+ R/D, pre-operation etc.			**60.1 (TPC)**

By: Jay Marx, Bill Edwards, Bob Minor et al.



Staged approach of GRETA

In 4 stages, each with increment of ¼ of the detector

First stage: **GRETINA** = ¼ of GRETA

30 crystals (10 modules)

Complete computer software development

Cost of $16.7 M

Construction period from 2004 – 2007

Proposal is being developed

Simulations using the GEANT code   Martina Descovich LBNL]

GRETINA performance is better than Gammasphere for many applications, especially for fast beams.

GRETA Conclusion

R&D efforts achieved *"proof of principle"*.

Engineering design started on critical items.

Exciting physics case has been identified for

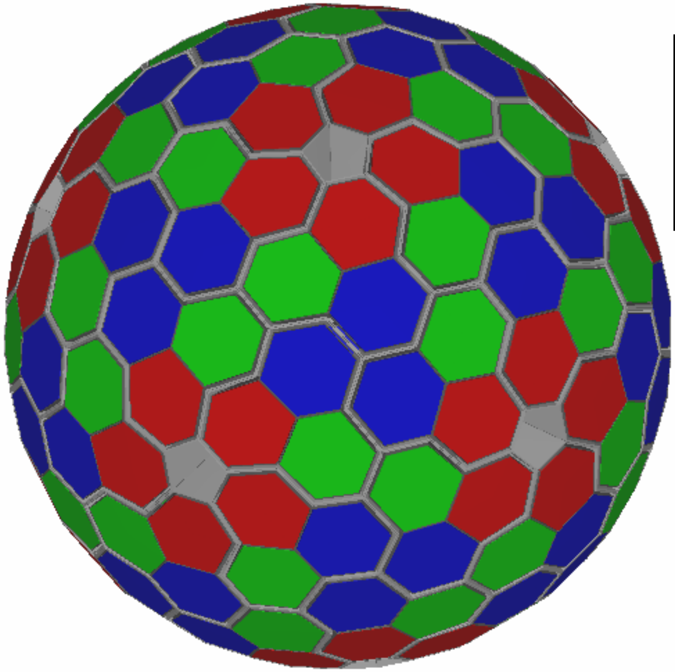
gretina.

National effort involving steering committee and working groups.

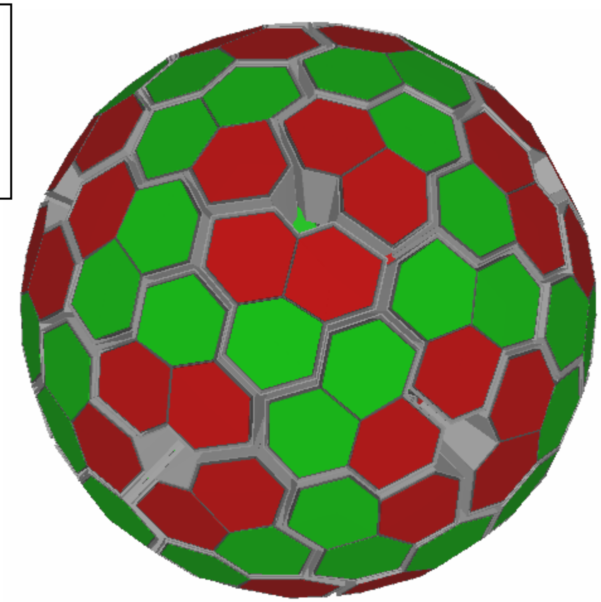
gretina /GRETA ready to initiate construction

Two candidate configurations for AGATA

Dino Bazzacco [INFN-Padova]



Ge crystals size:
length 90 mm
diameter 80 mm



180 hexagonal crystals of 3 shapes
60 triple-clusters, all equal

Inner radius	22 cm	(18)
Amount of germanium	310 kg	(220)
Solid angle coverage	80 %	(77)
Max. Singles rate	~50 kHz	

6480 segments

Efficiency:	40% (M_γ=1)	25% (M_γ=30)
Peak/Total:	65% (M_γ=1)	50% (M_γ=30)

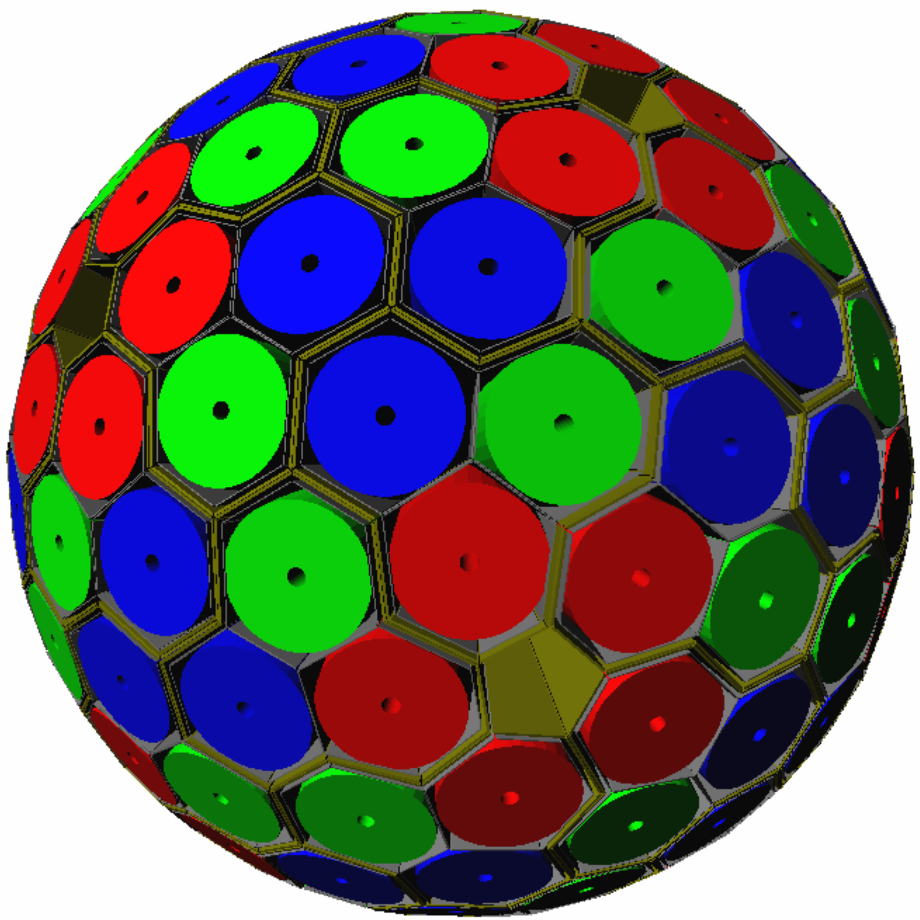
120 hexagonal crystals of 2 shapes
40 triple-clusters, 2 shapes

Inner radius	17 cm
Amount of germanium	220 kg
Solid angle coverage	74 %
Max. Singles rate	~70 kHz

4320 segments

Efficiency:	38% (M_γ=1)	21% (M_γ=30)
Peak/Total:	63% (M_γ=1)	47% (M_γ=30)

4π γ-array of 180 segmented Ge detectors



180 hexagonal crystals
60 triple-clusters
Inner radius 22 cm
310 kg of germanium
solid angle coverage 80 %
Singles rate 50 kHz
6480 segments

Efficiency: 40% (M_γ=1) 25% (M_γ=30)
Peak/Total: 65% (M_γ=1) 50% (M_γ=30)
FWHM(1 MeV) ~2 keV

Angular resolution of detected γ-rays ~1°
➔ FWHM(1 MeV, v/c=50%) ~ 6 keV !!!
(compared with ~50 keV of present arrays)

Construction ~8 years Cost ~40 M € Effort ~250 M-Y

GRETA and AGATA detector procurement

Currently only a single vendor for coaxial Ge tracking detectors.

Other vendors needed to encourage competitive bidding and to ensure adequate production capability.

Other Ge Tracking Detector Work Discussed

Detector characterization in Europe Andy Boston [Liverpool]

[Detailed studies of the response of segmented coaxial detectors]

Source tests of a Ge strip detector Kim Lister & Sean Freeman [ANL]

[Problems associated with charge collection in planar detectors]

Tigress Helen Scraggs

[Example of an array of segmented Clover detectors]

X-Array Kim Lister [ANL]

[Example of a focal plane compound tracking detector array, similar to GREAT Array].

CNS Ge Array for spectroscopy of fast moving exotic nuclei

Susumu Shimoura [CNS, Univ. Tokyo]

[Example of array of planar detectors for fast beam physics]

Majorana Project Craig Aalseth [PNNL]

[Application of Ge tracking detectors to double β decay and neutrino physics]

TRIUMF

ISAC

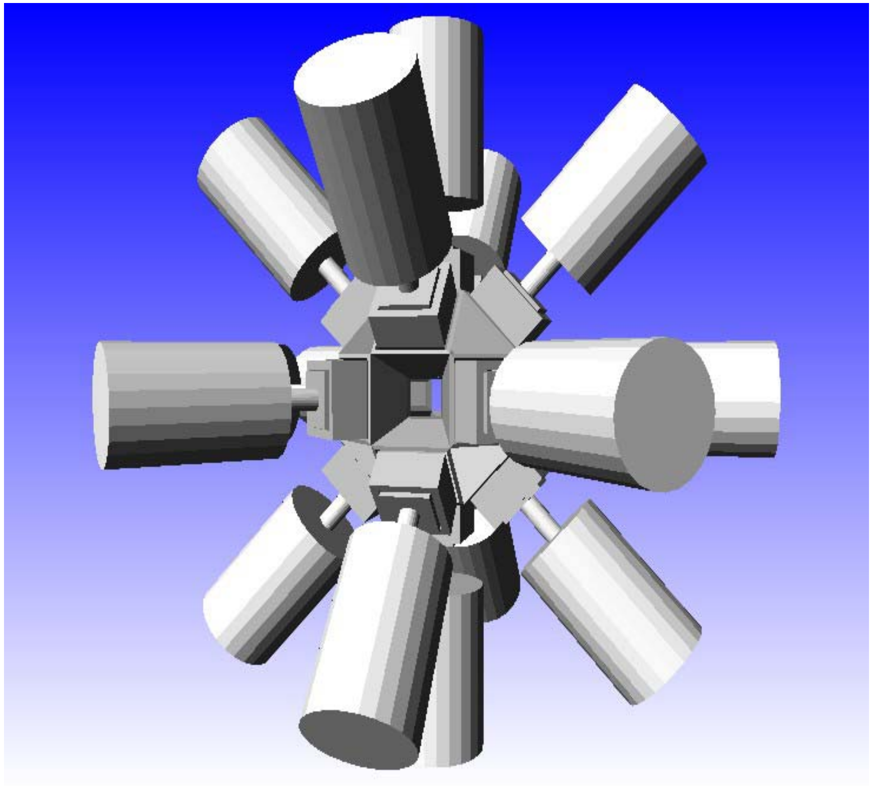
GAMMA-

RAY

ESCAPE

SUPRESSED

SPECTROMETER



Helen Scraggs

16 32-fold segmented Clover Ge Detectors

The X-Array:

Kim Lister [Argonne]

Compact Three Layer Concept:

A) Inner array for efficiently detecting (α,p,β,CE) decays

Highly segmented silicon DSSDs

Thin Wall Vacuum Envelope

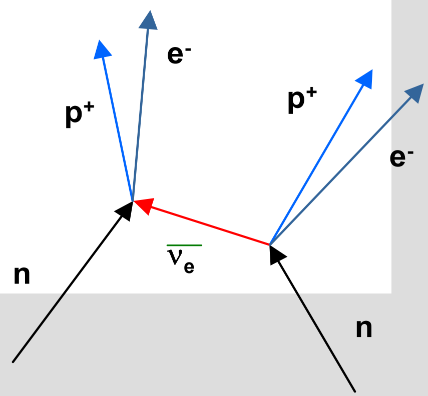
B) Array of large area planar detectors for efficiently detecting X-rays, and for polarization and correlation studies.

Highly segmented planar germanium DSSDs

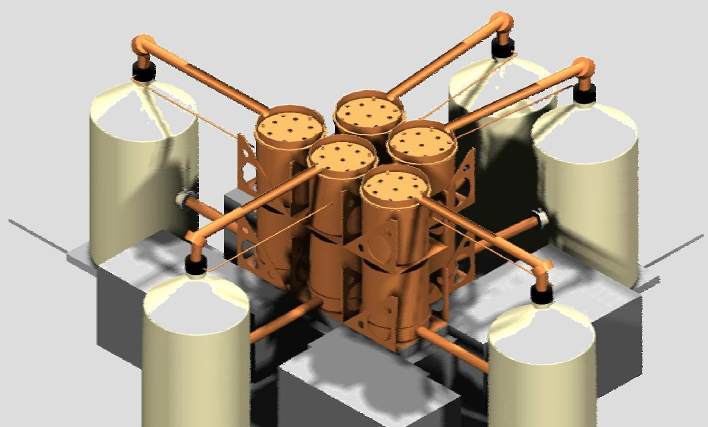
C) Calorimeter of low-segmentation large germanium detectors for efficient absorption of total gamma ray flux.

Large Volume non-segmented “clover” detectors

Majorana Overview
(http://majorana.pnl.gov)



- $0\nu\beta\beta$ decay of ^{76}Ge potentially measured at 2039 keV
- Sensitive to effective Majorana ν mass as low as 0.02-0.07 eV
- Based on well-known ^{76}Ge detector technology plus:
  - Pulse-shape analysis
  - Detector segmentation
  - *Ready to begin now*
- Requires:
  - Deep underground location
  - 500 kg enriched 85% ^{76}Ge
  - 210 crystals, 8 segments each
  - Advanced signal processing
  - Special materials (low bkg)



Baseline Concept

Craig Aalseth [PNNL]

Cost estimate: $100M

Internal auxiliary detectors for GRETA

The selectivity provided by auxiliary detectors is crucial for observing weak signals.

Demetrios Sarantites [Washington Univ.]

Residue detection:	Hercules
Light-ion detection	Nanoball
Neutron detection	Neutron shell

Ching-Yen Wu [Univ. Rochester]

4π heavy-ion detector	CHICO

Impact of Ge Tracking detectors

Tracking advances resolving power and sensitivity by orders of magnitude

GRETA will have a major impact on RIA scientific program.

GRETA will build on the success of Gammasphere and its user community
Gammasphere commissioned in 1995
Scientific community 400 scientists from 94 institutions.
386 refereed publications (April 02), 81 in Phy.Rev.Lett. or Phy.Letts.
Large number of university-based single investigators; 55 PhDs (Fall 2002).

Additional coaxial and planar tracking detectors and segmented Clover detectors will complement GRETA and play a major role at RIA.

Tracking has applications in other sciences and areas of human endeavor

Astrophysics, imaging in medicine and industry, environmental monitoring, homeland security

New concepts in gamma detection

Scintillators and wide band-gap semiconductors that operate at room temperature

Advanced gamma-ray detection systems	Lynn Boatner
3-D position-sensitive CZT and HgI_2	Zhong He
CZT detectors	Walter Reviol & Lee Sobotka
HgI_2 detectors	Ben Parry

Advanced gamma-ray detection systems

Lynn Boatner [ORNL]

- Promising new developments in scintillator technology.

- Lutecium orthophosphate LPO and lutecium oxysilicate LSO have excellent properties.

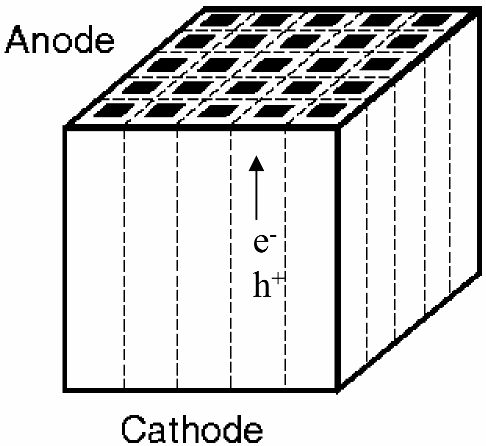
    40nsec decay constant

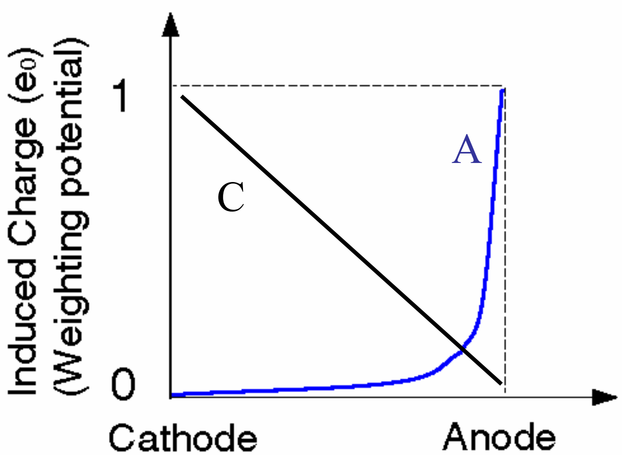
    Good light output.   [Comparable to CsI]

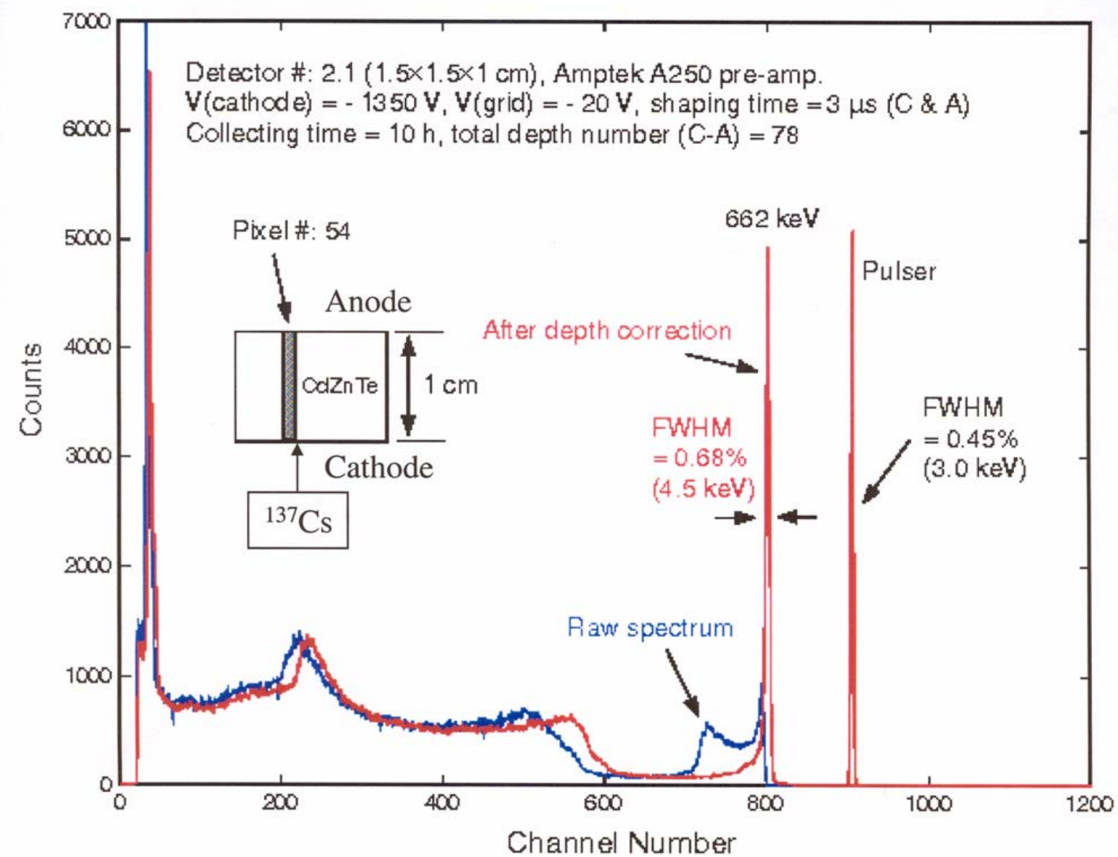
    Light output matches the photodiode response

3-D position-sensitive CdZnTe γ-ray detectors

Zhong He [Univ. Michigan]
Walter Reviol & Lee Sobotka [Washington Univ.]







Summary on 3-D CdZnTe

- Energy resolution:
  1.1% FWHM at 662 keV for single-pixel events → (?)
  2.0% FWHM for two-pixel events → ?
- Position resolution in 3-D:
  1.2 mm in X-Y and ~ 0.5 mm in Z at 662 keV
- Energy depositions and 3-D positions of multiple-interactions are fully readout using ASIC.
- Allow compensation for material deficiencies.
- Current development:
  Larger detectors and better material
  Improved miniaturized ASIC (for tile-able systems)

- Detector operation can be **simple** for end users

3-D position-sensitive HgI_2 γ-ray detectors

Zhong He [Univ. Michigan]
Ben Parry [CTT]

Advantages

high Z (80-53)

high density (6.4 g/cm3)

(1 cm HgI2 ≈ 2-3 cm of CZT, more of Ge)

large band-gap (2.13 eV)

(room-temperature operation)

Challenges

very low hole mobility, severe hole trapping

low electron mobility

(require higher bias ~1 kV/mm and long shaping time)

Conclusions on HgI_2

It is possible to construct HgI_2 gamma-ray spectrometers at thickness ~ **1 cm** if a **3-D** position sensitive single-polarity charge sensing technique is employed, and using low biases (2-2.6 kV) and moderate shaping times (6-10 μs).

- Energy resolutions of 1.4% - 2% FWHM at 662 keV were obtained from 6 out of 7 pixel anodes.

- There is a potential to achieve better resolution using 1 cm thick devices.

Summary of γ-ray detectors required for RIA

1: 4π Ge tracking array, GRETA

- GRETA will have orders of magnitude greater sensitivity and resolution and will be absolutely central to science at RIA
- GRETA must be modular, and easy to relocate plus set up subsections
- Additional tracking detectors will be needed to supplement GRETA to serve simultaneous multiple beams.

2: Special purpose *γ*-ray detectors

- Arsenal of versatile and flexible gamma ray detectors, that can be used both for dedicated and general experiments.
- Many detectors already available can be used.

4: Additional R&D

- Ge tracking detectors; prototyping, characterization, electronics, tracking algorithms
- Investigate wide band-gap semiconductors [CdZnTe, $HgI_{2]}$, and new scintillators

Costs

	$M
1: 4π Ge tracking array, GRETA	60.1 [TPC]
2: Dedicated gamma detector systems:	
High resolution, compact arrays for decay spectroscopy	2.5 *
Medium resolution high efficiency array [BaF_2 , new scintillator]	5.0
Additional coaxial Ge tracking detectors	?
Total absorption spectrometer	0.5*
NaI anticoincidence barrel	0.1*
Many smaller X-ray and gamma detectors	?

* Included in Decay and Fundamental Interactions summary