Gamma-Ray Tracking

Augusto O. Macchiavelli

Nuclear Science Division
Lawrence Berkeley National Laboratory

Many thanks to
Heather Crawford, Dirk Weisshaar and Andreas Wiens

Thank You I-Yang!

Outline

Introduction

Concept of γ-ray tracking

Proof of principle

- Segmented detectors
- Electronics
- Position reconstruction

Towards a 4π array: GRETA

- Expected performance

GRETINA

- Status of the project

Applications

Summary and conclusions

NNPSS2015
Lecture on Gamma-ray Tracking
June, 2015

Homework

Problem #1

The following data was taken with a prototype detector using and ^{241}Am and ^{60}Co sources

Peak#	Centroid	FWHM (channels)
1	282.03	5.62
2	5975.50	9.31
3	6788.85	10.02

Determine the Fano factor and the noise contribution to the energy resolution

Problem #2

Estimate the amplitude of the signal for a 1MeV gamma at the output of a segment preamp.

Email solutions by Monday !

Atomic nuclei constitute unique many body systems of strongly interacting fermions. Their properties and structure, are of paramount importance to many aspects of physics.

Many of the phenomena encountered in nuclei share common basic physics ingredients with other mesoscopic systems, thus making nuclear structure research relevant to other areas of contemporary research, for example in condensed matter and atomic physics.

These are exciting times in the field of physics of nuclei:

Existing and planned exotic beam facilities worldwide and new detector systems with increased sensitivity and resolving power not only will allow us to answer some important questions we have today, but most likely will open up a window to new and unexpected phenomena.

New developments in theory and computer power are shaping a path to a predictive theory of nuclei and reactions.

4 August 1972, Volume 177, Number 4047

SCIENCE

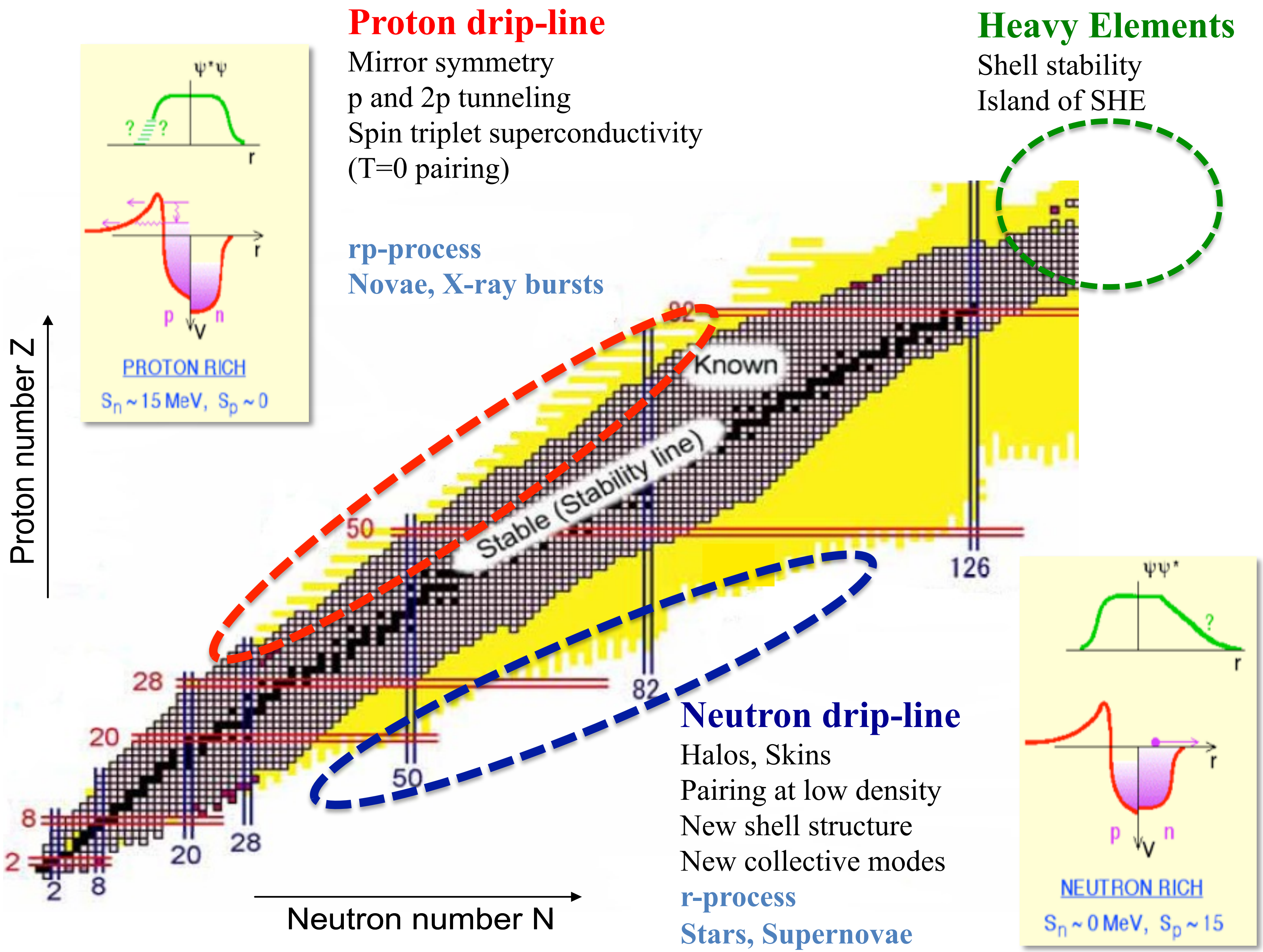
More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

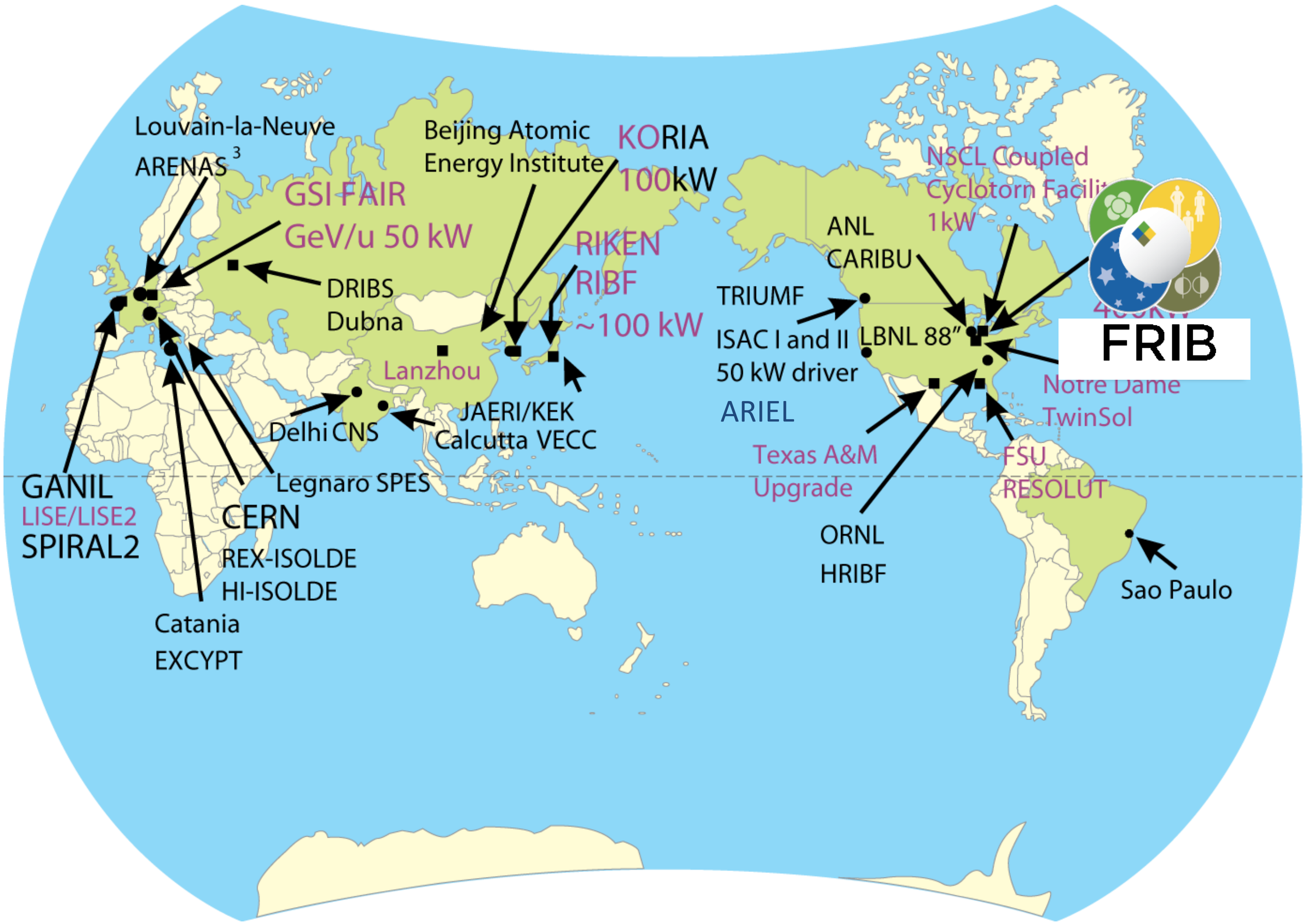
less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires re-



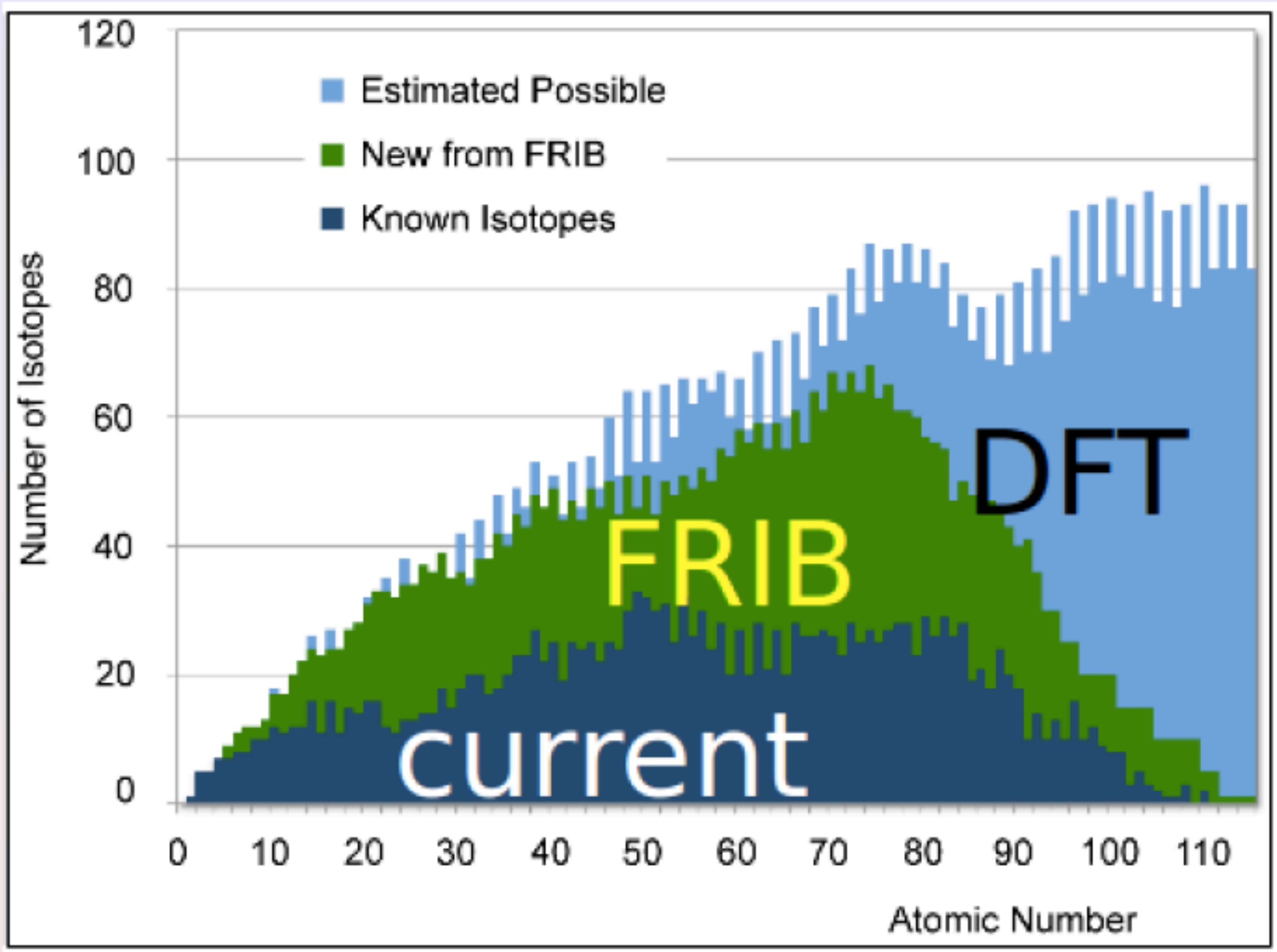
Proton drip-line
Mirror symmetry
p and 2p tunneling
Spin triplet superconductivity
(T=0 pairing)
rp-process
Novae, X-ray bursts
Heavy Elements
Shell stability
Island of SHE
PROTON RICH
S_n ~ 15 MeV, S_p ~ 0
p
n
V
r
Known
Stable (Stability line)
Proton number Z
Neutron number N
2
8
20
28
50
82
126
Neutron drip-line
Halos, Skins
Pairing at low density
New shell structure
New collective modes
r-process
Stars, Supernovae
NEUTRON RICH
S_n ~ 0 MeV, S_p ~ 15

World view of rare isotope facilities



From Brad Sherrill - MSU

Black – production in target
Magenta – in-flight production



Estimated Possible
New from FRIB
Known Isotopes
Number of Isotopes
Atomic Number
0
20
40
60
80
100
120
0
10
20
30
40
50
60
70
80
90
100
110
DFT
FRIB
current

Gamma-ray Spectroscopy and Nuclear Physics

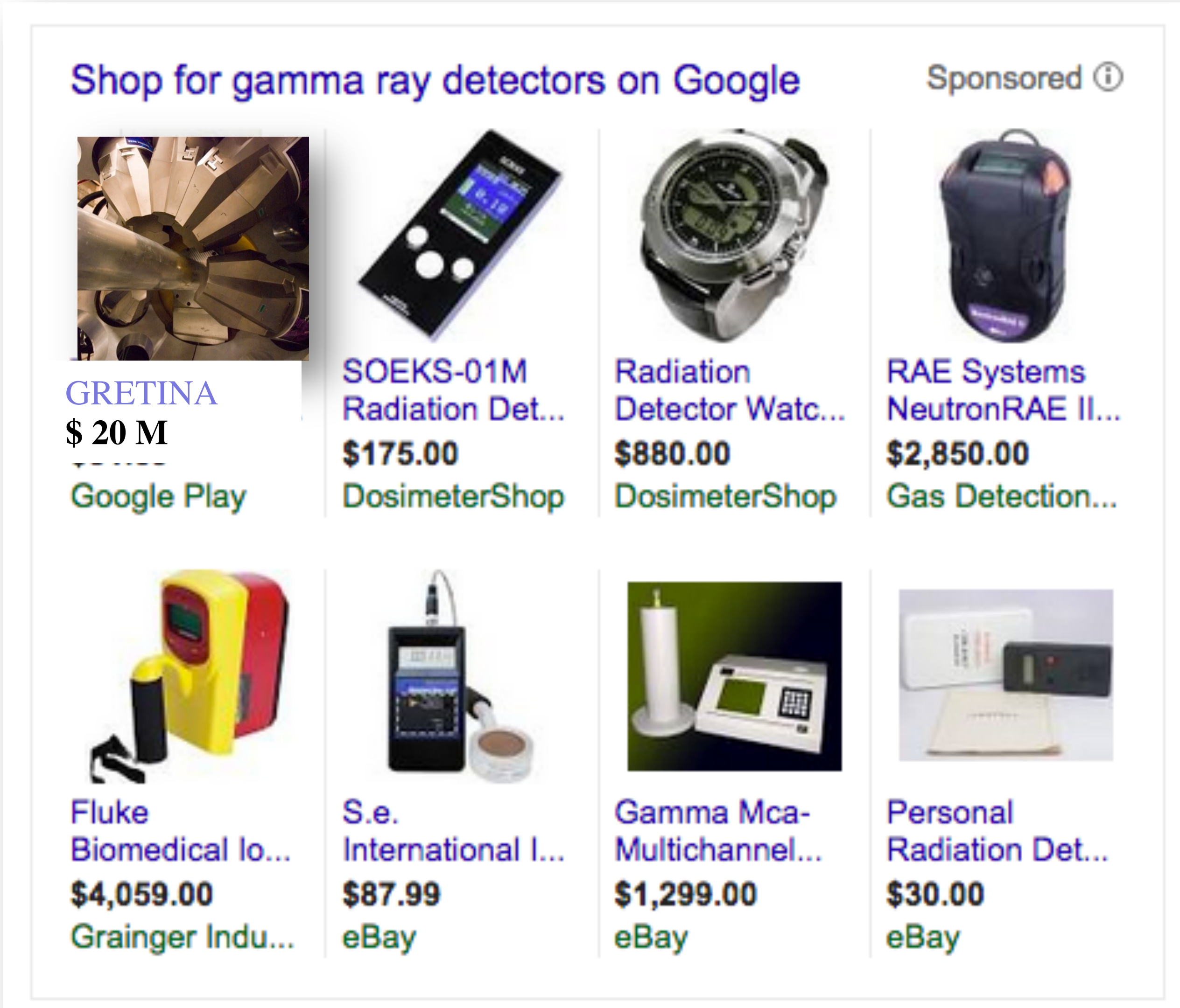
Gamma-ray spectroscopy has played a major role in the study of the atomic nucleus.

- Coincidence relations → Level/decay scheme
- Angular distributions /correlations → Multipolarity, spins
- Linear polarization → E/M, parity
- Doppler shifts → Lifetimes, B(E/M λ)

"Effective" Energy resolution (δE), Efficiency (ε), Peak-to-Background (P/T)

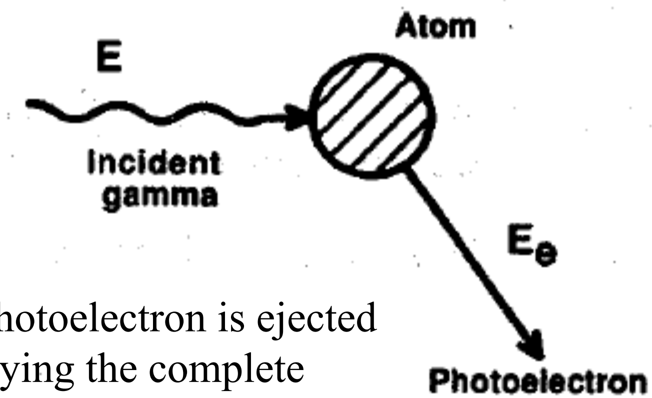
Resolving Power

Which detectors should we use ?



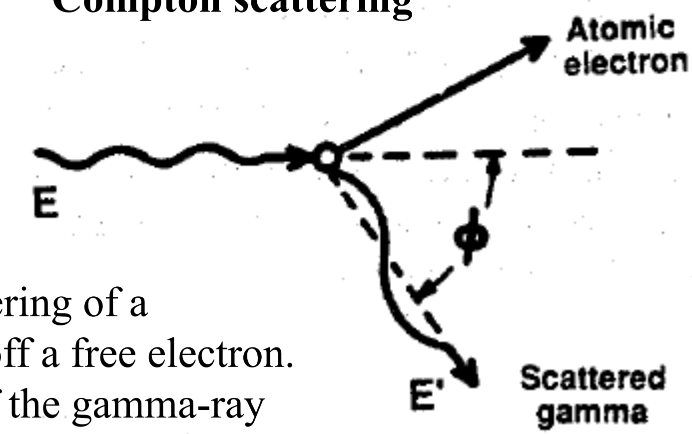
Interaction of gamma-rays with matter

Photo effect



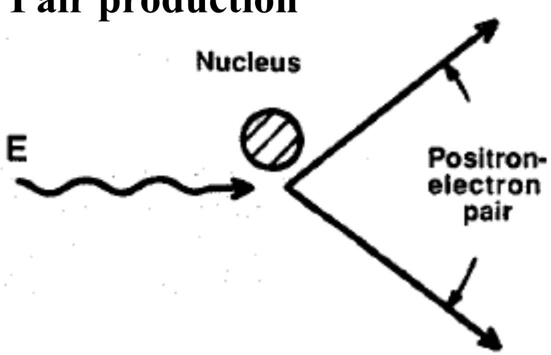
A photoelectron is ejected carrying the complete gamma-ray energy (- binding)

Compton scattering

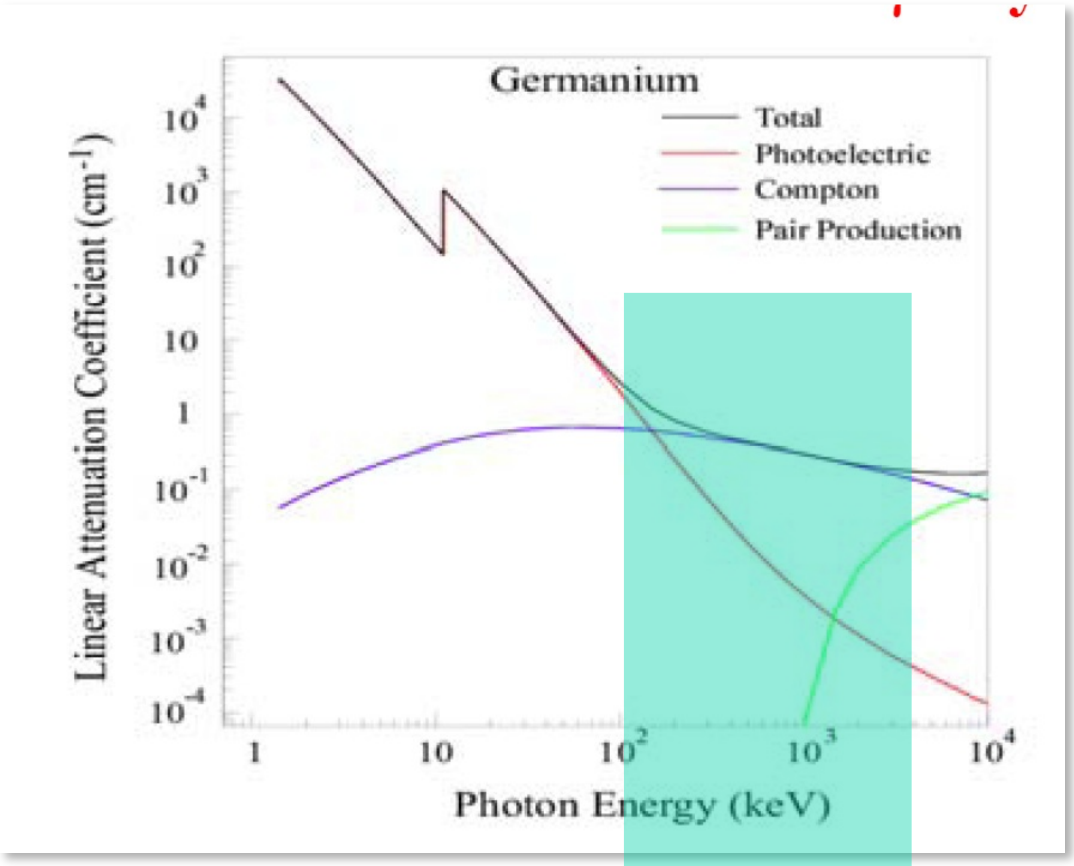


Elastic scattering of a gamma ray off a free electron.
A fraction of the gamma-ray energy is transferred to the Compton electron

Pair production



If gamma-ray energy is >> 2 $m_o c^2$ (electron rest mass 511 keV), a positron-electron can be formed in the strong Coulomb field of a nucleus. This pair carries the gamma-ray energy minus 2 $m_o c^2$.



Photoelectric:
~ Z^{4-5}, $E_g^{-3.5}$

Compton:
~ Z, E_g^{-1}

Pair production:
~ Z^2, increase with E_g

Example; 1.33 MeV
5 interactions: 4 Compton, 1 photo
Separation of interactions: 0.5 – 5 cm

Scintillators

Scintillators are materials that produce 'small flashes of light' when struck by ionizing radiation (e.g. particle, gamma, neutron). This process is called '**Scintillation**'.

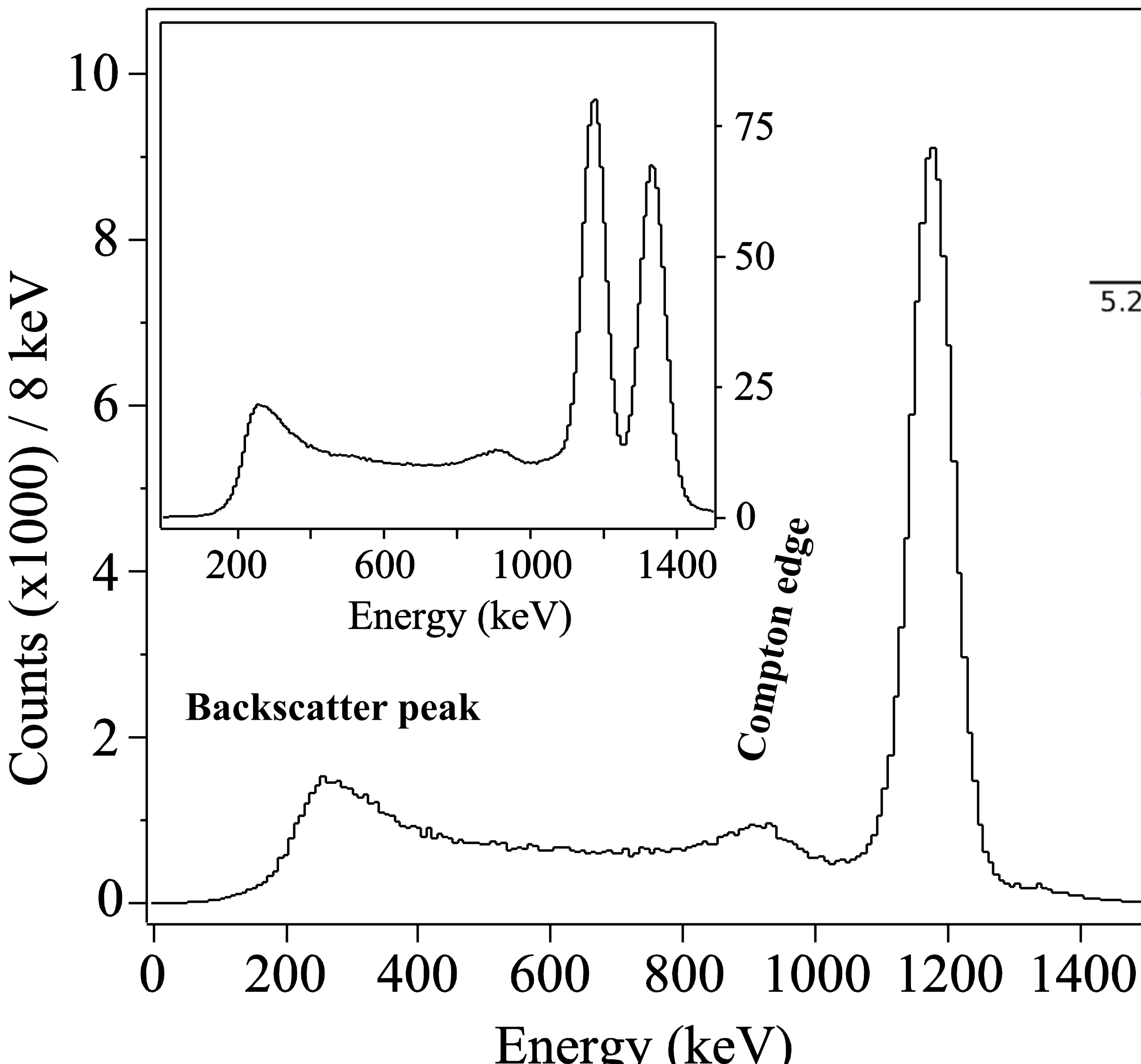
Scintillators may appear as solids, liquids, or gases.

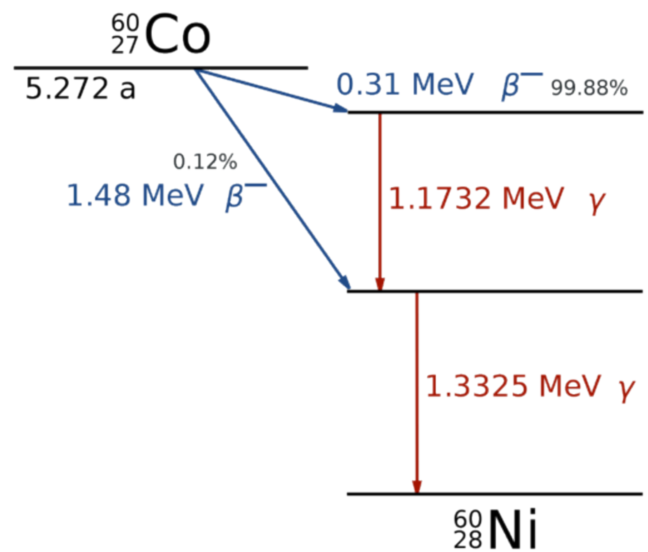
Major properties for different scintillating materials are:

- Light yield and linearity **(energy resolution)**
- How fast the light is produced **(timing)**
- Detection efficiency

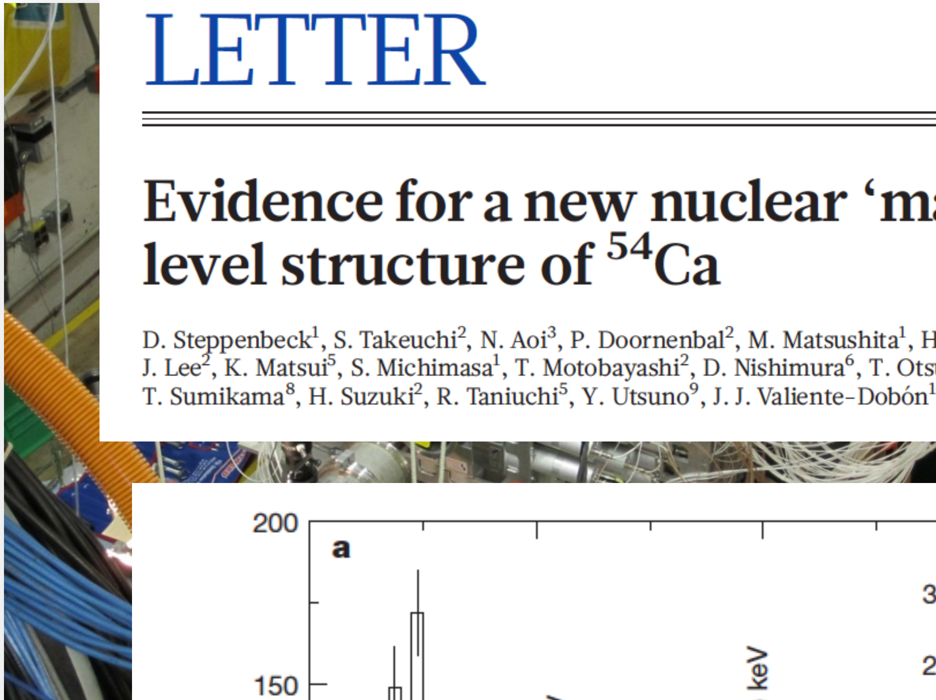
Organic Scintillators ("plastics"):
Light is generated by fluorescence of molecules; usually fast, but low light yield
Inorganic Scintillators:
Light generated by electron transitions within the crystalline structure of detector; usually good light yield, but slow

Scintillator spectrum (here CsI(Na))





CAESAR at NSCL



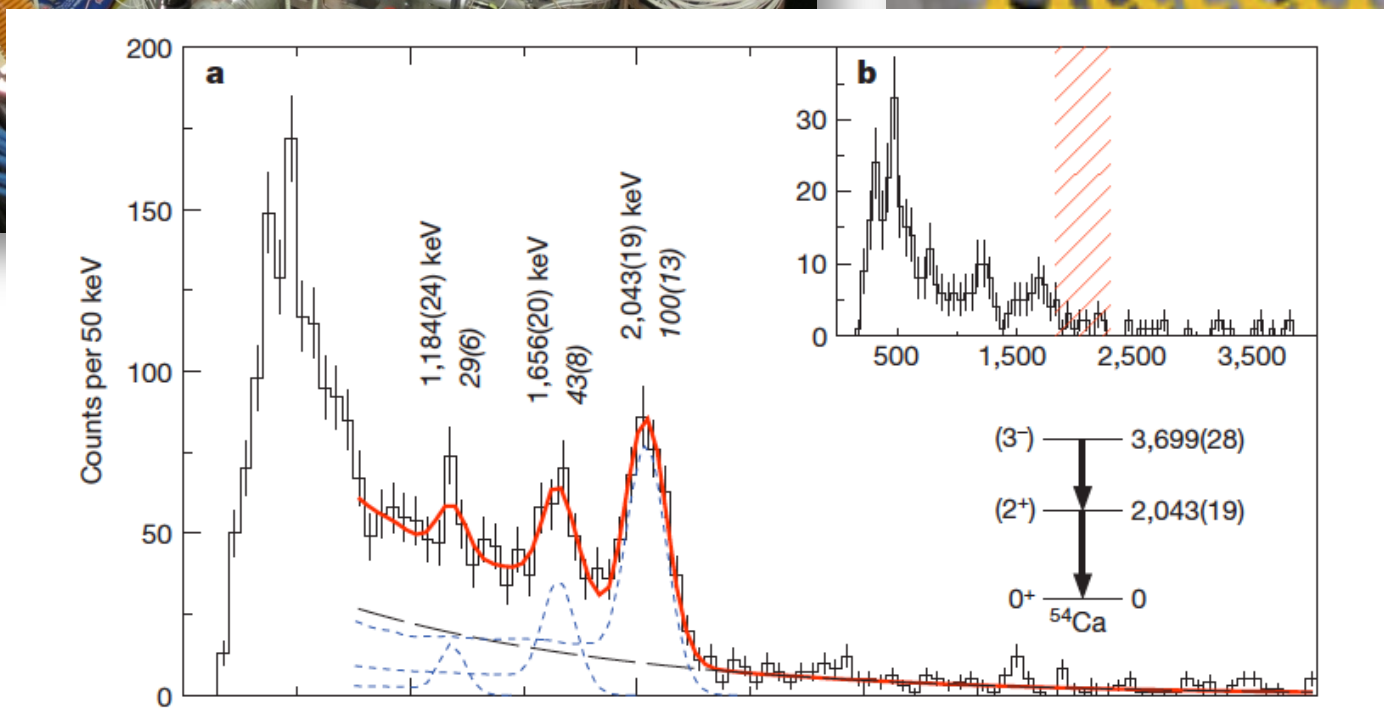
LETTER

doi:10.1038/nature12522

Evidence for a new nuclear ‘magic number’ from the level structure of ^{54}Ca

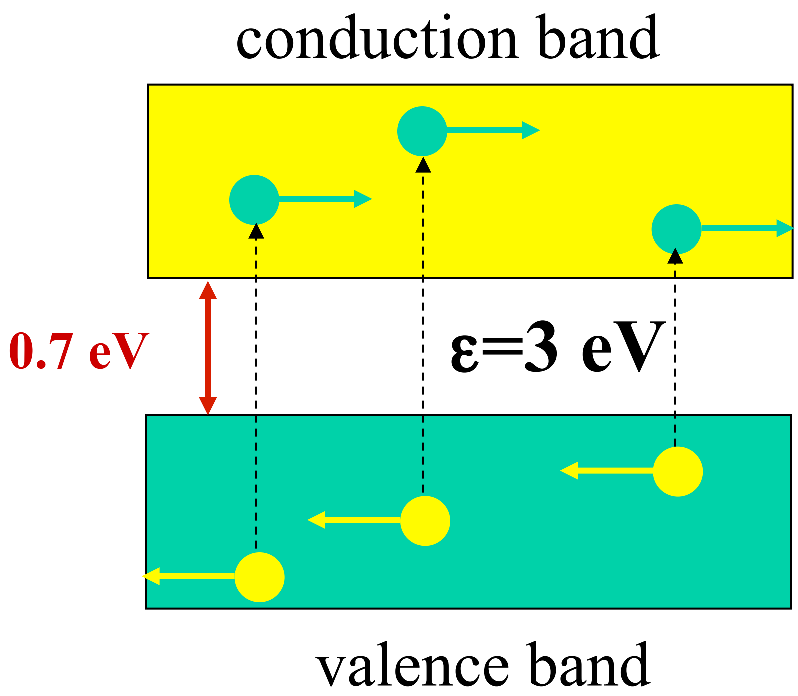
D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

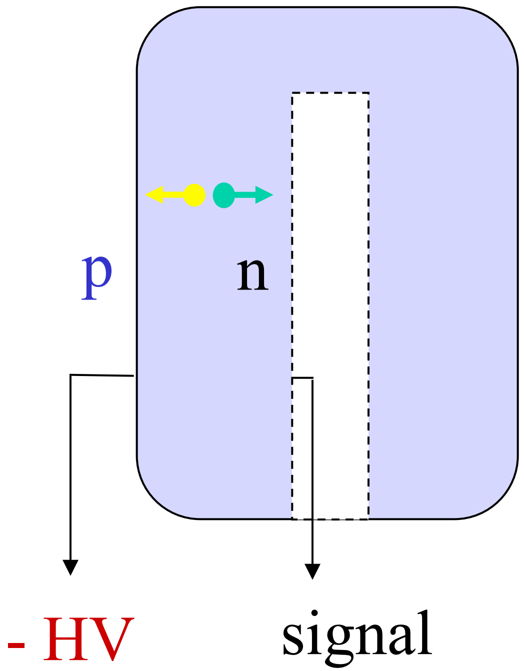
RIBF



Germanium Semi-conductor Detectors

Energy resolution !



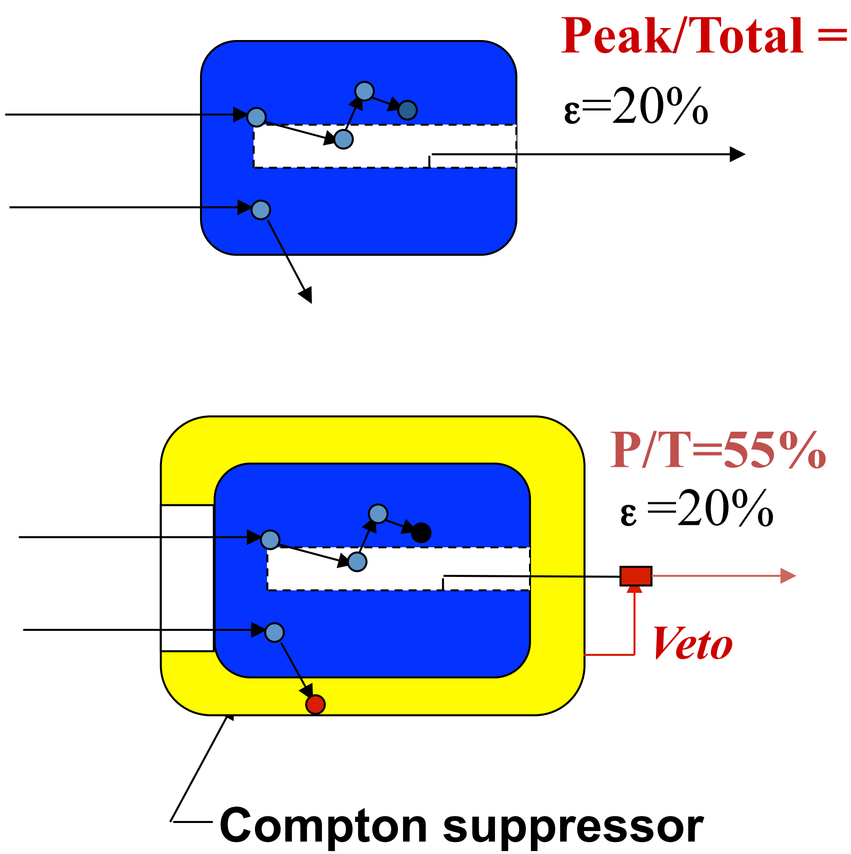


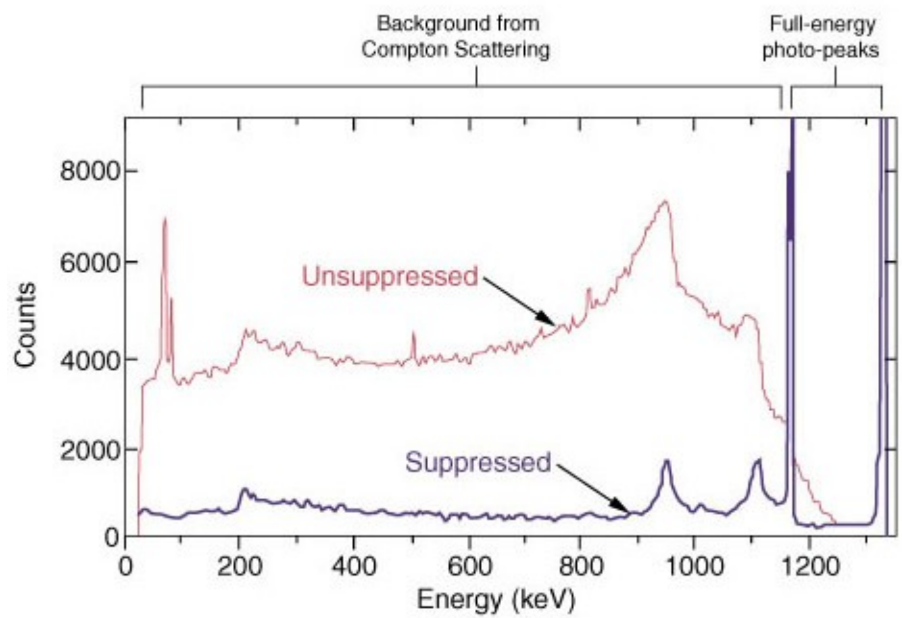
Intrinsic energy resolution determined by statistics of charge carriers ~

$$\sqrt{N} \rightarrow FWHM = 2.35\sqrt{\mathrm{F}\ \ \mathrm{E}\gamma / \varepsilon}$$

Compton Suppression

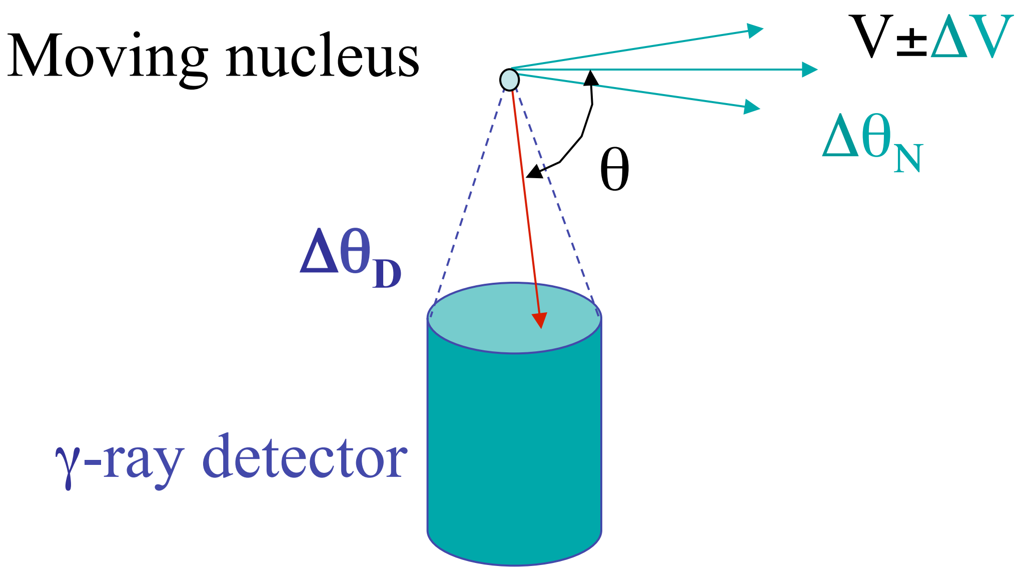
Improve peak-to-total ratio





CAESAR, EUROBALL, GAMMASPHERE

Effective Resolution: Doppler Broadening



Doppler shift

$$E_\gamma = E_\gamma^0 \frac{\sqrt{1-\frac{V^2}{c^2}}}{1-\frac{V}{c}\cos\theta}$$

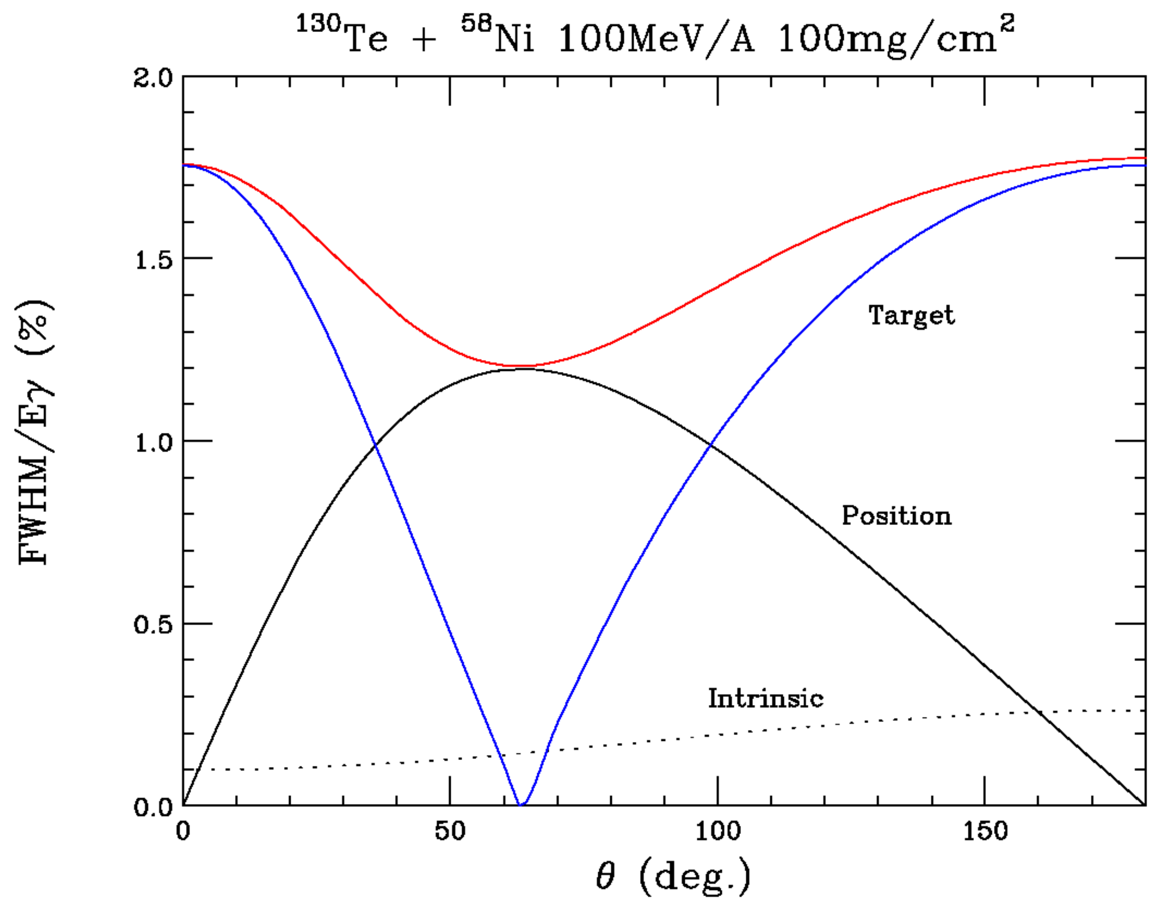
Broadening of detected gamma ray energy due to:

- Spread in speed ΔV
- Distribution in the direction of velocity $\Delta\theta_N$
- Detector opening angle $\Delta\theta_D$

➔ **Need accurate determination of V and θ.**

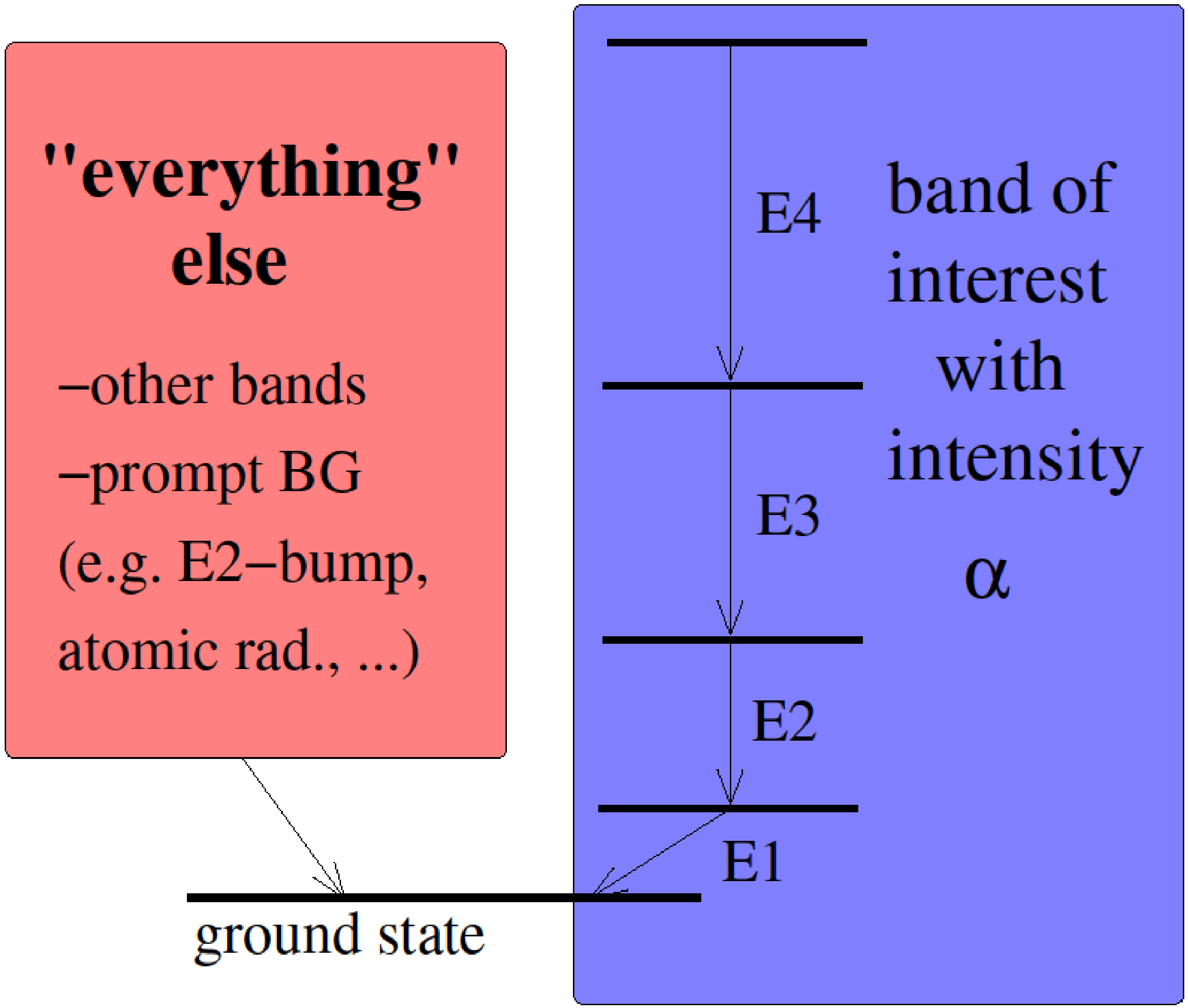
➔ Minimize opening angle and particle detector

Doppler Broadening



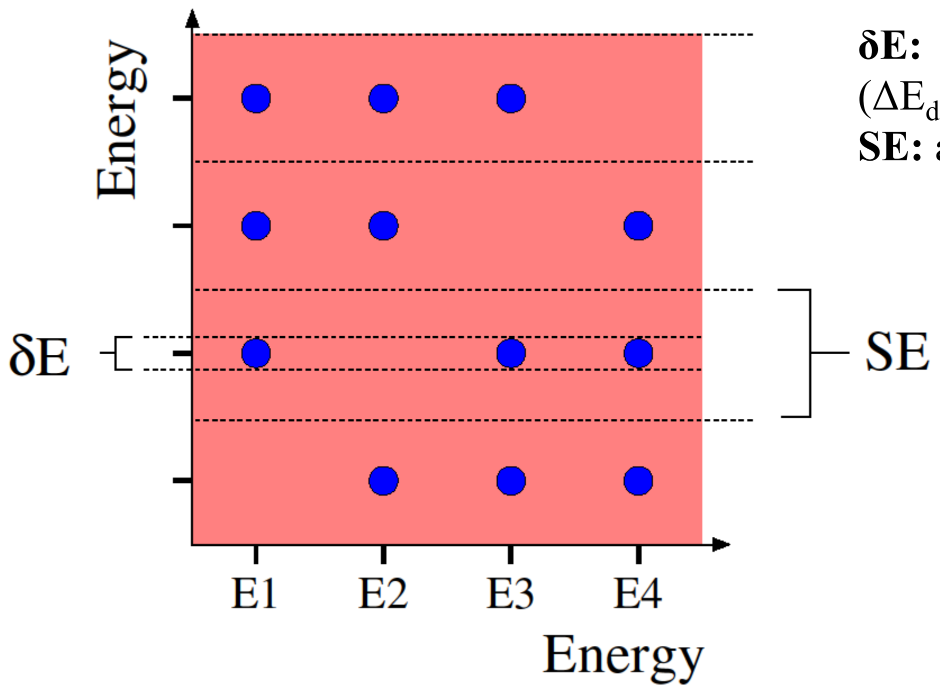
Resolving Power…

A figure of merit (resolving power) could be measured by the ability to observe weak branches from rare and exotic nuclear states.

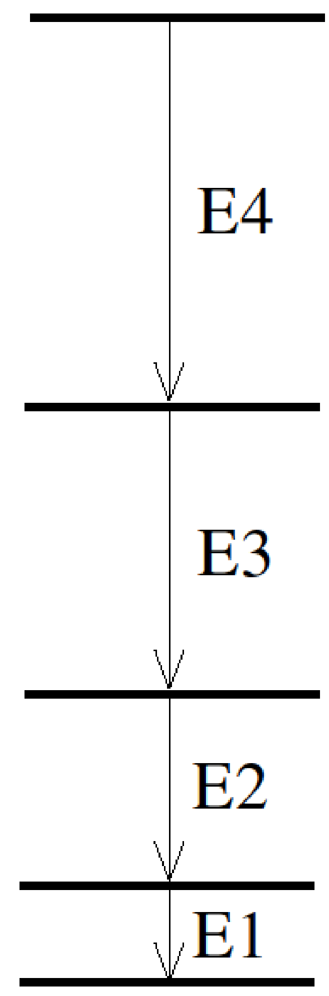


Improving Peak-to-Background…

…using F-fold coincidences (here 'matrix': F=2)



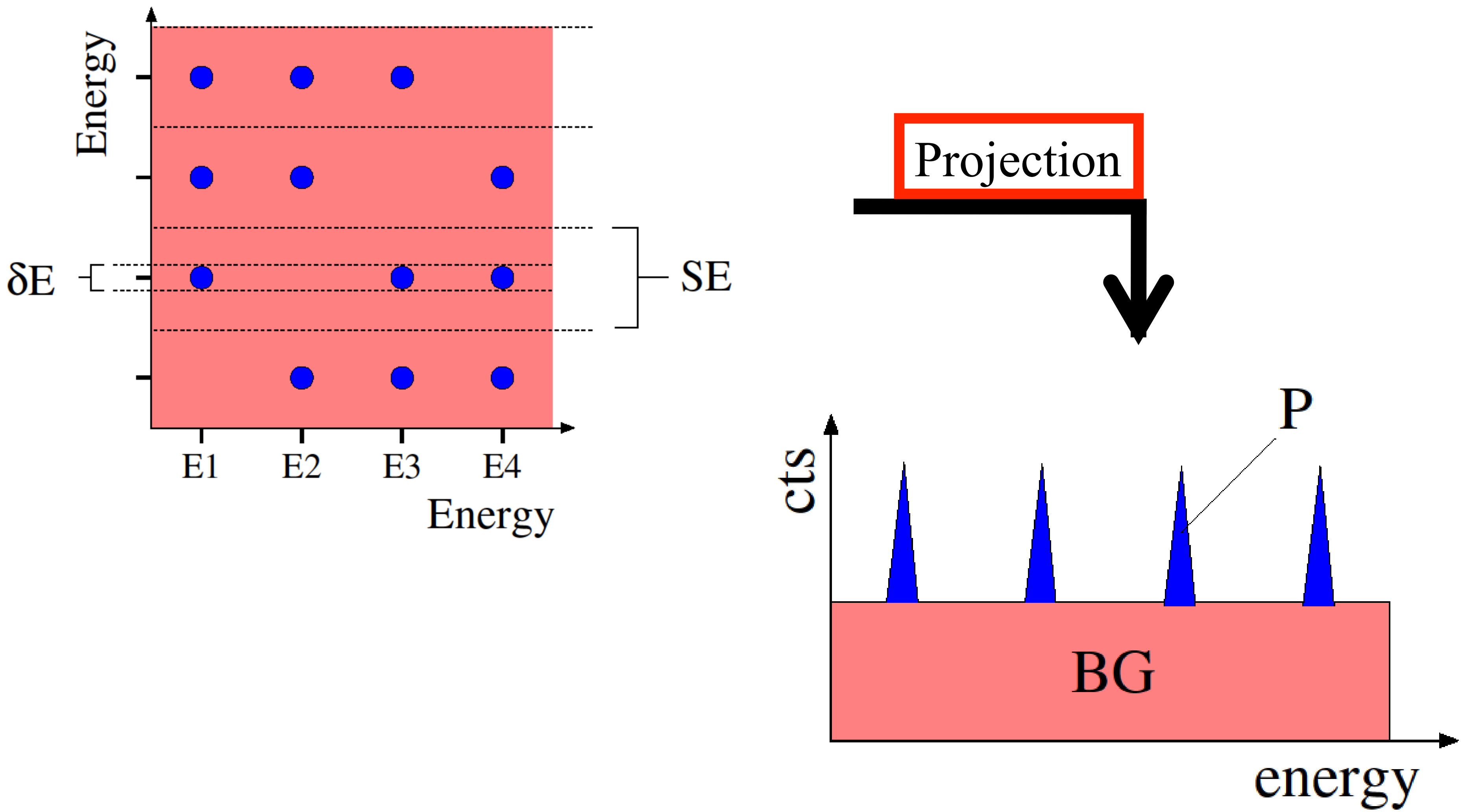
δE: 'effective' E-resolution (ΔE_{det} and $\Delta E_{Doppler}$)
SE: average energy spacing

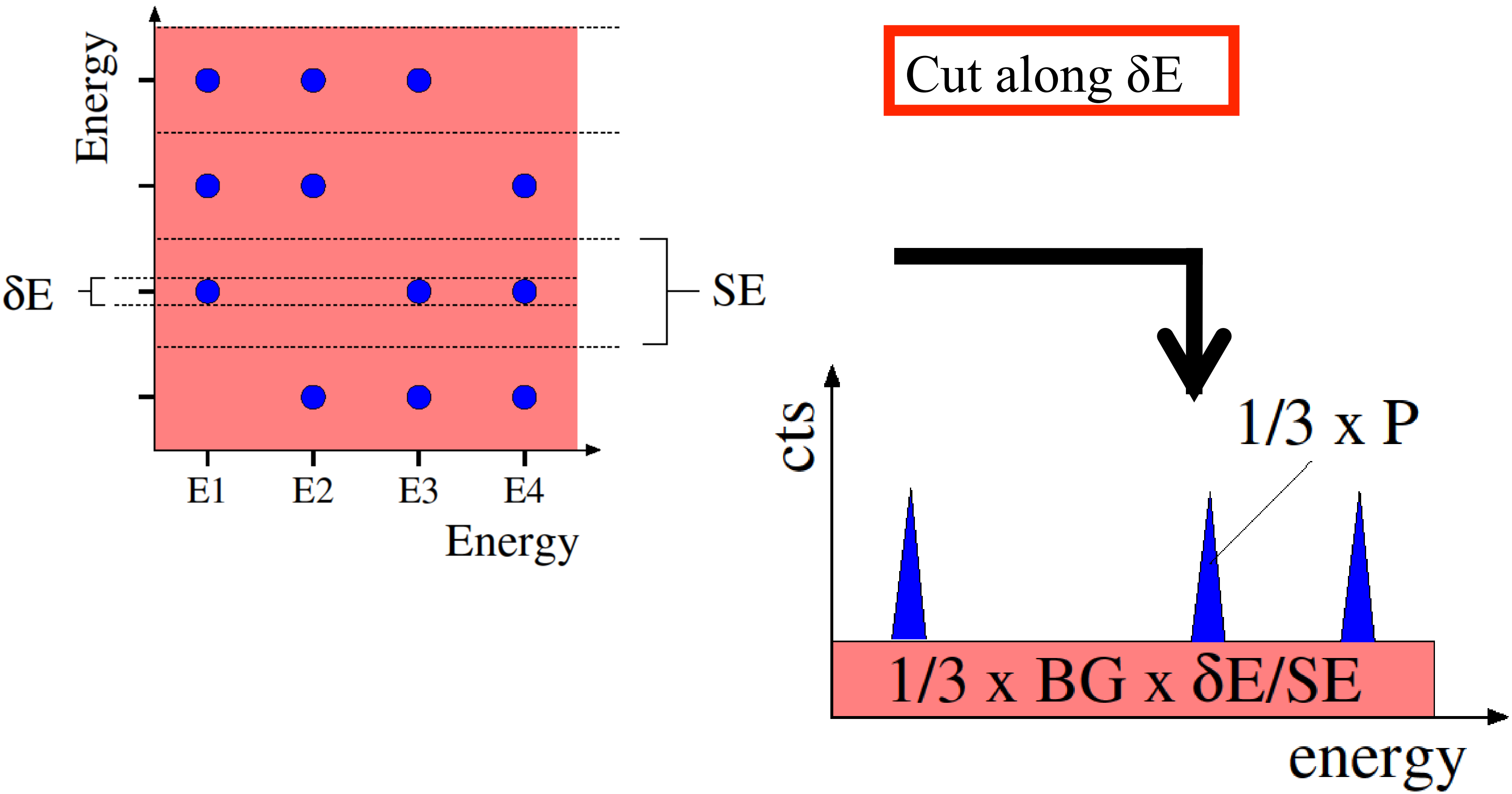


→ E_x-E_y coincidences go into peak (blue)
→ "everything else" spread over red area, as it isn't coincident with any E_x

Improving Peak-to-Background…

…using F-fold coincidences (here ‘matrix’ : F=2)





Improvement of P/BG by factor **SE/δE** !!!

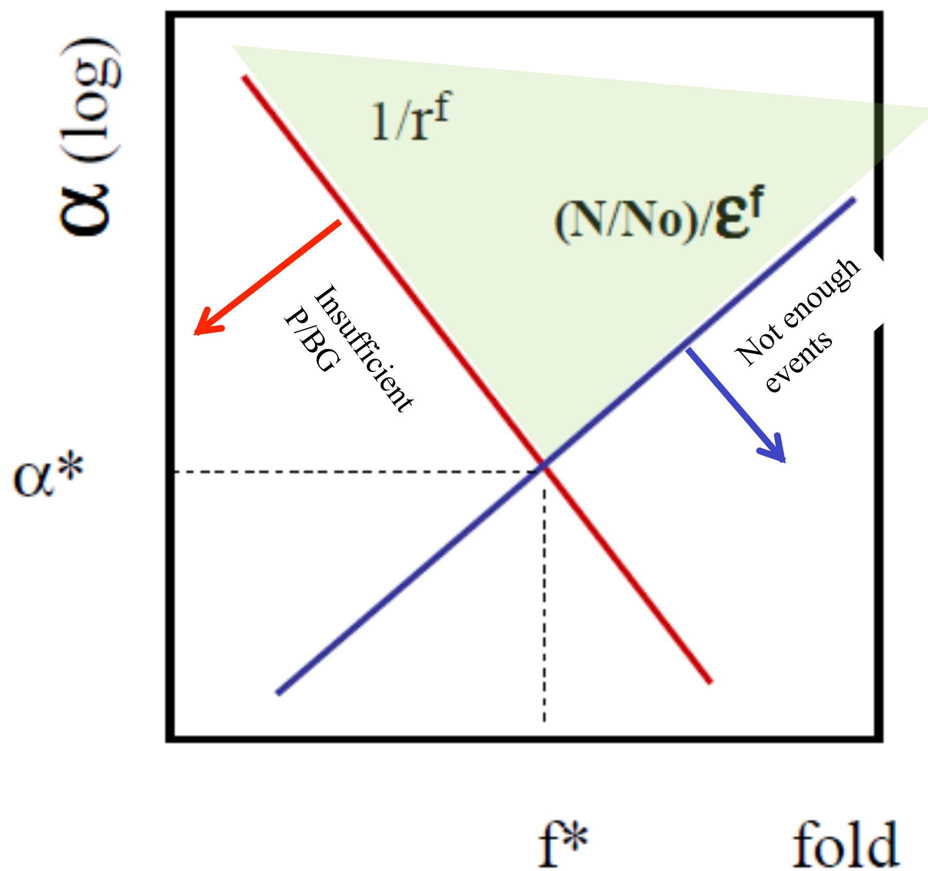
With $r \approx (\frac{SE}{\delta E})(\frac{P}{T})$

$$\alpha = 1/r^f$$

The counts in the peak of interest

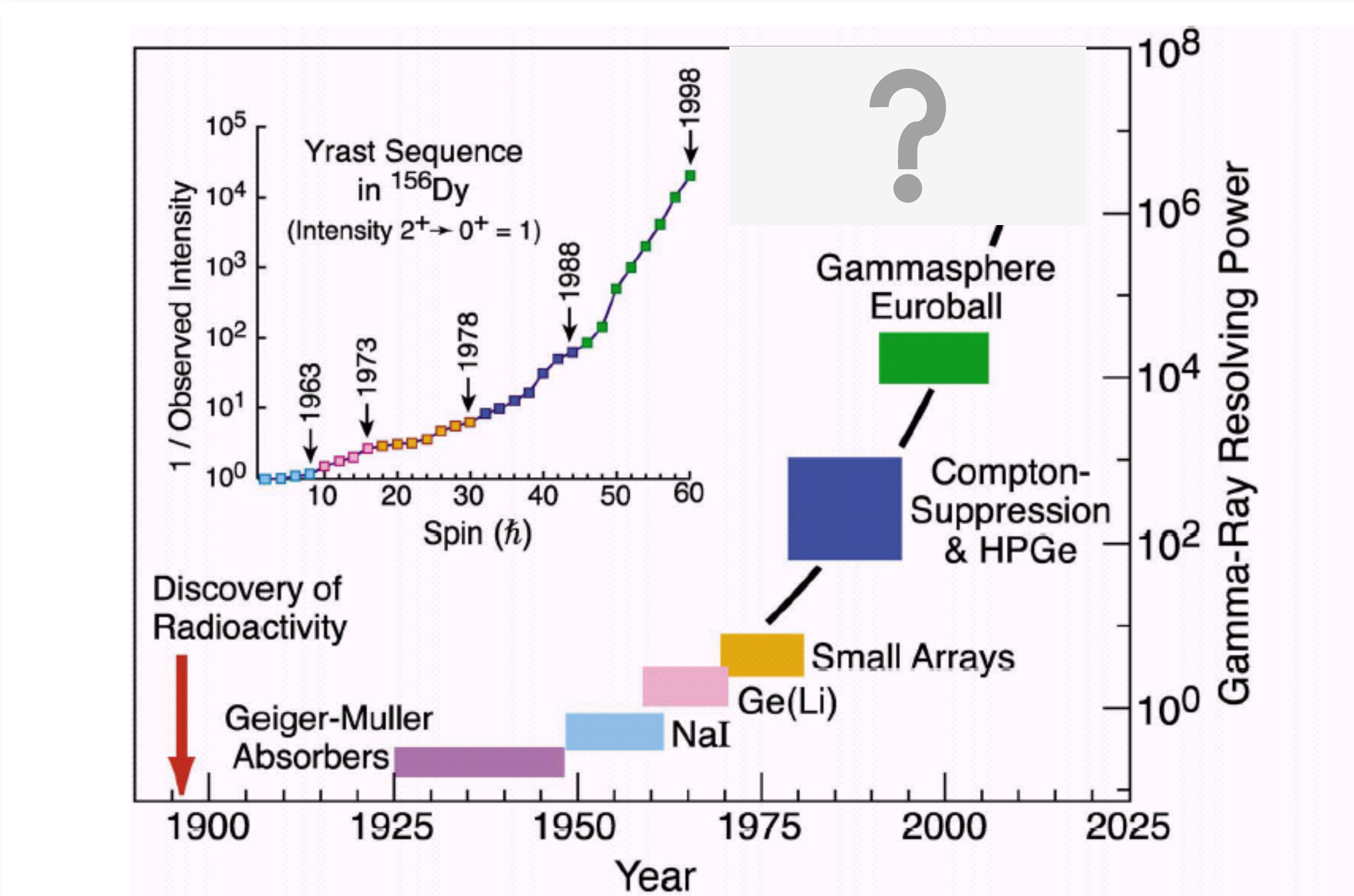
$$N = \alpha N_o \varepsilon^f$$

Note: r >1, ε<1



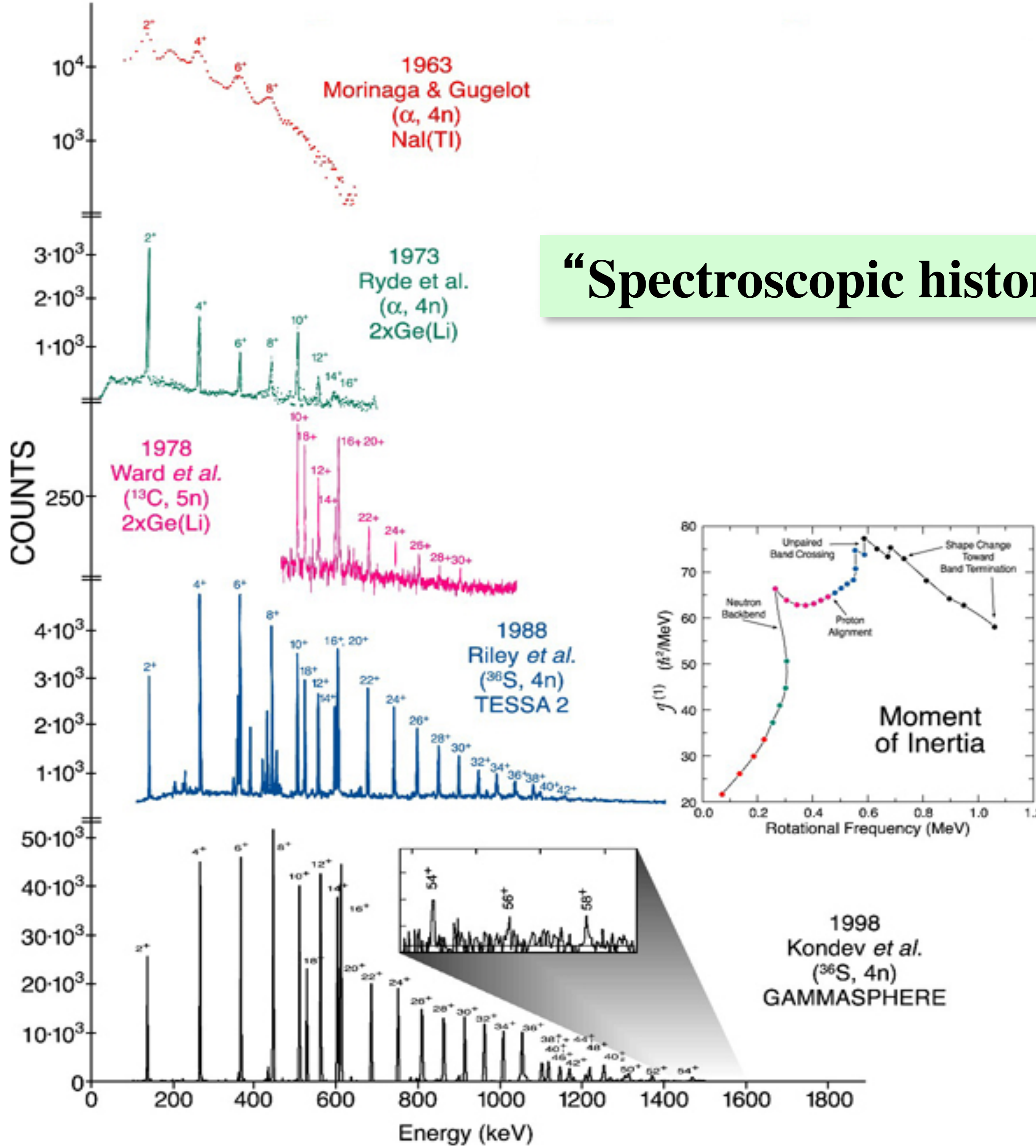
The resolving power is $RP = \frac{1}{\alpha^*} = r^{f^*}$

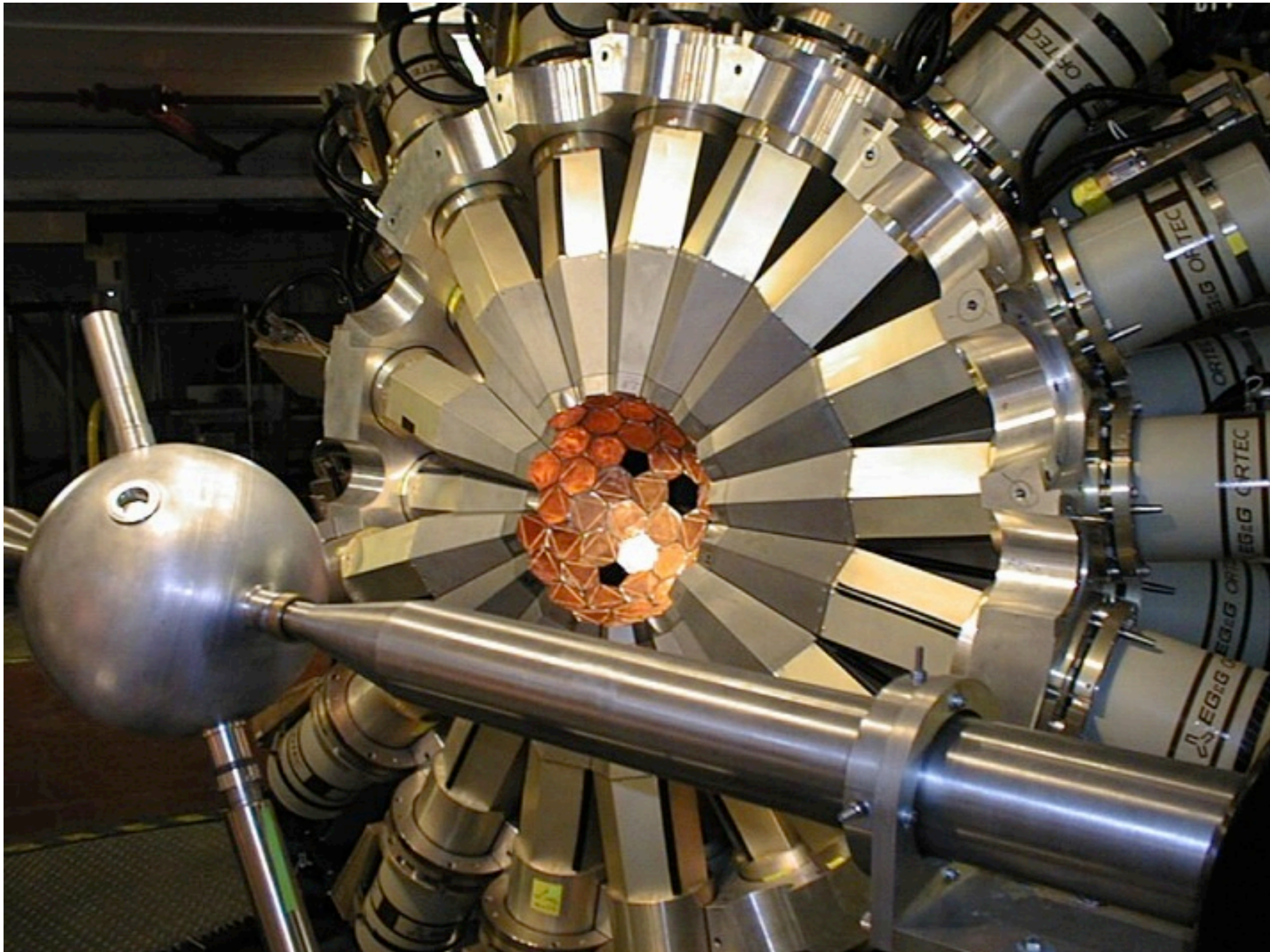
Evolution of Gamma-ray Spectroscopy Resolving Power



Development of new detectors and techniques have always led to discoveries of new and unexpected phenomena.

“Spectroscopic history” of ^{156}Dy

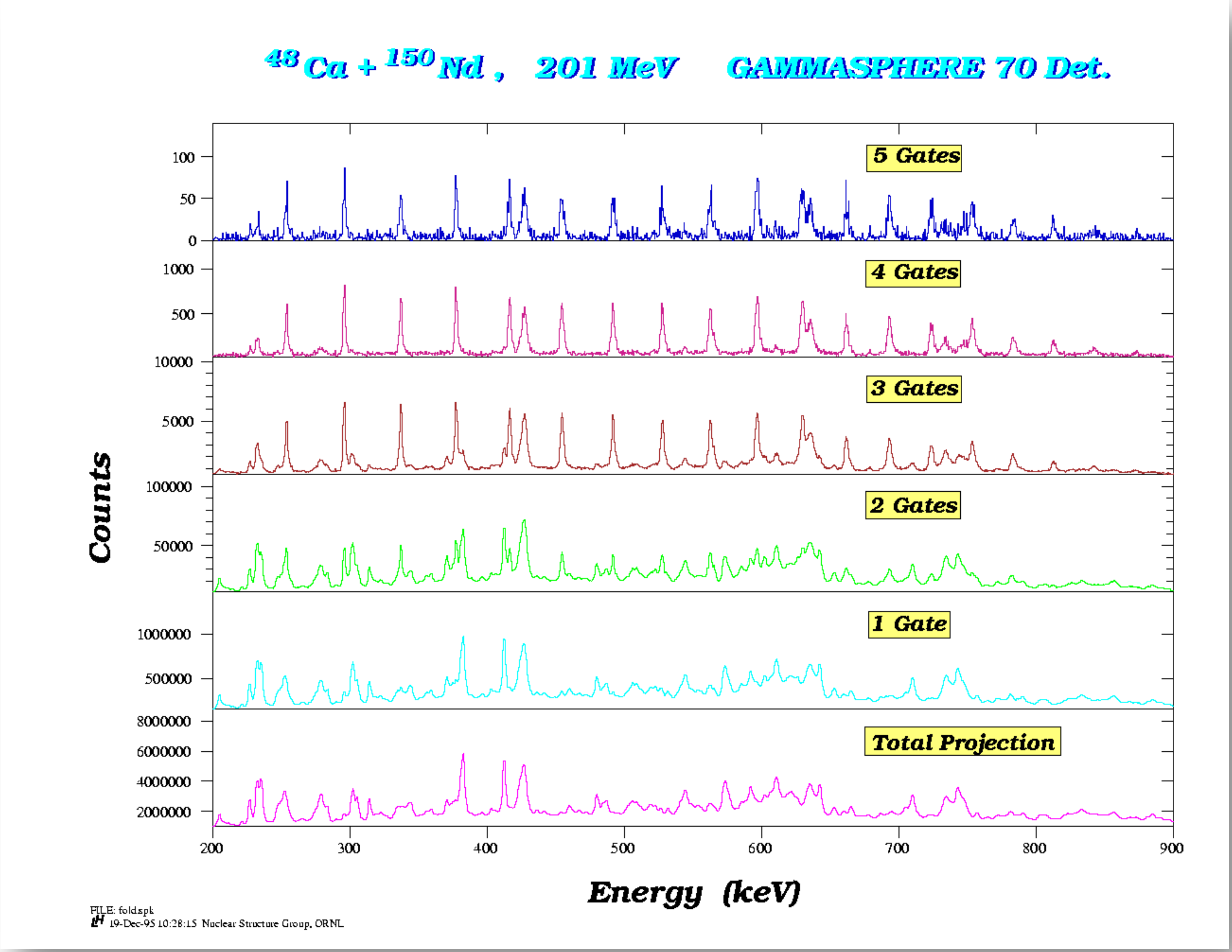




Number of modules	110
Ge Size	7cm (D) × 7.5cm (L)
Distance to Ge	25 cm

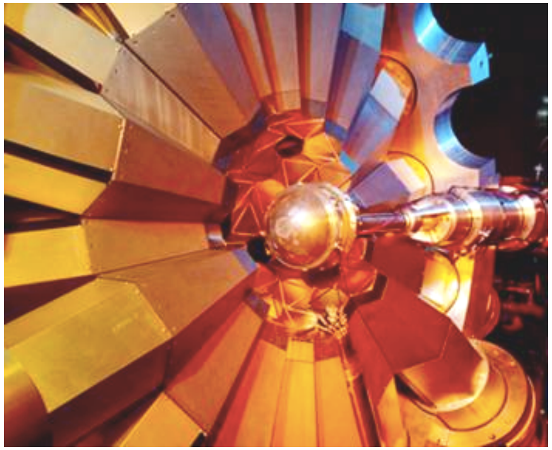
Peak efficiency	9% (1.33 MeV)
Peak/Total	55% (1.33 MeV)
Resolving power	10,000

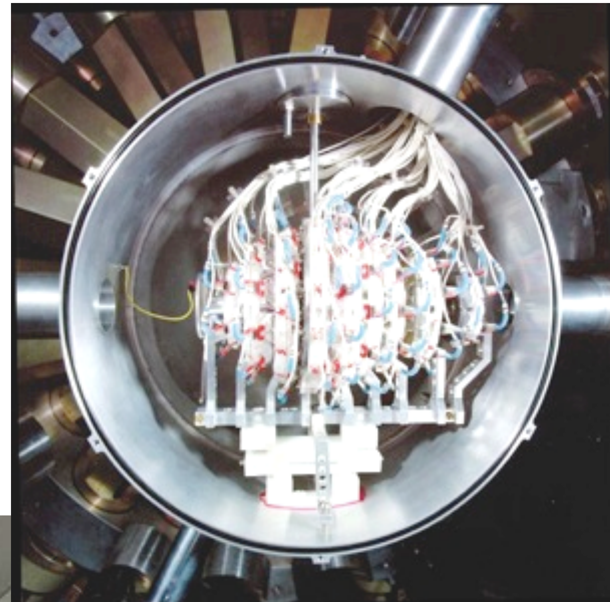
An example:

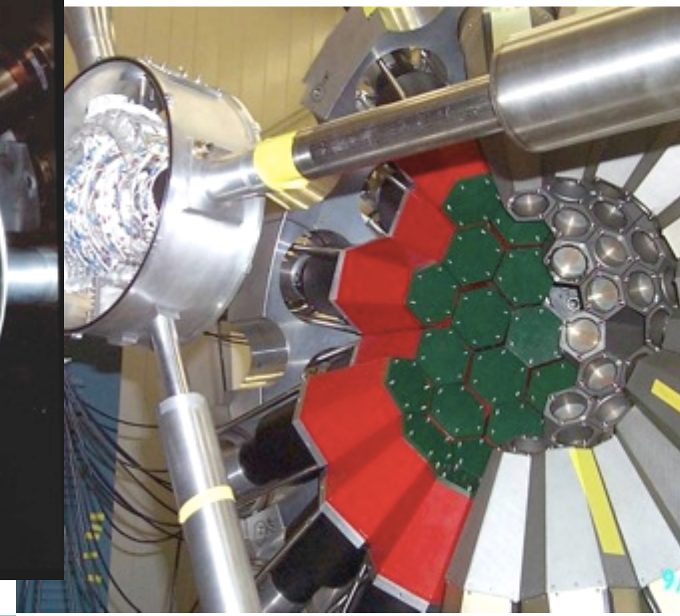


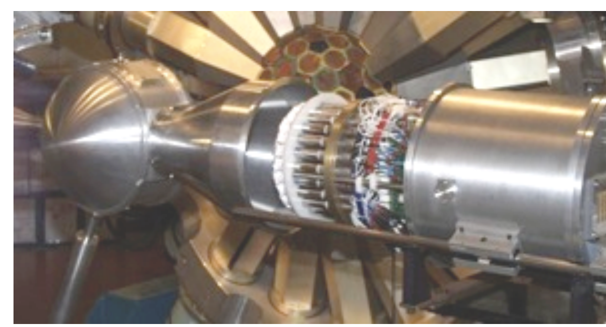
48 Ca + 150 Nd , 201 MeV GAMMASPHERE 70 Det.
5 Gates
4 Gates
3 Gates
2 Gates
1 Gate
Total Projection
Counts
Energy (keV)
100
50
0
1000
500
10000
5000
100000
50000
1000000
500000
8000000
6000000
4000000
2000000
200
300
400
500
600
700
800
900
FILE: fold.spk
19-Dec-95 10:28:15 Nuclear Structure Group, ORNL

Auxiliary Devices









ELSEVIER

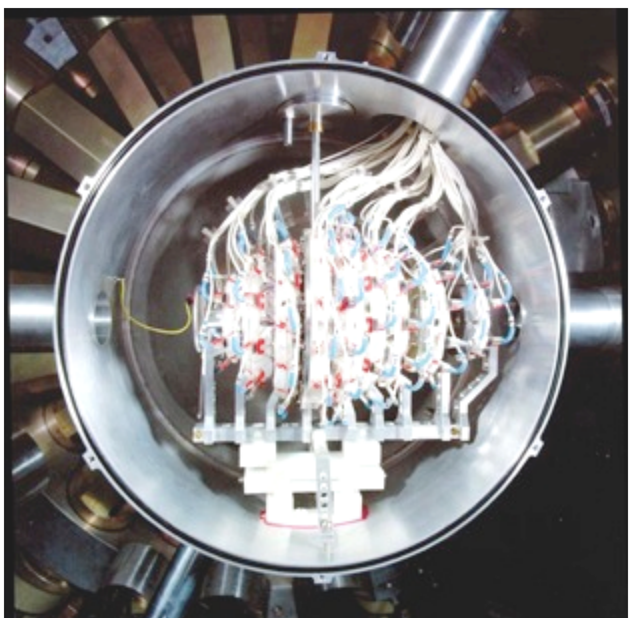
Nuclear Instruments and Methods in Physics Research A 381 (1996) 418–432

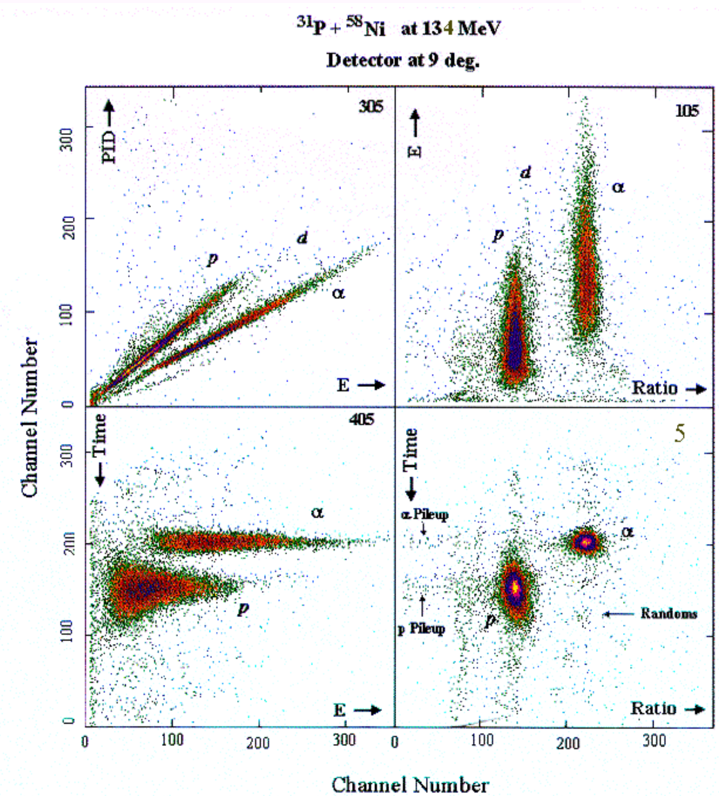
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

"The Microball"
Design, instrumentation and response characteristics of a 4π-multidetector exit channel-selection device for spectroscopic and reaction mechanism studies with Gammasphere

D.G. Sarantites[a,*], P.-F. Hua[a], M. Devlin[a], L.G. Sobotka[a], J. Elson[a], J.T. Hood[a], D.R. LaFosse[a], J.E. Sarantites[a] M.R. Maier[b]

[a] *Department of Chemistry, Washington University, St. Louis, MO 63130, USA*
[b] *Engineering Division Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA*

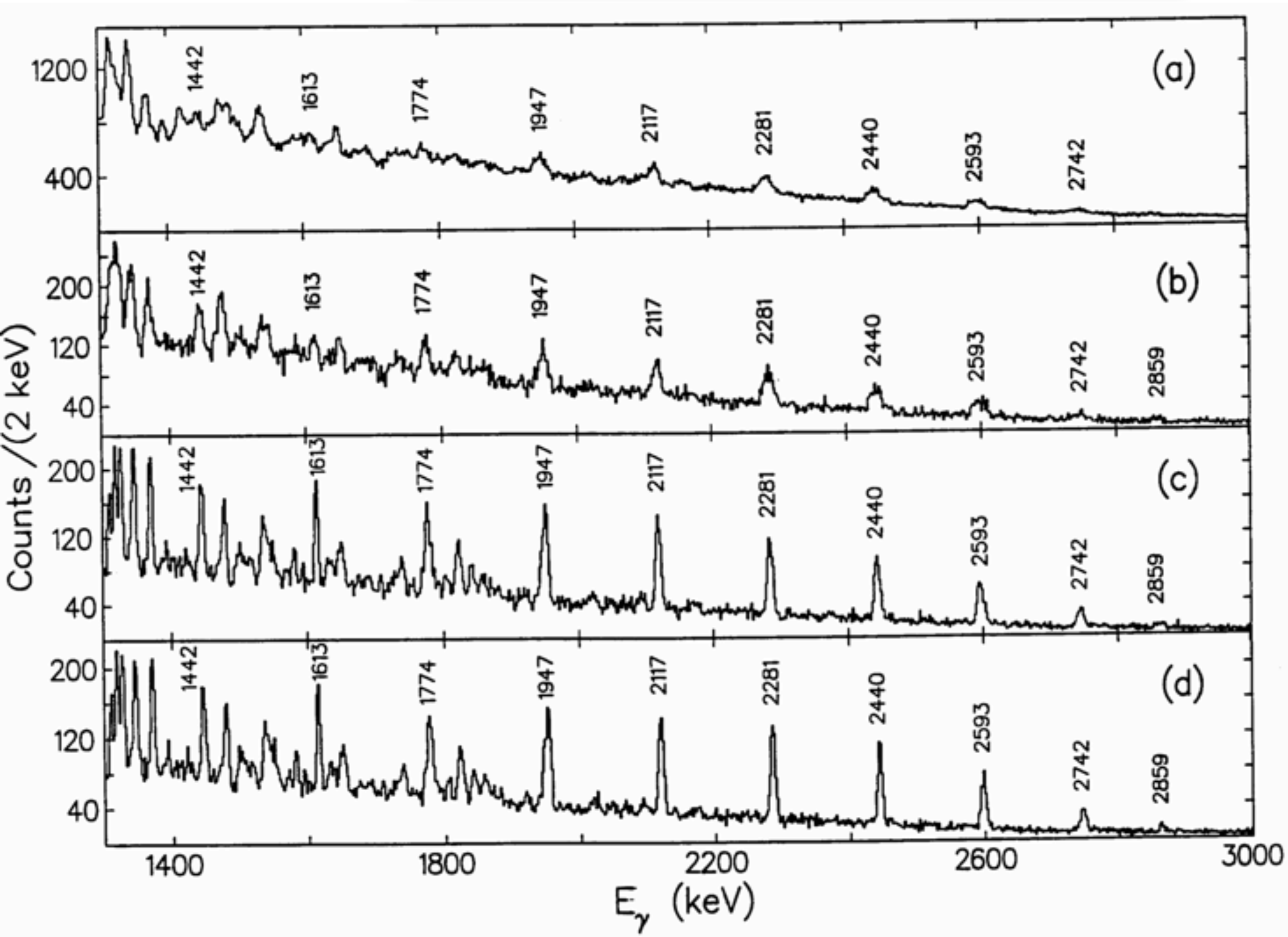




- Channel selection - lower background
- Recoil correction - better Resolution

$^{28}Si + ^{58}Ni \Rightarrow ^{80}Sr + \alpha 2p$ Yrast SD band

No Background subtraction



GS alone γγ

MB + GS γγ, no Recoil C.

MB + GS γγ + RC (const β)

MB+GS γγ + RC-β(E_π)

N·H
ELSEVIER

Nuclear Instruments and Methods in Physics Research A 452 (2000) 205–222

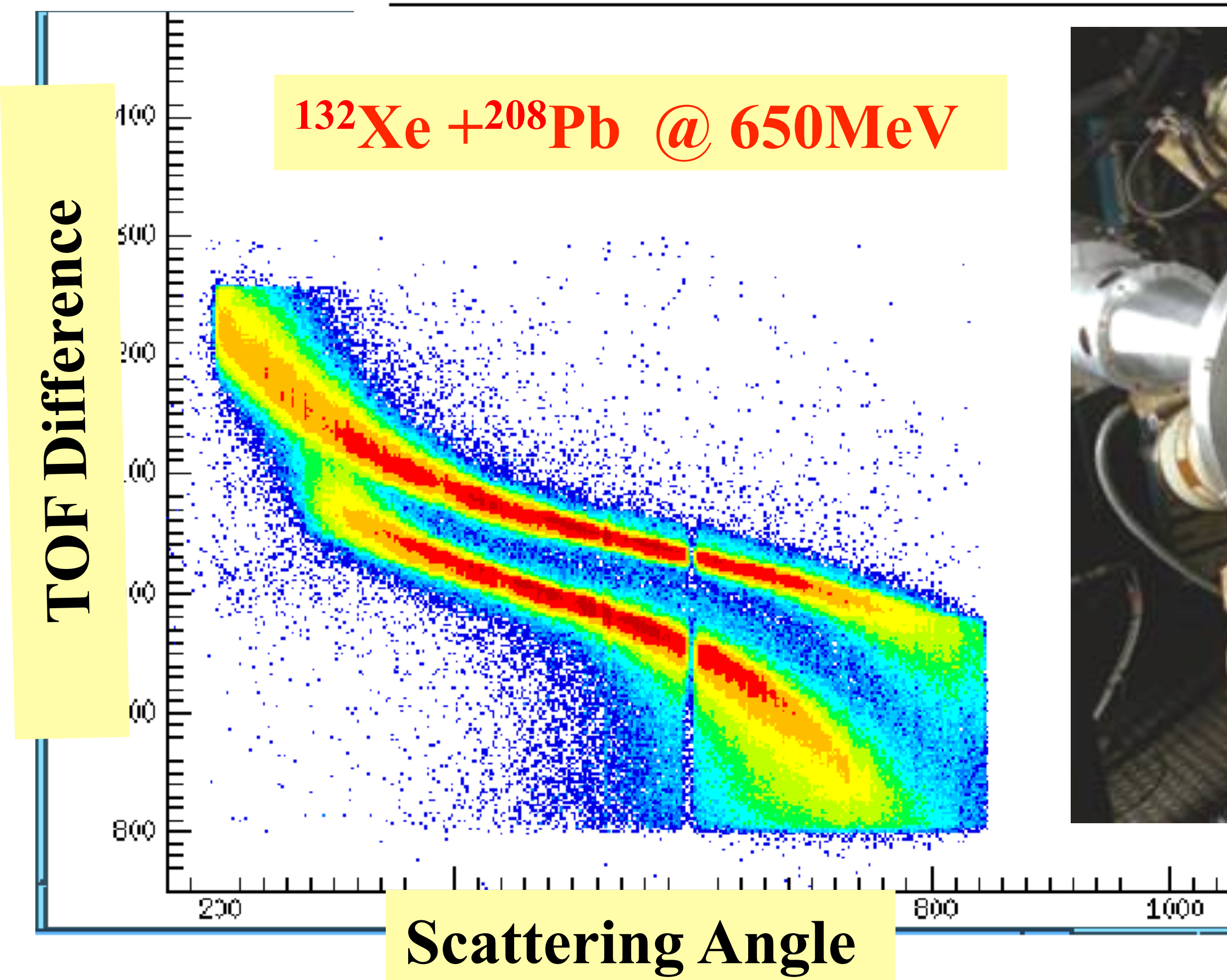
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
www.elsevier.nl/locate/nima

CHICO, a heavy ion detector for Gammasphere☆

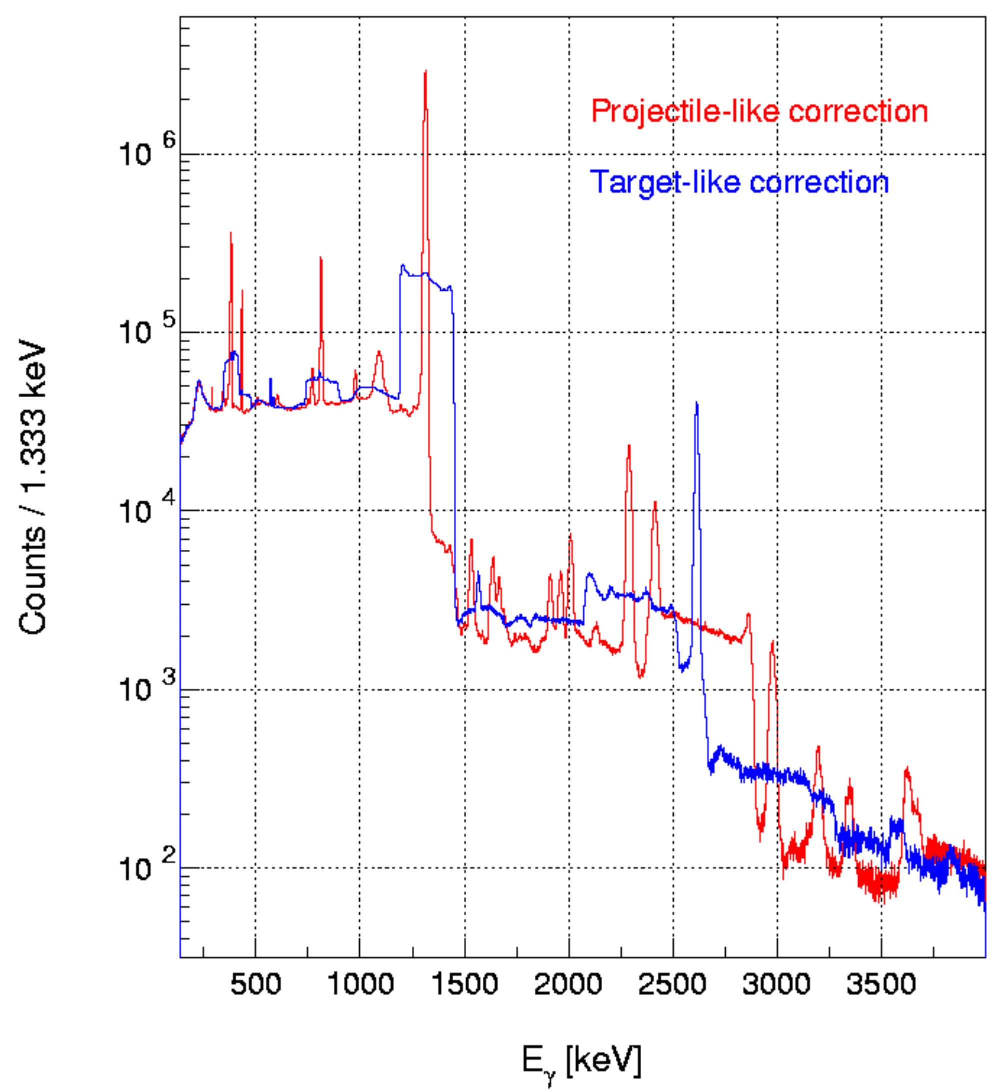
M.W. Simon*, D. Cline, C.Y. Wu, R.W. Gray, R. Teng, C. Long[1]

Nuclear Structure Research Laboratory, University of Rochester, 271 East River Road, Rochester, NY 14623, USA

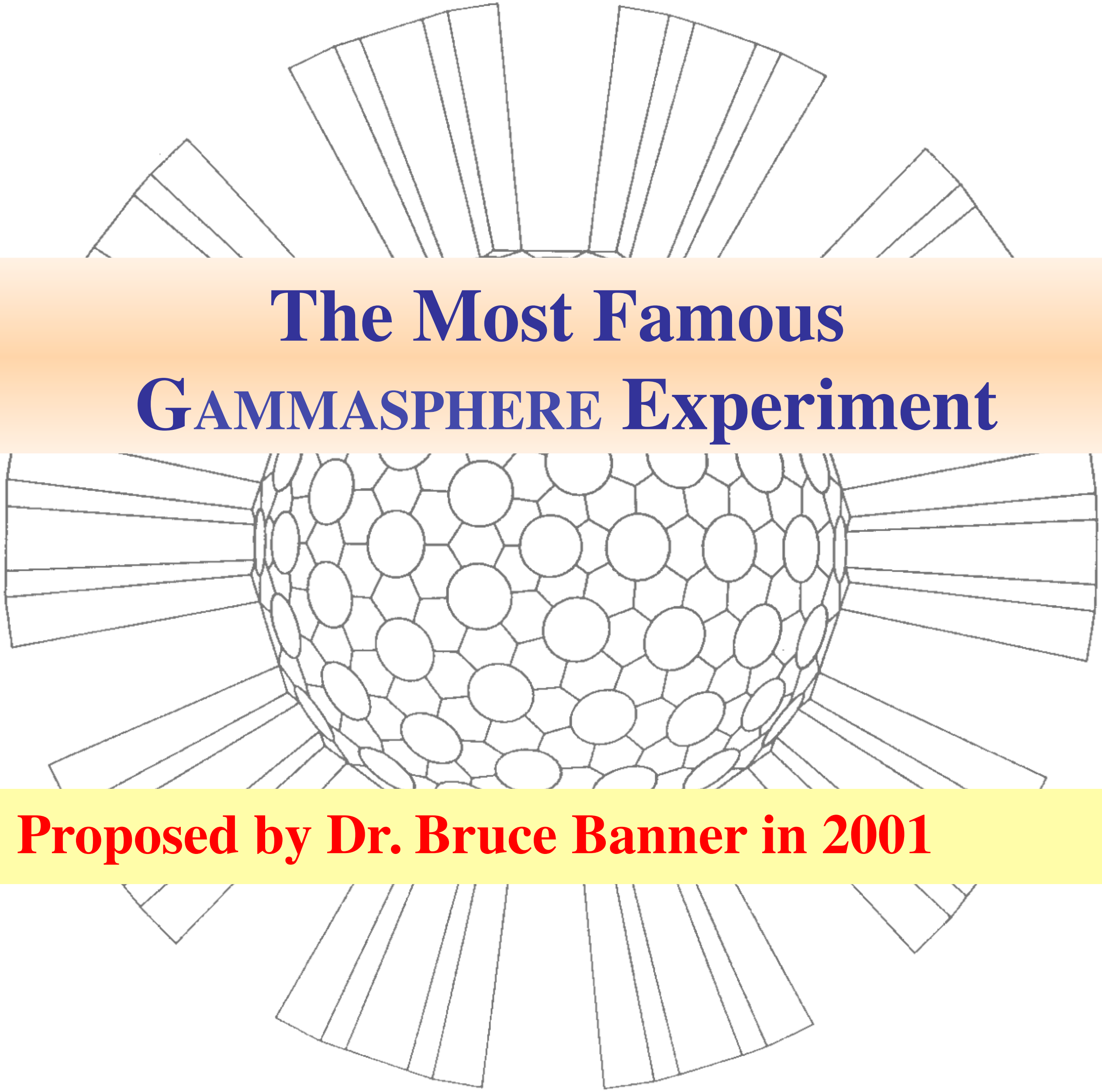
Received 19 January 2000; accepted 7 March 2000



$^{136}Xe + ^{208}Pb$ at 650 MeV

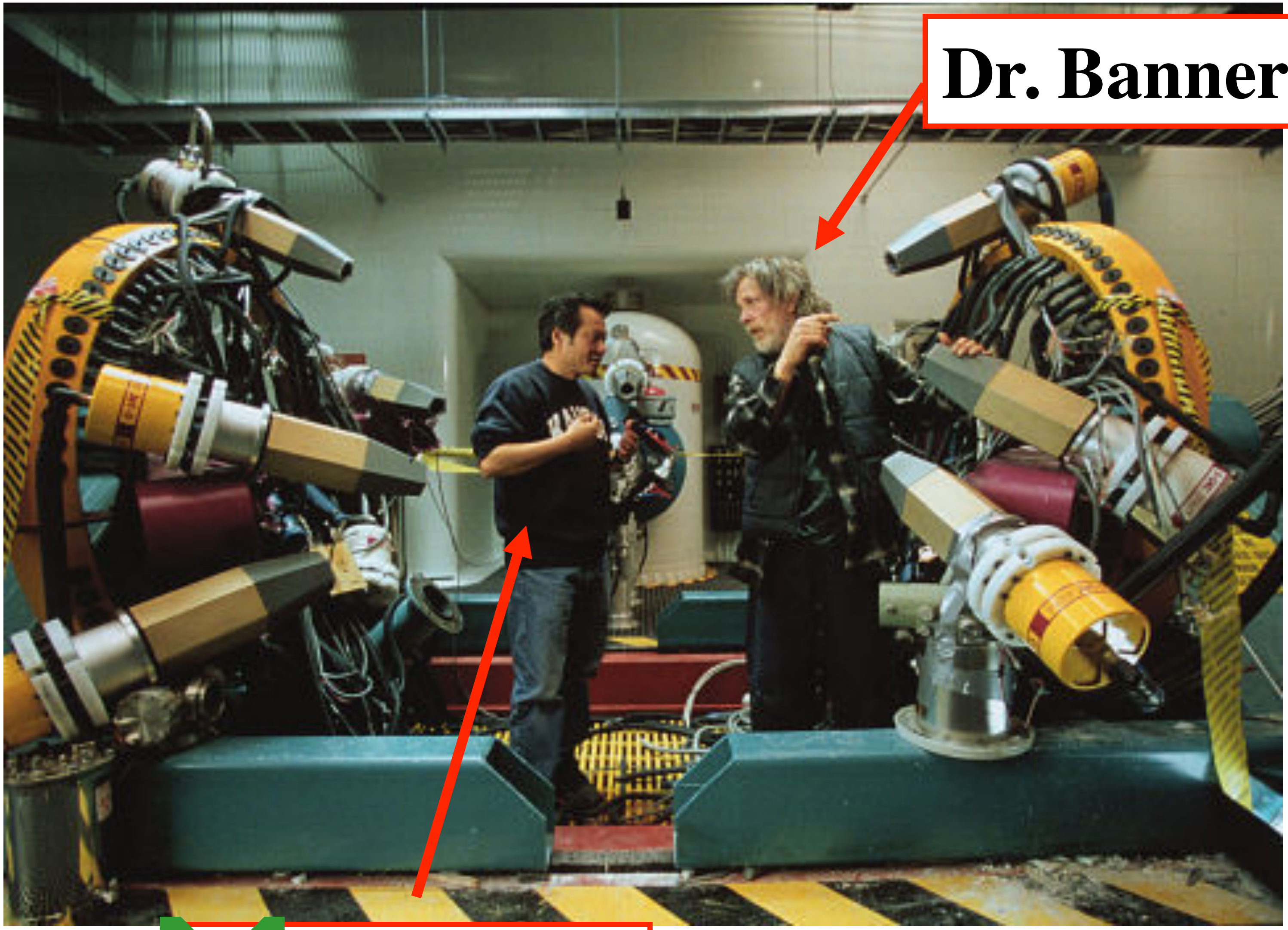


The Most Famous GAMMASPHERE Experiment



Proposed by Dr. Bruce Banner in 2001

Setting-up the Experiment



Dr. Banner Sr.

YAng Lee

Every serious pl ... mmasphere on

Argonne NATIONAL LABORATORY

ATLAS

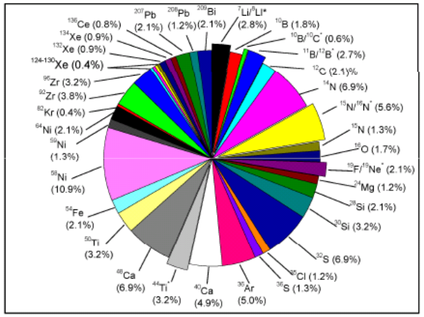
Argonne Tandem Linear Accelerator System

The prime national facility for nuclear structure research

The ATLAS facility is a leading facility for nuclear structure research in the United States. It provides a wide range of beams for nuclear reaction and structure research to a large community of users from the US and abroad. The full range of all stable ions can be produced in ECR ion sources, accelerated in the world's first superconducting linear accelerator for ions to energies of 7-17 MeV per nucleon and delivered to one of several target stations. About 20% of the beam-time is used to generate secondary radioactive beams. These beams are used mostly to study nuclear reactions of astrophysical interest and for nuclear structure investigations.

User community

ATLAS provides beams and experimental instruments for a large community of nuclear scientists. In 2006, there were 436 active users, including 75 graduate students. Typically, research at ATLAS results in 10 Ph.D. theses and 60 publications in peer reviewed scientific journals every year. Beam time is allocated based on the recommendations of a Program Advisory Committee which meets twice a year.



Distribution of ATLAS beams in FY2006

Research programs

The ATLAS research programs focus on the key questions that are central to our understanding of baryonic matter and on the description of the astrophysical processes that generate energy and produce elements in the stars. These areas of research have been endorsed in several major reviews of the science. Specific issues being addressed are 1) the quantum structure of nuclei, 2) nuclear shapes,

GAMMASPHERE is one of the forefront instruments available for experiments at ATLAS. It consists of 110 Compton-suppressed Ge detectors used to detect gamma rays emitted from compound nuclei formed by fusion of accelerated heavy ions and target nuclei.

3) exotic decay modes, 4) masses of exotic nuclei, 5) fundamental interactions, 6) nuclear reactions of astrophysical importance, 7) properties of the heaviest nuclei and 8) accelerator mass spectrometry.

Future developments

Since its inception in 1985, the ATLAS facility has continually been upgraded in order to be at the forefront of nuclear research. At present, the Californium Rare Ion Breeder Upgrade, CARIBU, is being built. This facility will provide for the acceleration of neutron-rich fission fragments from a one Curie ^{252}Cf source to study neutron-rich nuclei, particularly those of relevance for the astrophysical rapid neutron capture process responsible for the production of a large fraction of the heavy elements in the Universe. A novel superconducting solenoid spectrometer, HELIOS, which is ideal for the study of the structure of these neutron-rich species, is under construction and an energy upgrade of ATLAS is also under way. In order to fully explore neutron-rich nuclei, a current frontier in nuclear physics research, a major new facility for beams of radioactive ions is in the planning stages.

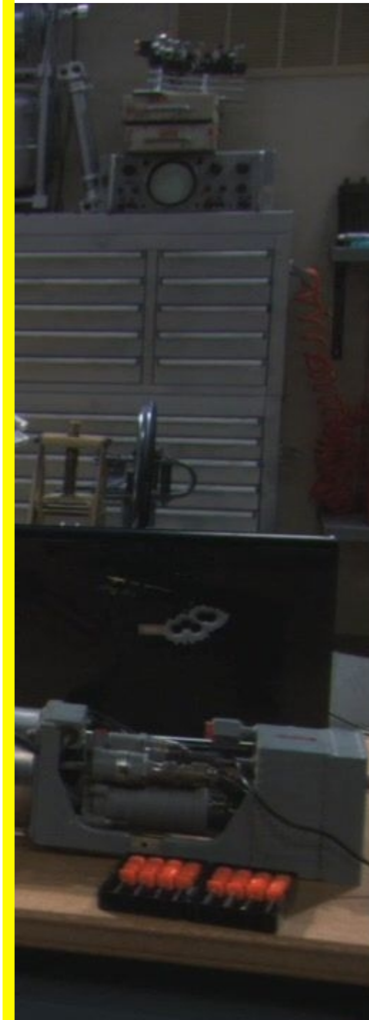
Contact

Robert V. F. Janssens, Scientific Director, Janssens@anl.gov
December 2006

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a U.S. D... mana...



Courtesy of Robert Janssens

Towards the "Ultimate" Ge Array

Nuclear Instruments and Methods in Physics Research A 422 (1999) 195–200

Gamma-ray tracking detectors

I.Y. Lee

Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Nuclear Instruments and Methods in Physics Research A 430 (1999) 292–310

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

GRETA: utilizing new concepts in γ-ray detection☆

M.A. Deleplanque*, I.Y. Lee, K. Vetter, G.J. Schmid[1], F.S. Stephens, R.M. Clark, R.M. Diamond, P. Fallon, A.O. Macchiavelli

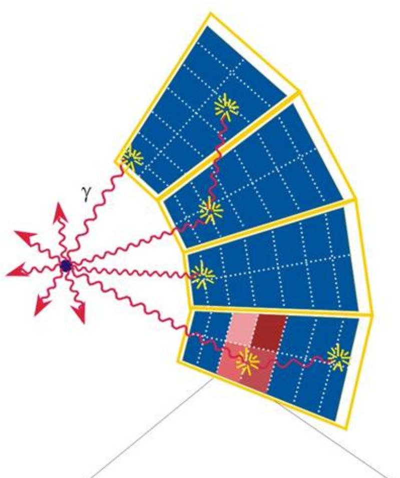
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

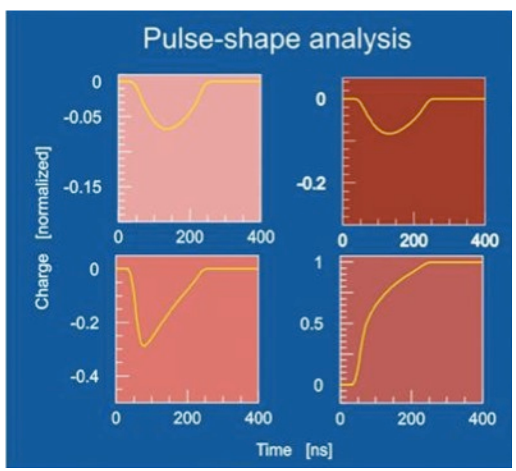
Pulse shape analysis in segments

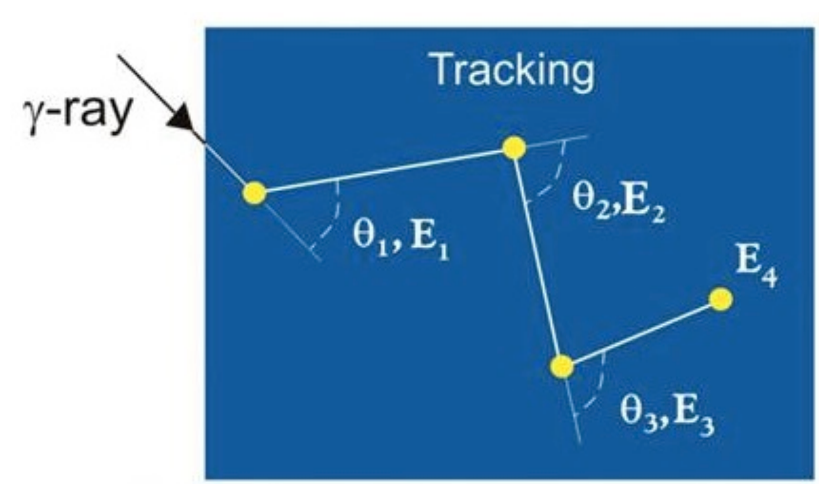
➔ 3D position of interaction points

Tracking of photon interaction points

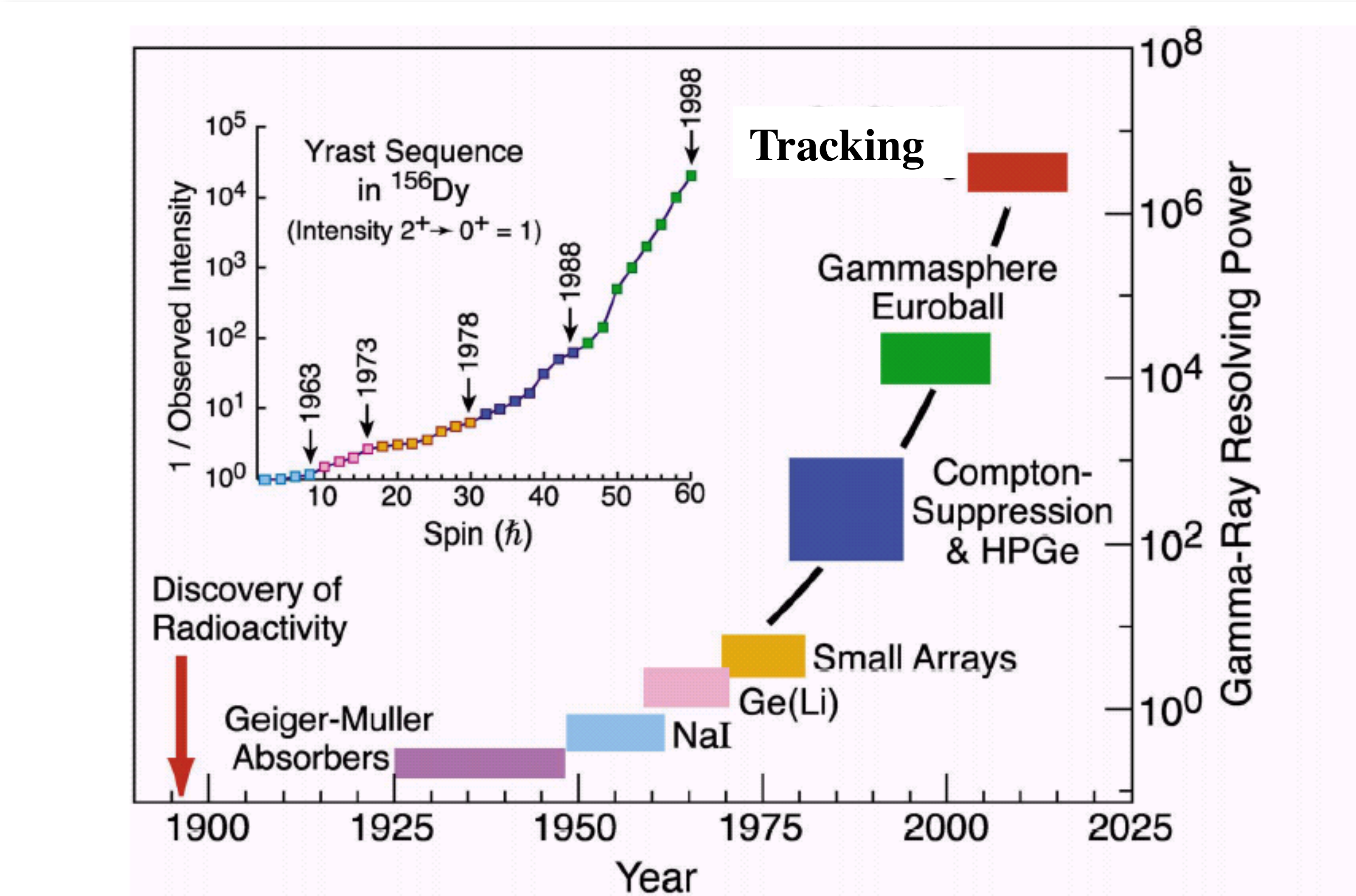
➔ energy and position of γ-ray



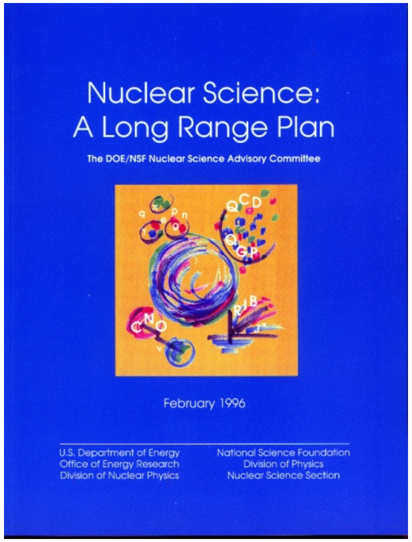


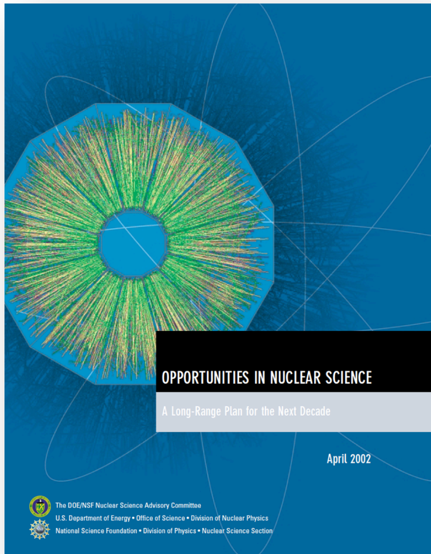


Evolution of Gamma-ray Spectroscopy Resolving Power

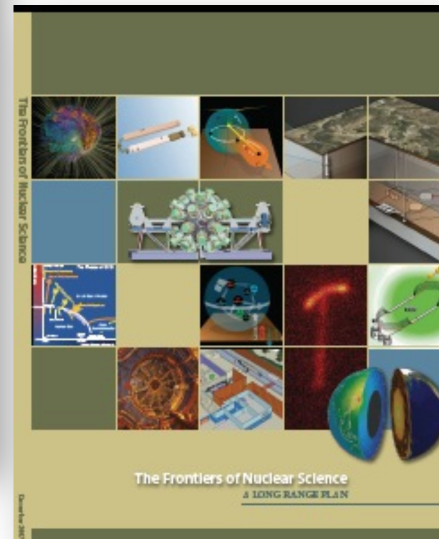


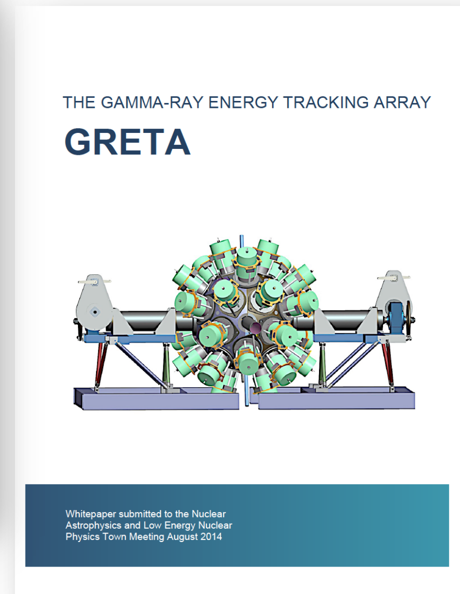
Gamma-ray tracking and the Long Range Plans





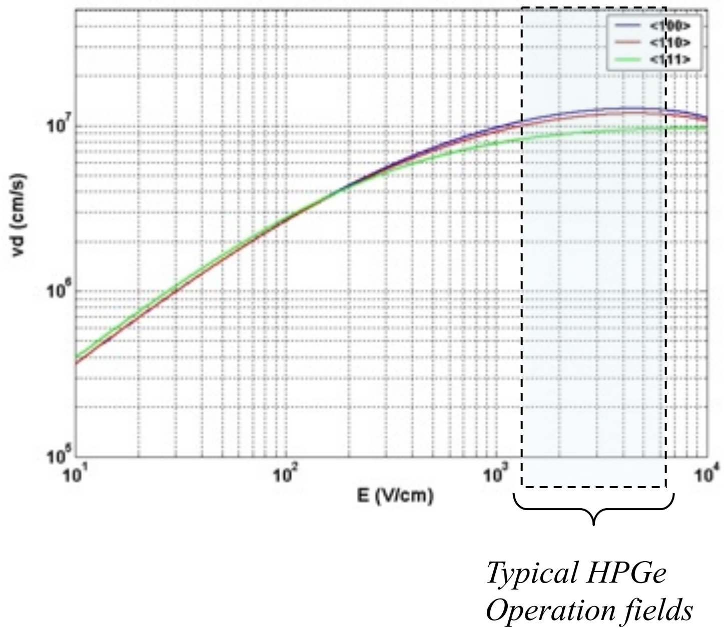
"Construction of GRETA should begin immediately upon the successful completion of the GRETINA array"
2007 LRP





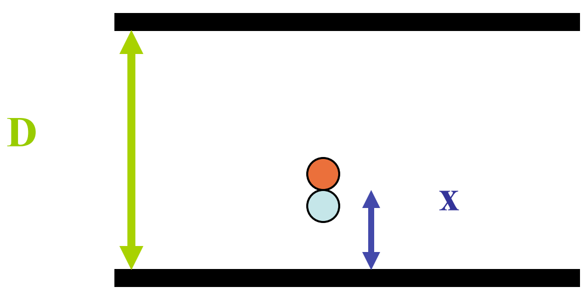
"The detection of gamma-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions." 2002 LRP

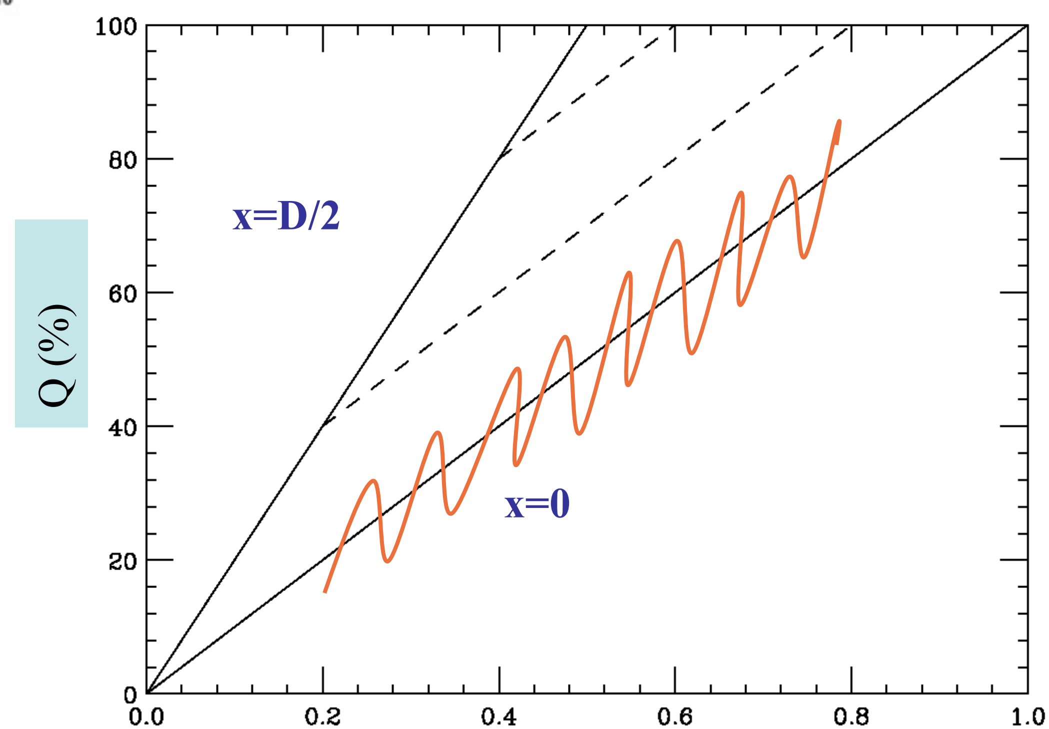
Calculated electron drift velocity



$$v \approx 0.1mm/n\sec$$

$$10n\sec/mm$$



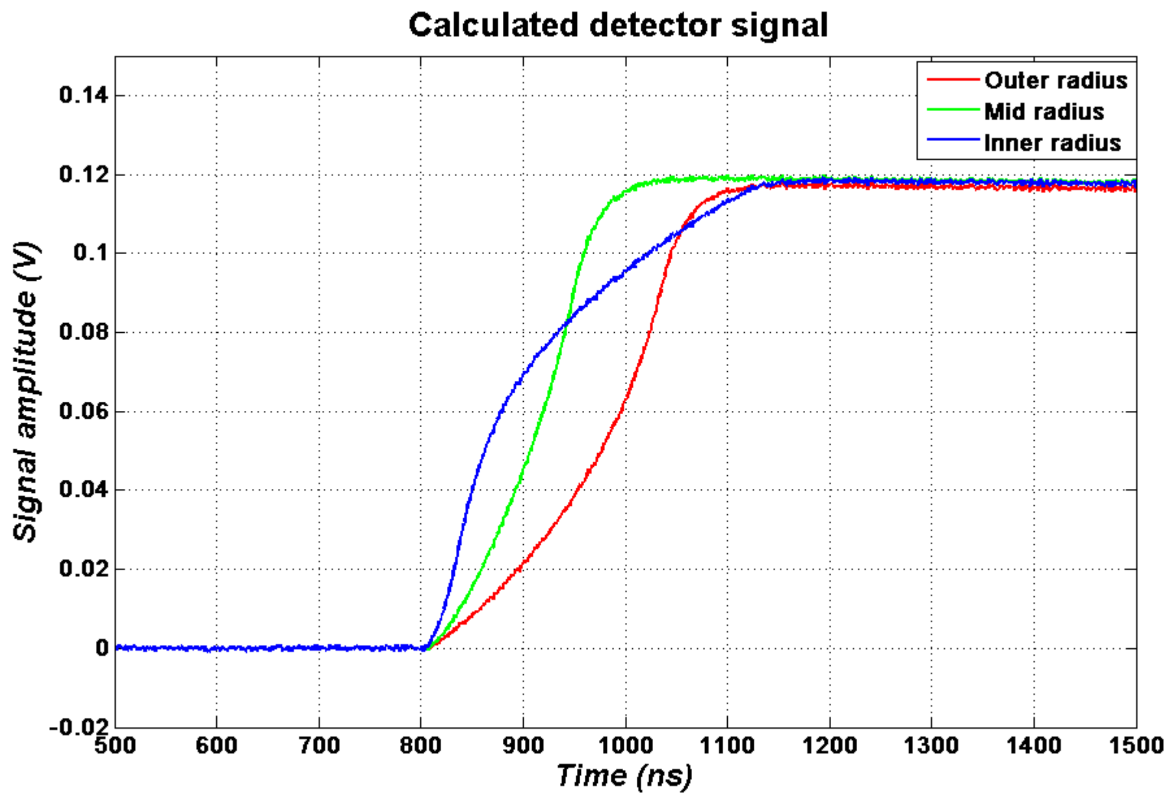


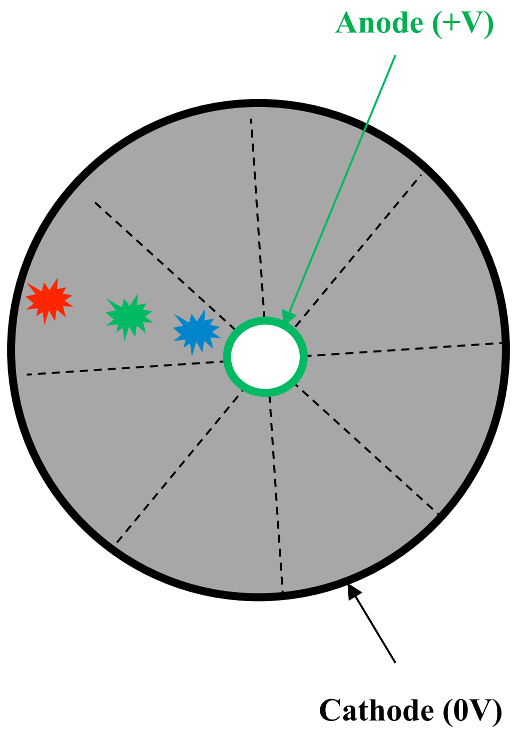
$$\delta x \geq (D/Q)\sigma$$

$$\tilde{t} = t/(v/D)$$

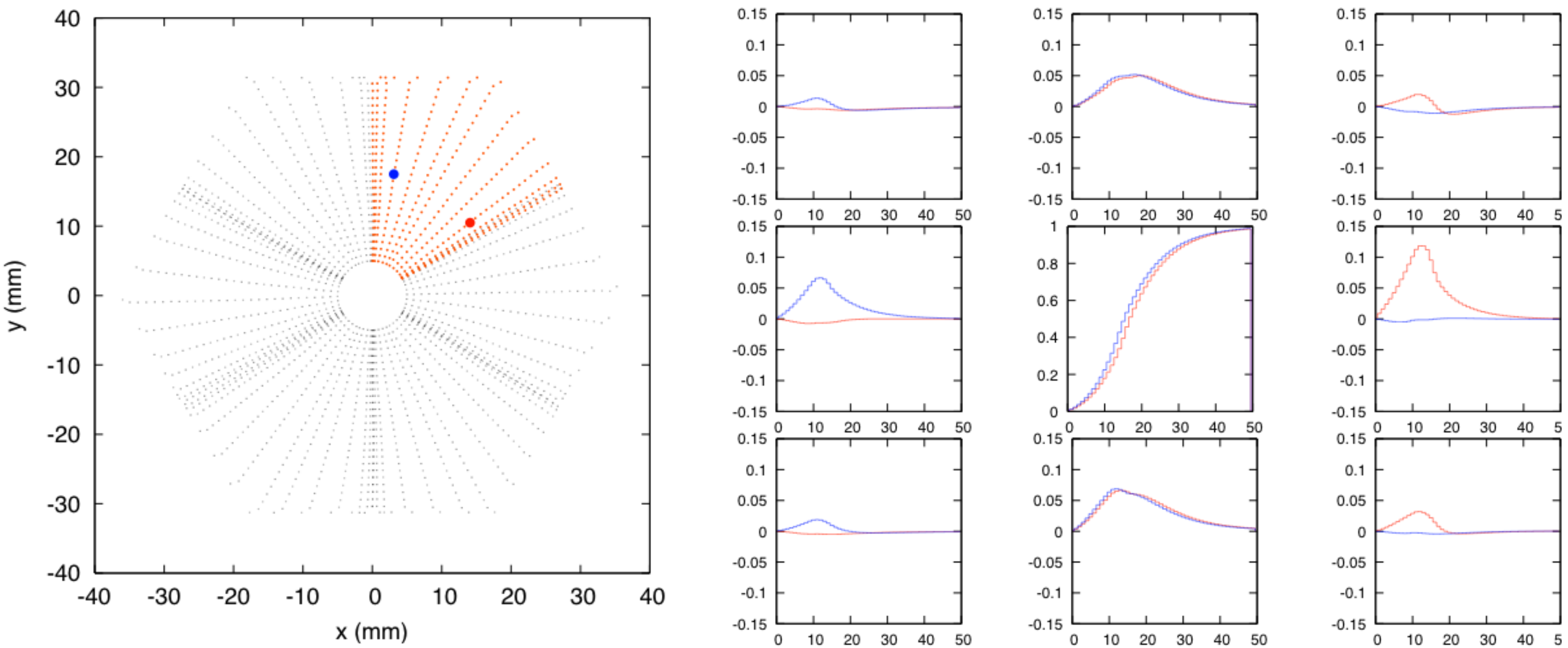
$$\delta x \geq 1mm$$

Position sensitivity





Position sensitivity

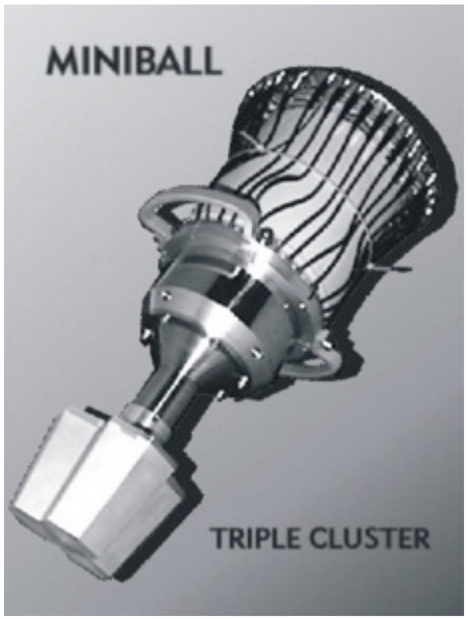


Technical Challenges

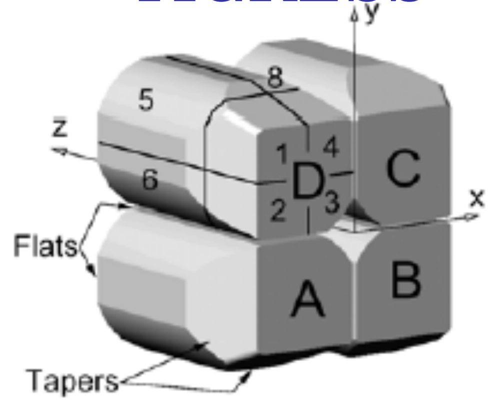
- **Advances in Ge detector production**
  - **Segmentation size ~ 2 cm → 30-40 segment/crystal**
  - **Planar or irregular tapered hexagon shape**
- **Fast electronics**
  - **ADC with 10 nsec sampling rate, > 12 bit resolution**
- **Efficient algorithms**
  - **Signal analysis – position**
  - **Tracking – scattering sequence**
- **Computing power**

Segmented Germanium Detectors

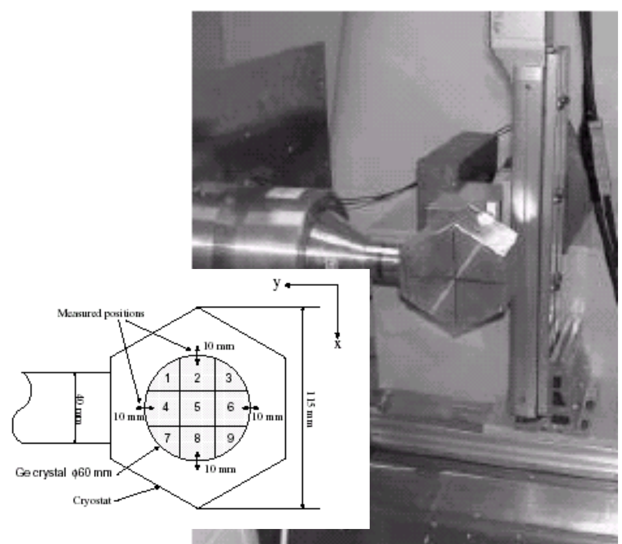
MINIBALL



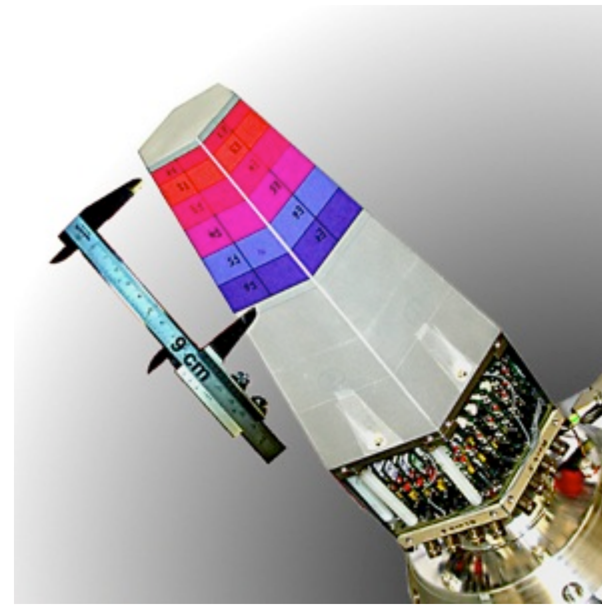
TIGRESS



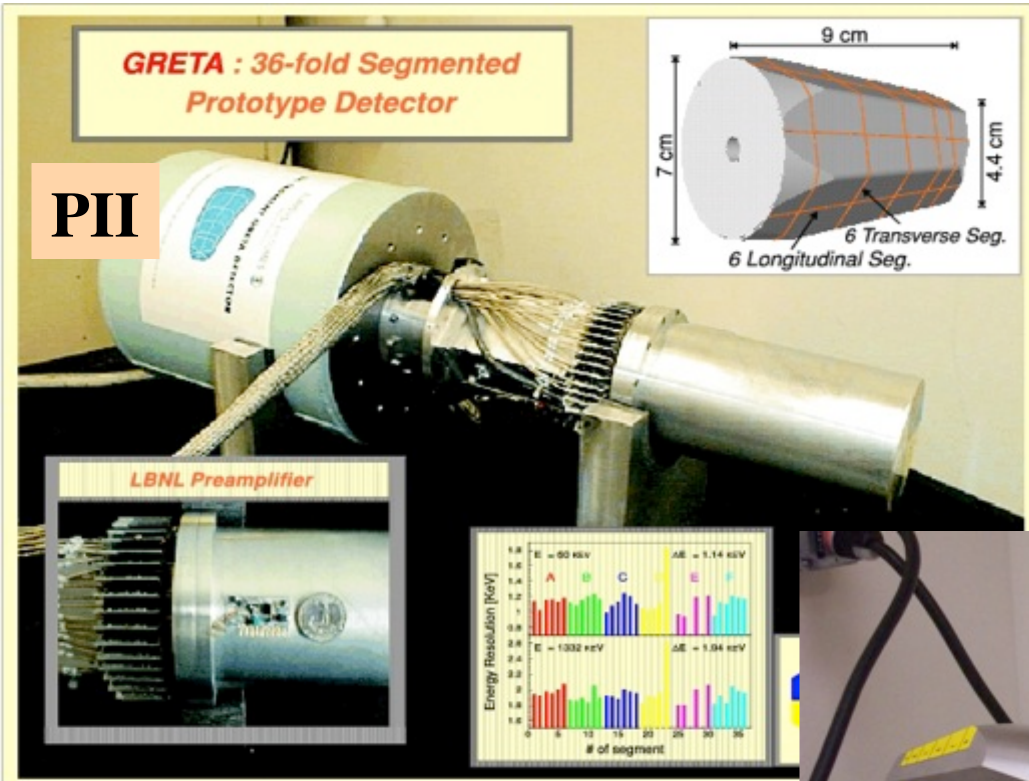
GRAPE

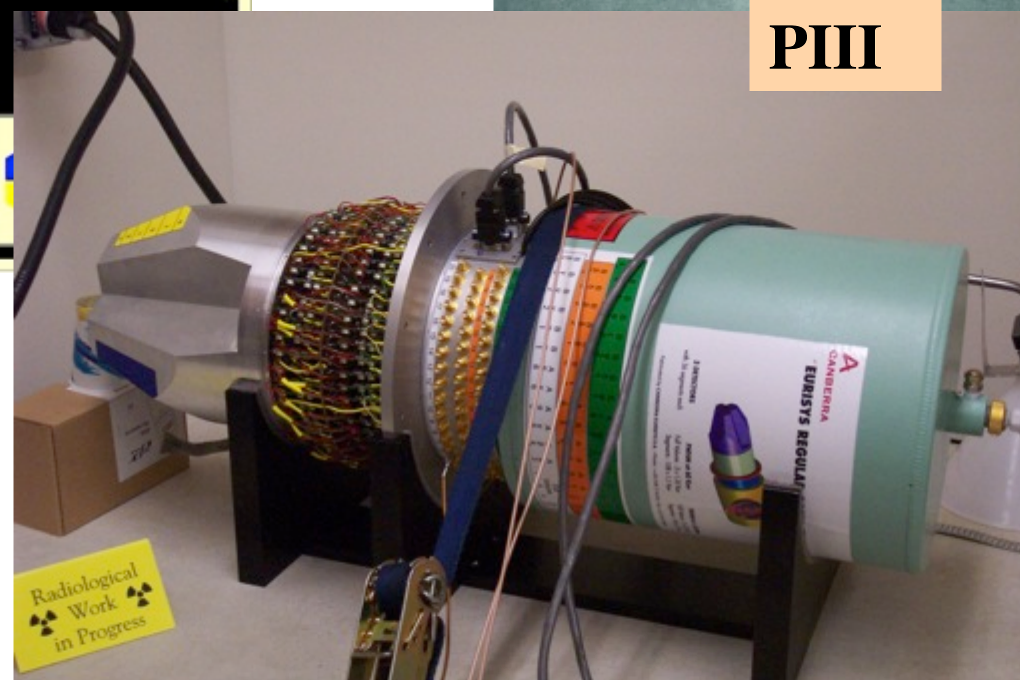


AGATA

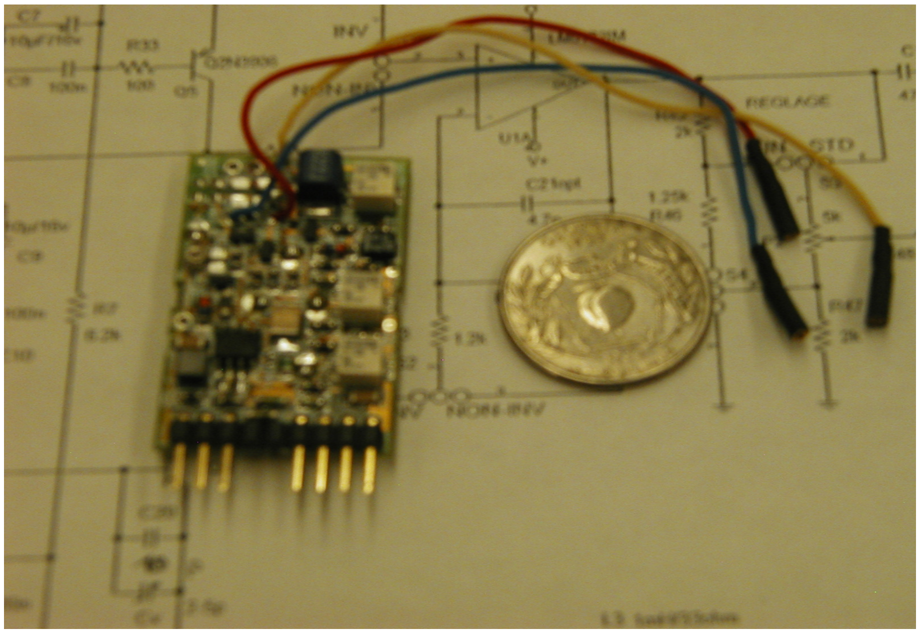


Prototype detectors at LBNL





Pre-Amps



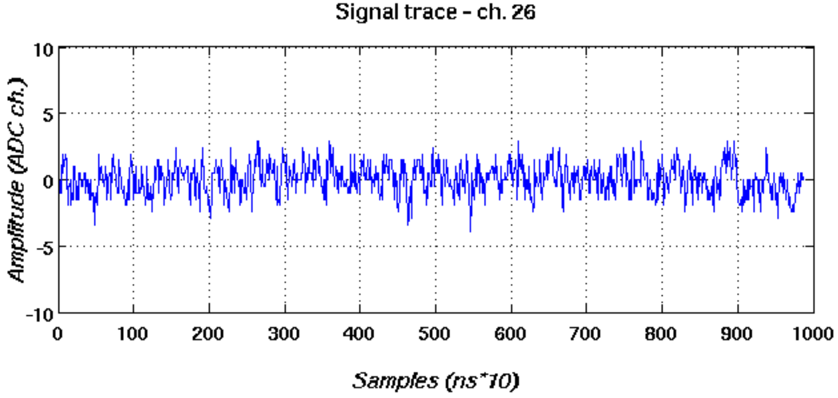
Eurisys PSC823

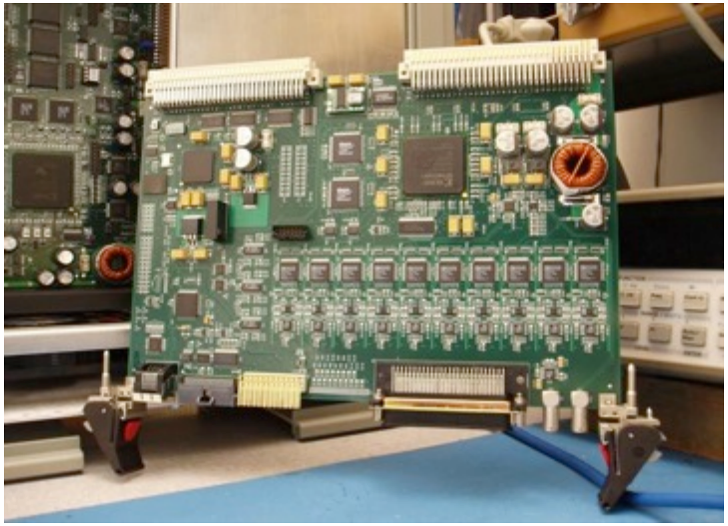
FET	IF1320
Gain	200mV/MeV
Rise Time	~40nsec
Decay Time	50µsec
Power	50mW

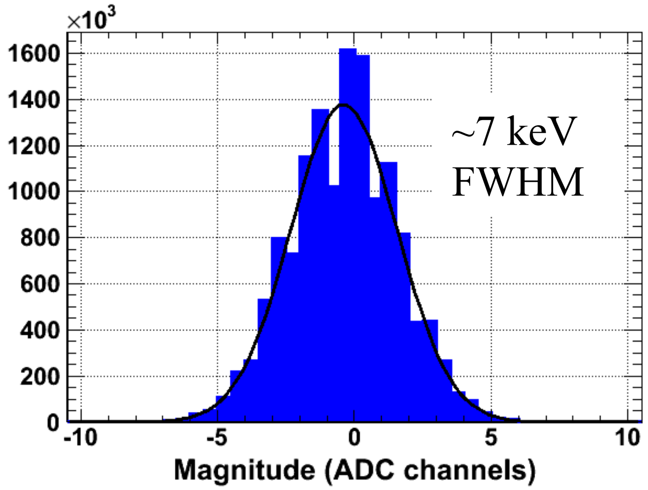
Performance with detector:	Energy resolution	1.15 keV	Am
		2.5 keV	Co
	Noise level	4 keV	(20MHz)

Electronics

Digitizer module (LBNL)
14bit, 100 MHz
Energy
Leading edge time
Constant fraction time
Pulse shape



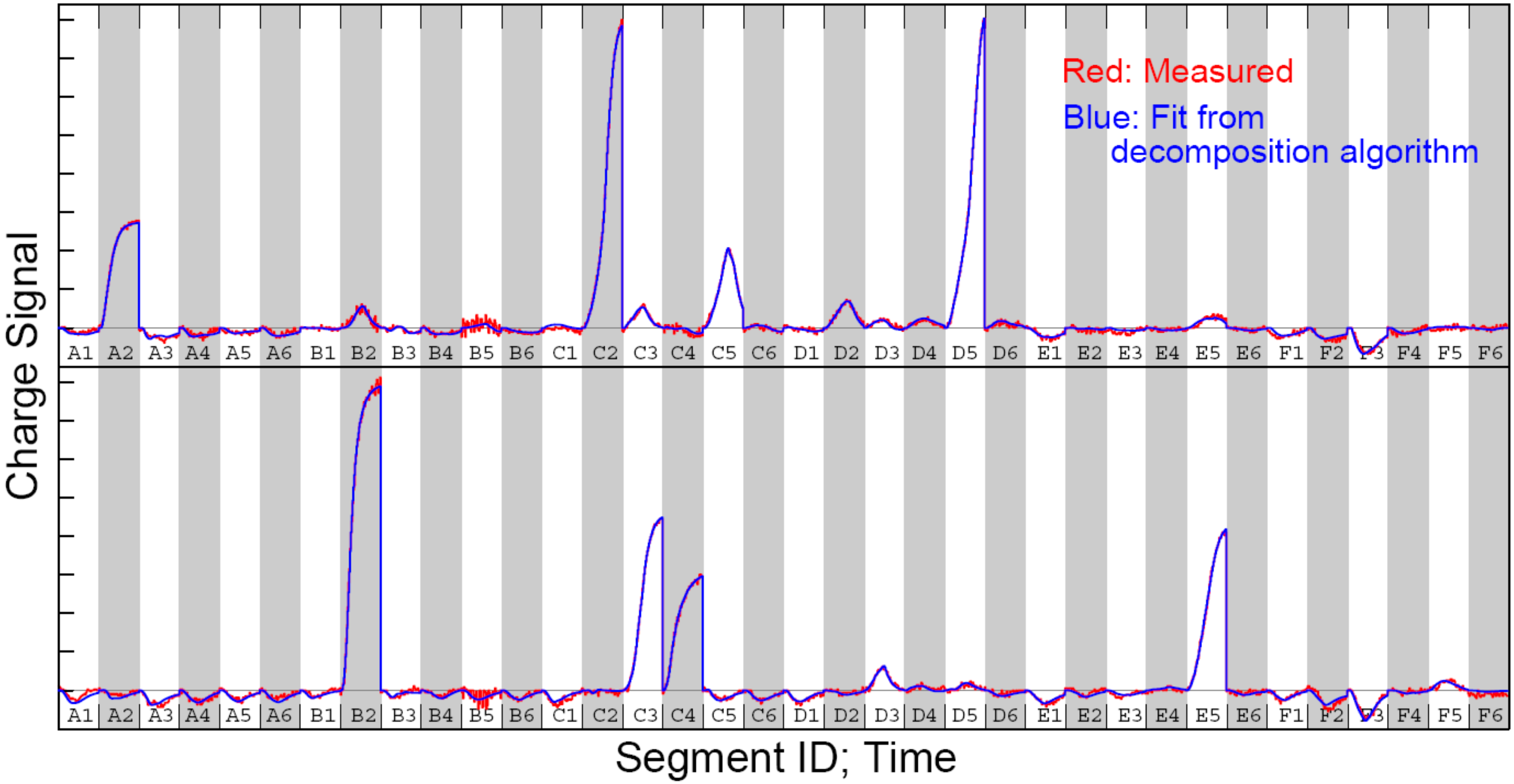




Signal Decomposition

- Use the measured signal shapes from the segments – net charge and induced signal.
- Compare with a library of (measured/calculated) basis signal shapes of single interaction.
- Determine the energy and position of interaction points.
- Why is it hard?
  - Multiple interactions in one segment.
  - Multiple segment with net charge in a detector.
  - Computing intensive calculation.

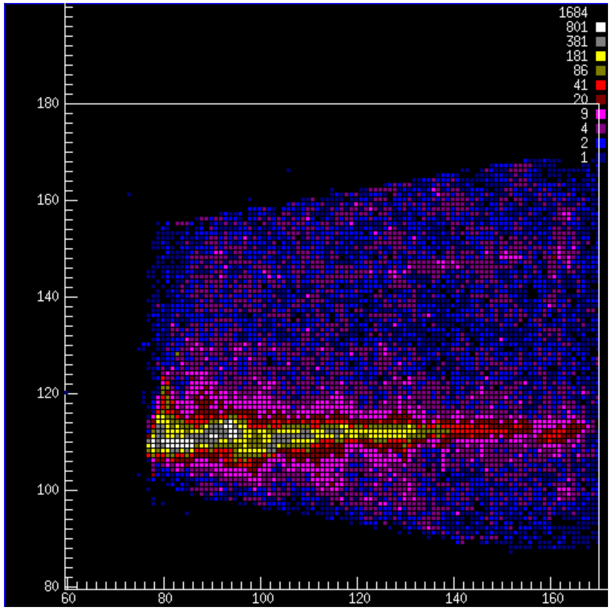
- Measured signals with multiple gamma ray hits (red), fitted with a linear combination of basis signals (blue) , using Grid search followed by least-square fitting.
- The analysis gives (x, y, z, E) of the interaction points.

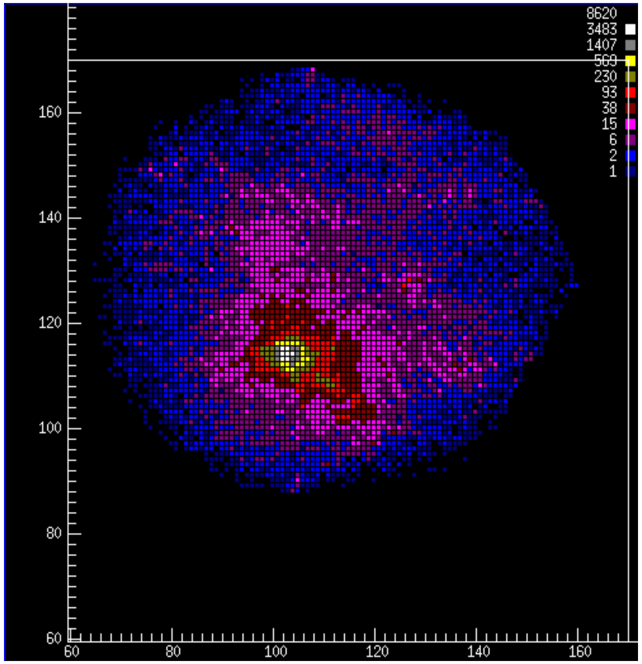


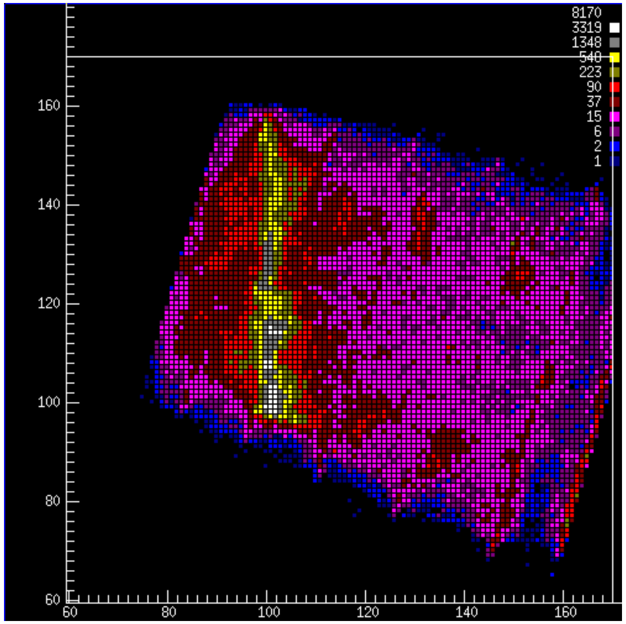
Position resolution

- Collimated beam of ^{137}Cs 663 keV
- Highest energy point from signal decomposition

singles



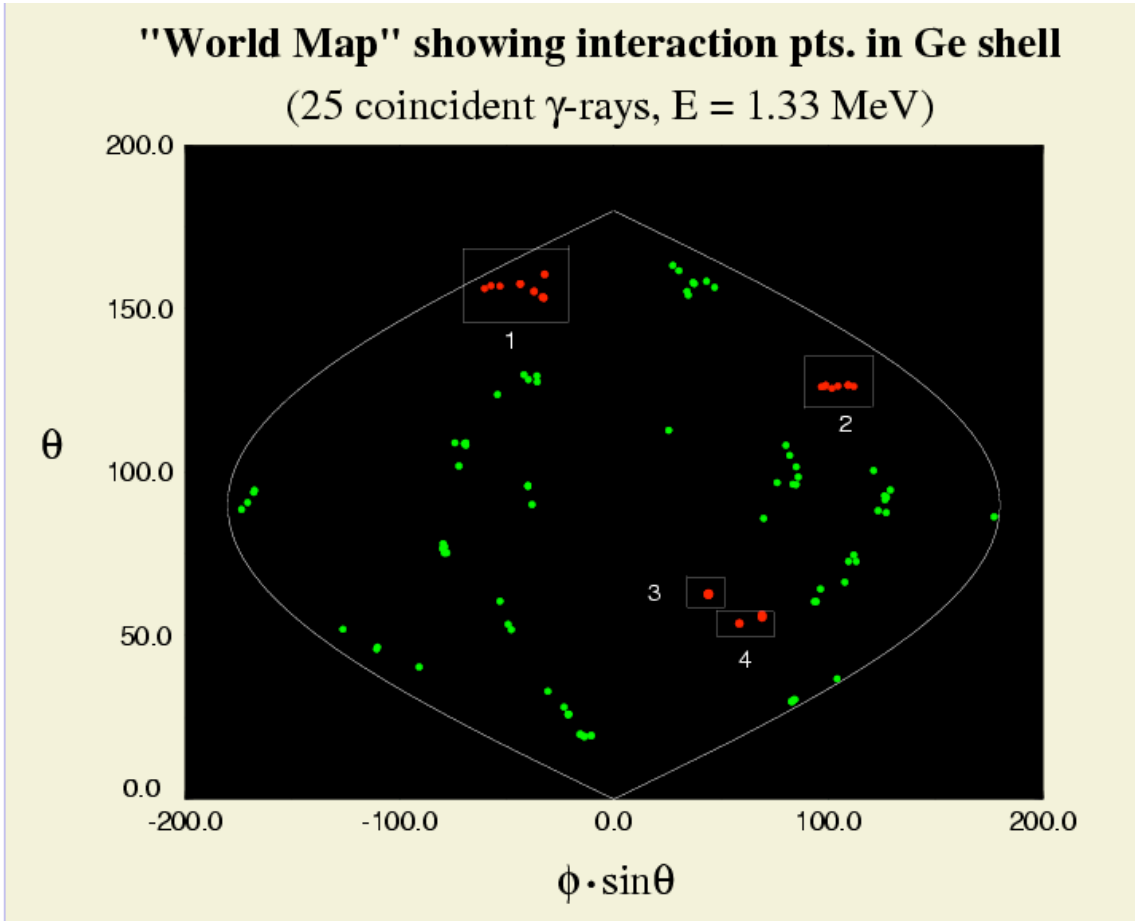


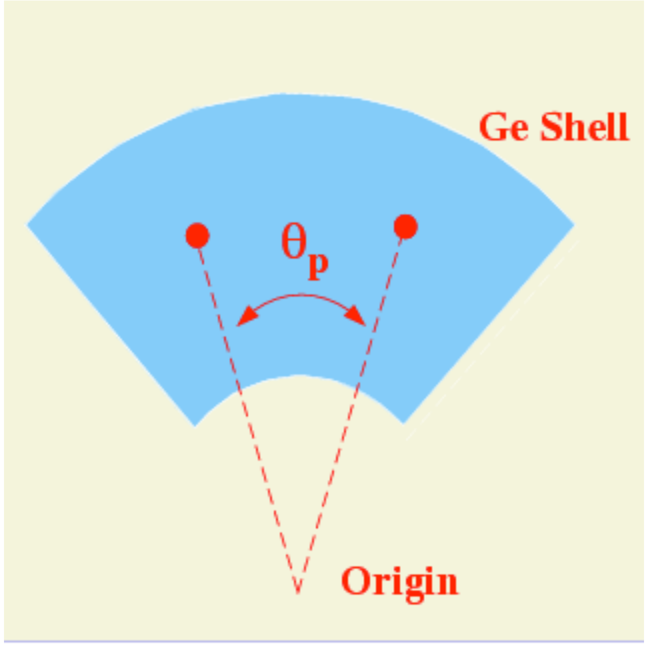


- $\sigma_{x,y,z} \sim 2$ mm

Tracking

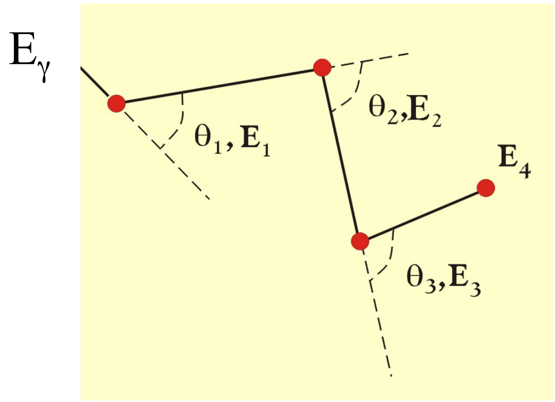
first step – cluster finding





Any two points with $\theta < \theta p$ are grouped into the same cluster

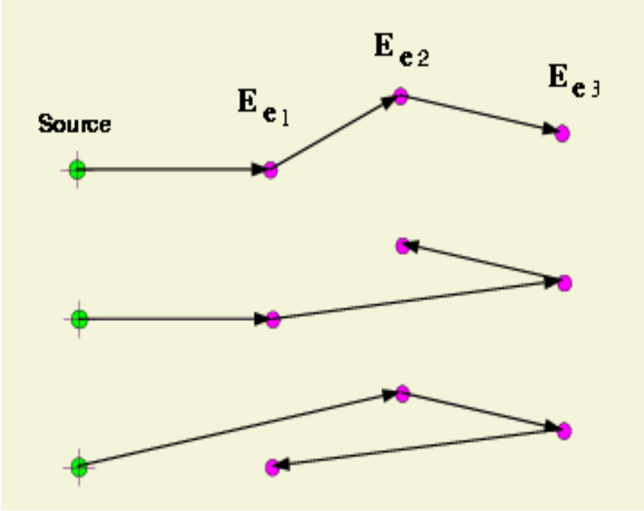
Tracking



$$E_e = E_\gamma \left(1 - \frac{1}{1 + \frac{E_\gamma}{0.511}(1 - \cos\theta)} \right)$$

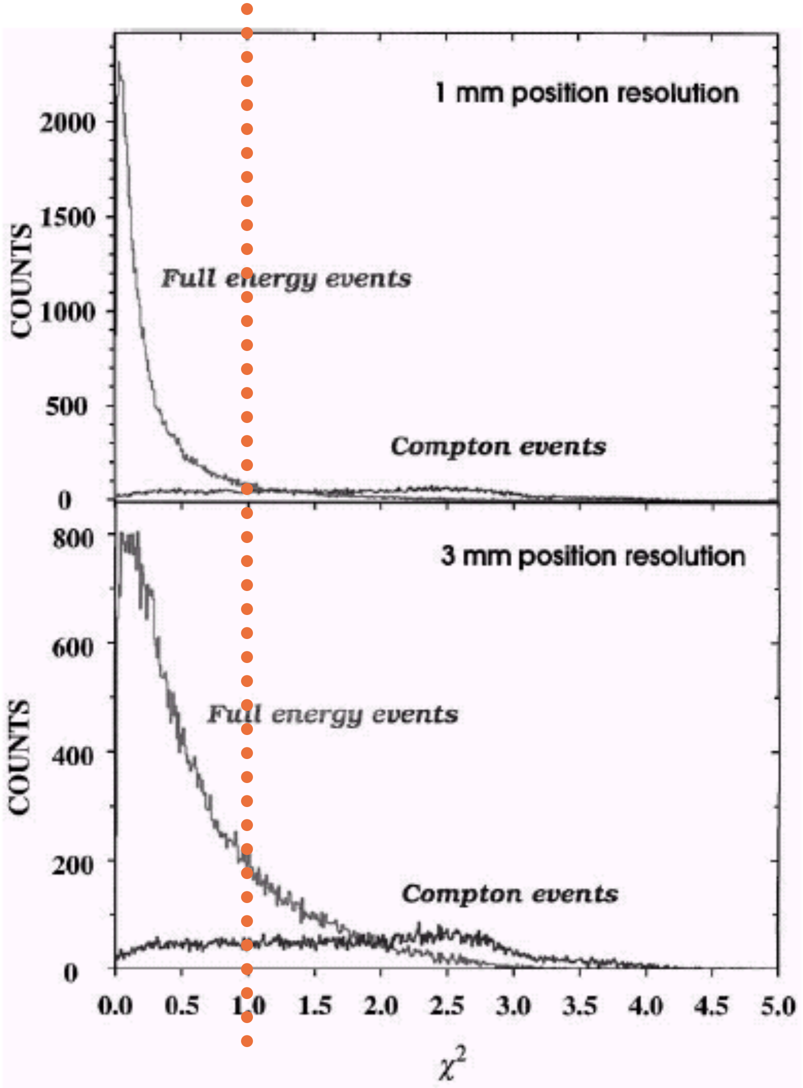
Problem: 3!=6 possible sequences

Assume: $E_\gamma = E_{e1} + E_{e2} + E_{e3}$;γ-ray from the source



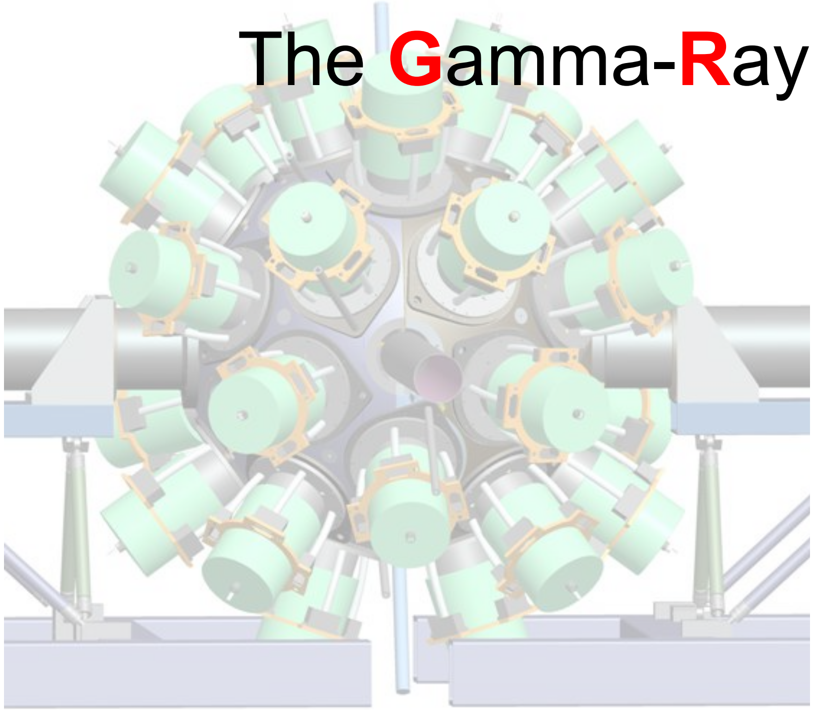
$$\chi^2 = \frac{1}{N-1} \sum_{i=1}^{N-1} \left(\frac{\theta^i - \theta_C^i}{\sigma_\theta^i} \right)^2$$

Sequence with the minimum $\chi^2 < \chi^2_{max}$
➔correct scattering sequence
➔rejects Compton and wrong direction


1 mm position resolution
Full energy events
Compton events
COUNTS
2000
1500
1000
500
0
3 mm position resolution
Full energy events
Compton events
COUNTS
800
600
400
200
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
χ^2

ε~ 40% and P/T~ 55%

The Gamma-Ray Energy Tracking Array



GRETA

AGATA ADVANCED GAMMA TRACKING ARRAY

ADVANCED GAMMA TRACKING ARRAY

Key properties

- Efficiency (~40% at 1MeV)
- 4π Coverage

  No solid angle lost to Compton suppression shields.

  Angular distributions/correlations.

  High-energy efficiency by proper summing of scattered γ-rays.

- Position resolution ($\sigma_{x,y,z}$ = 2 mm)

  Position of 1^{st} interaction --> Excellent Doppler reconstruction, in-beam energy resolution.

- Peak-to-background (~ 55%)

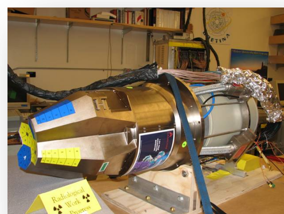
  Tracking --> Reject partial-energy events, maintaining good spectral quality.

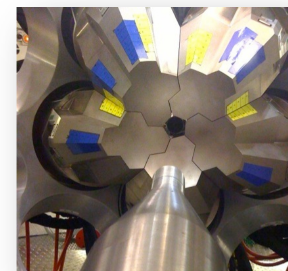
- Polarization

  Compton-reconstructed full-energy event yield polarization information

Gamma Ray Energy Tracking In beam Nuclear Array

Critical Decisions





GRETINA CD1
2004

GRETINA CD0
2003

GRETINA CD2A/3A
2005

GRETINA CD2B/3B
2007

GRETINA CD4
2011

2002

2012

NSAC Long Range Plan

NSAC Long Range Plan

BERKELEY LAB

Argonne NATIONAL LABORATORY

MICHIGAN STATE UNIVERSITY

OAK RIDGE NATIONAL LABORATORY

Washington University in St. Louis

$20M Funded by US- DOE Nuclear Physics Office

Nuclear Instruments and Methods in Physics Research A 709 (2013) 44–55

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA

S. Paschalis [a,*], I.Y. Lee [a,**], A.O. Macchiavelli [a], C.M. Campbell [a], M. Cromaz [a], S. Gros [a], J. Pavan [a], J. Qian [a], R.M. Clark [a], H.L. Crawford [a], D. Doering [a], P. Fallon [a], C. Lionberger [a], T. Loew [a], M. Petri [a], T. Stezelberger [a], S. Zimmermann [a], D.C. Radford [b], K. Lagergren [b], D. Weisshaar [c], R. Winkler [c], T. Glasmacher [c], J.T. Anderson [d], C.W. Beausang [e]

[a] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[b] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[c] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[d] *Argonne National Laboratory, Argonne, IL 60439, USA*
[e] *Department of Physics, University of Richmond, 28 Westhampton Way, Richmond, VA 23173, USA*

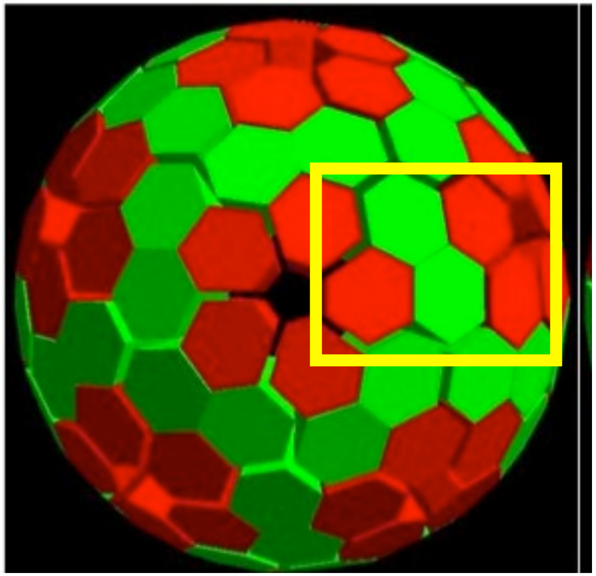
Geodesic tiling of the sphere

12 pentagons and …

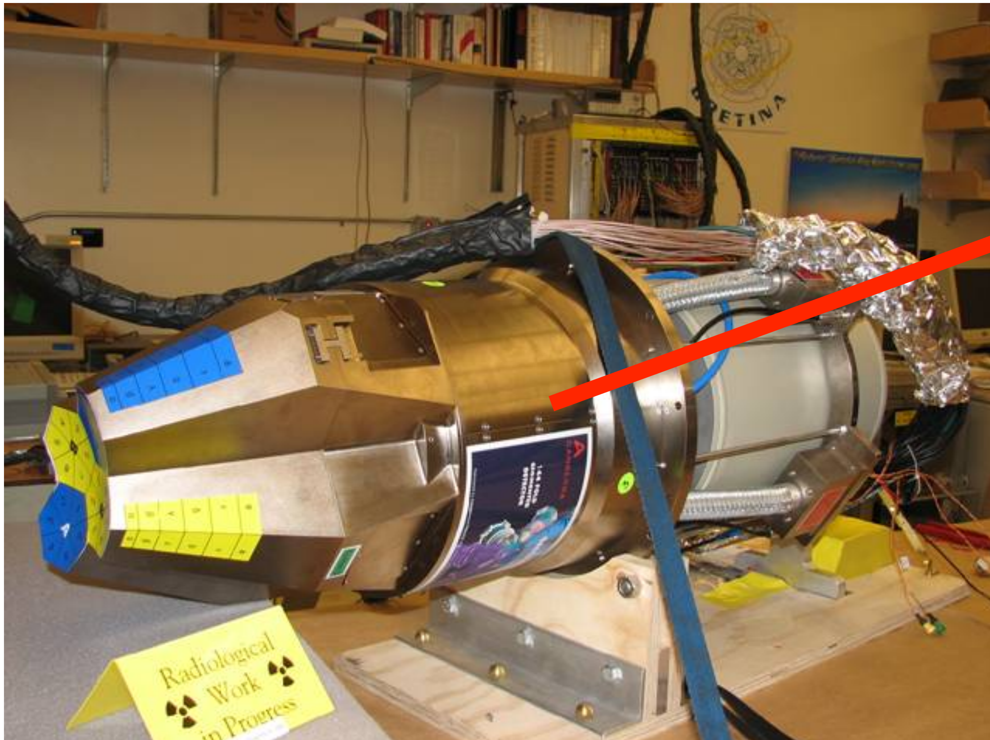
Number of hexagons	Number of different hexagonal shapes
80	2 (20, 60)
110	3 (20, 30, 60)
120	**2 (60, 60)**
150	3 (30, 60, 60)
180	3 (60, 60, 60)
200	4 (20, 60, 60, 60)

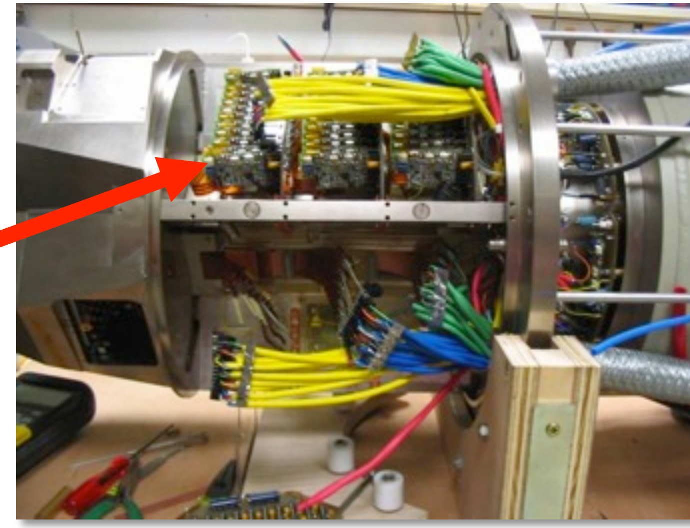
GS

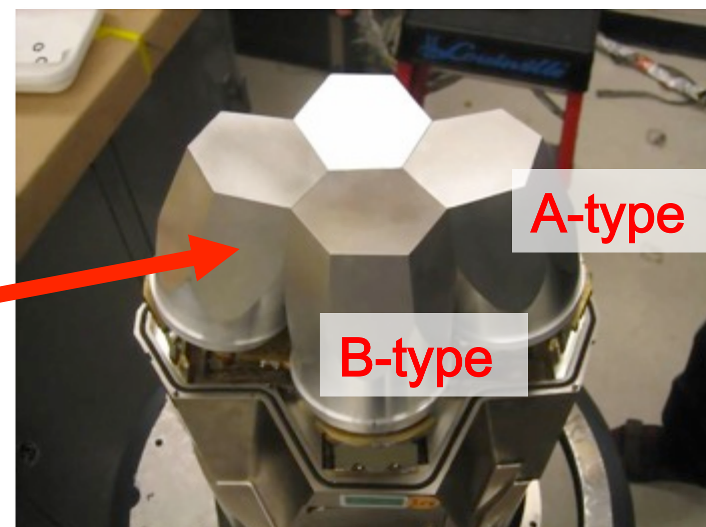
AGATA



Detector Modules (Canberra/France)

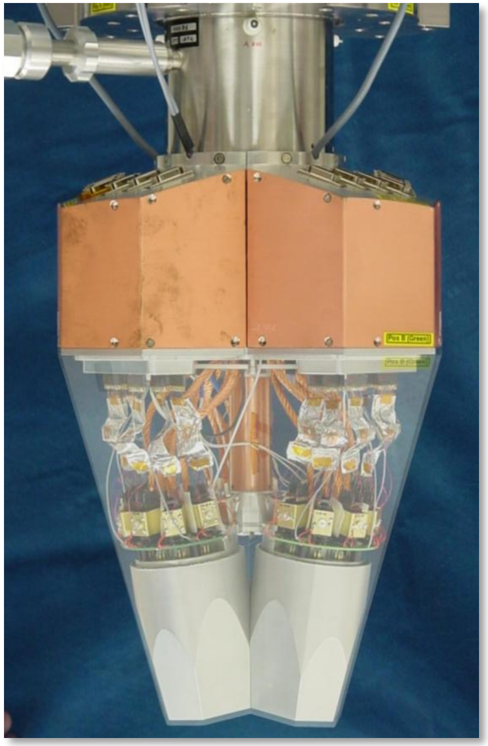




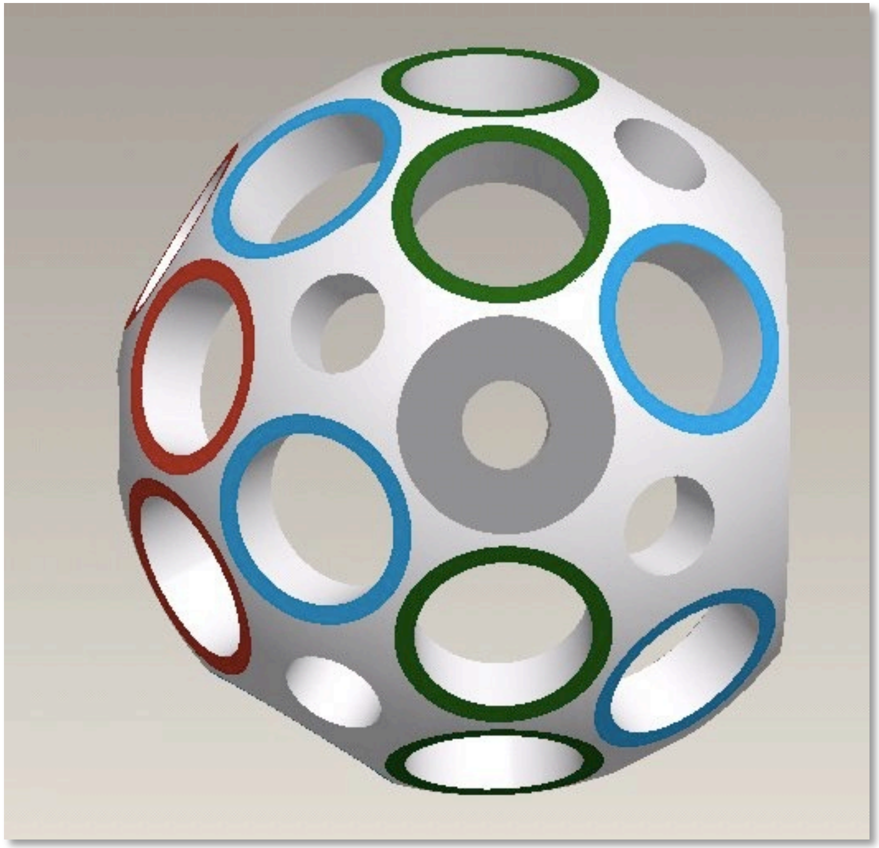


36 segments/crystal
4 crystal/ module
148 signal channels /module
Cores Cold FETs
Segments Warm FETs

AGATA Demonstrator



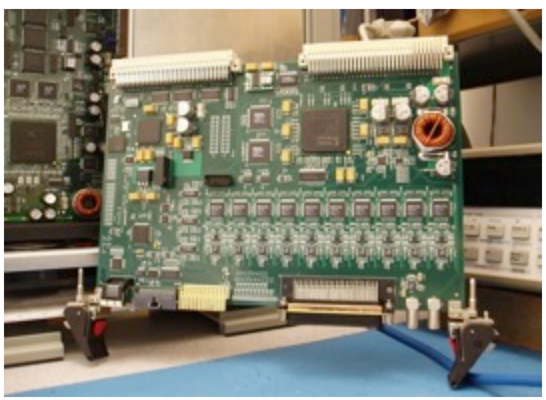
Courtesy of Dino Bazzacco



RING	ANGLE	SLOTS
1	-	-
2	58	4
3	90	8
4	122	4
5	148	5

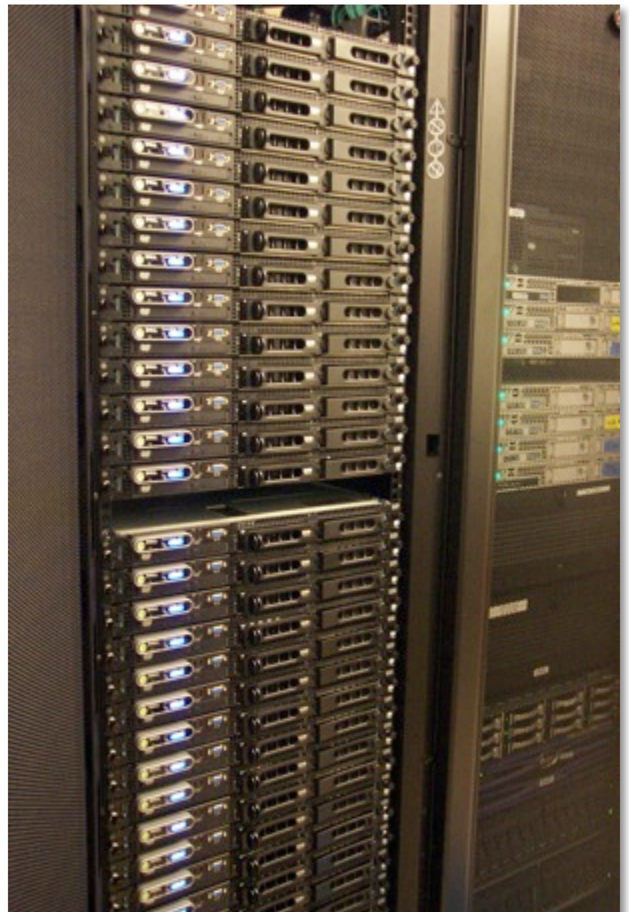
Electronics and DAQ System

Digitizer module
14bit, 100 MHz
Energy
CC: 2.5, 5, 10, 30 MeV
S: 10 MeV
Leading edge time
Pulse shape

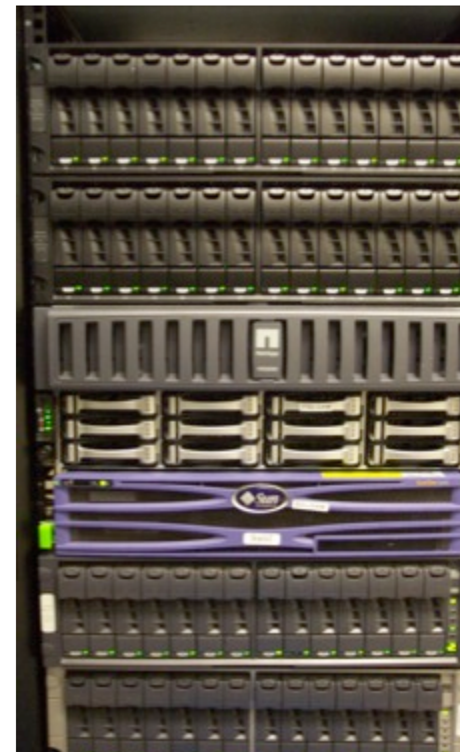


EPICS

- Installed 62 nodes, 2 CPU/node, 4 core/ CPU



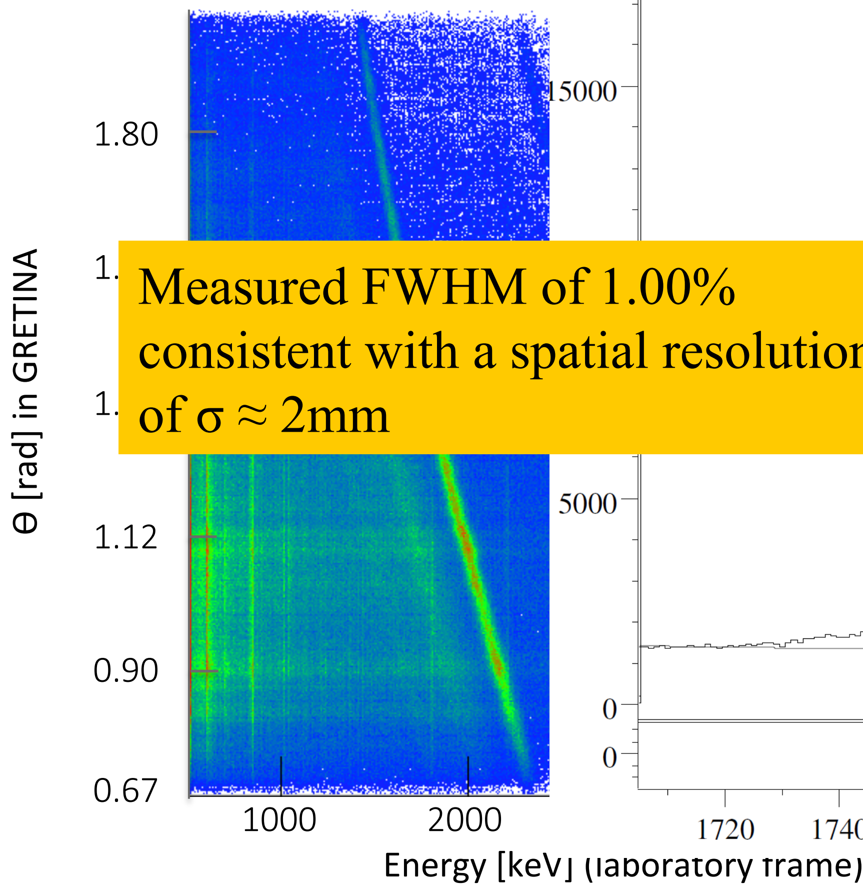
- 50 TB of disk space

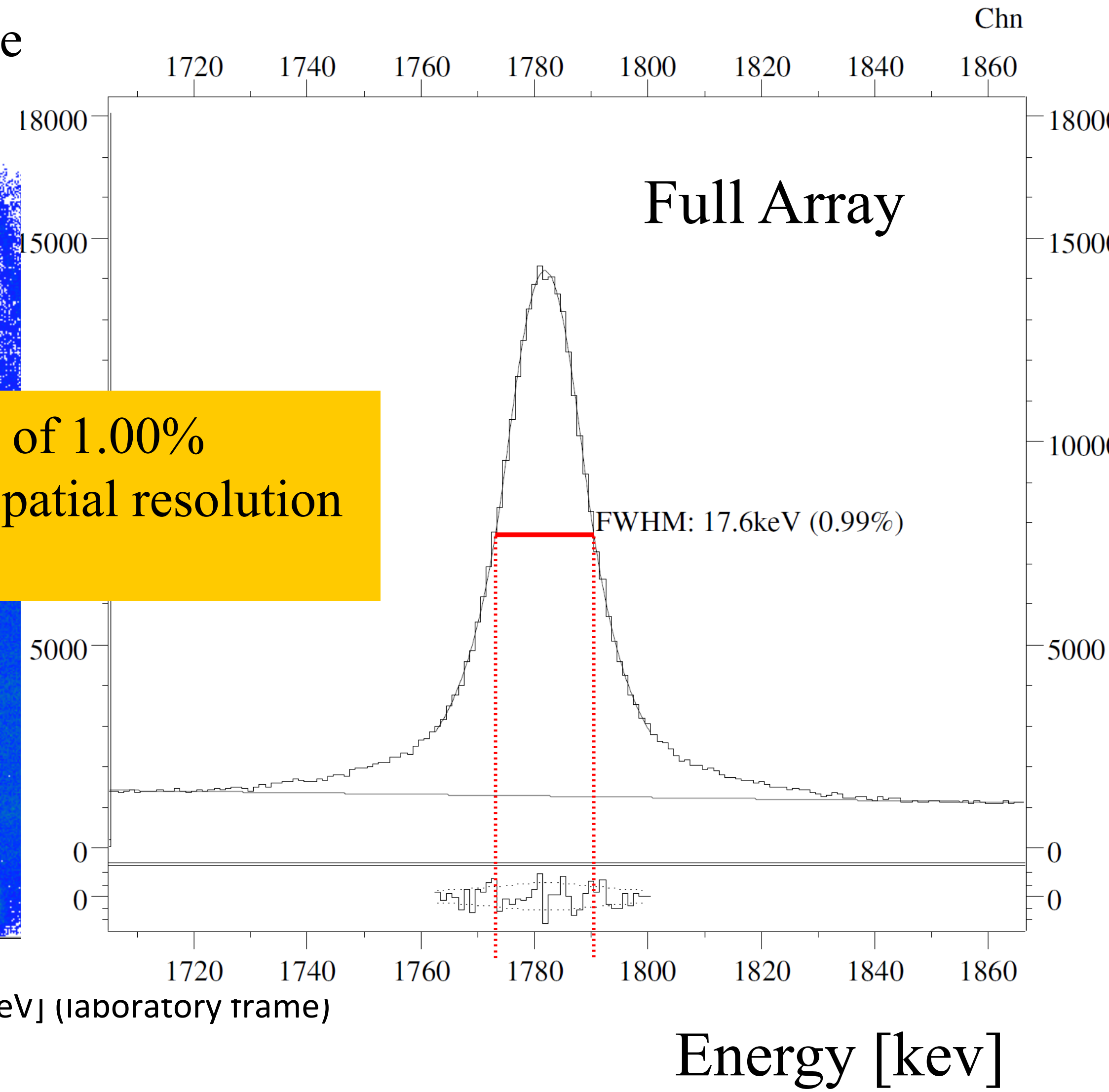


56 Nodes $\geq$ 20000 gammas/s

Position resolution

- **11007** — Weisshaar, D. e





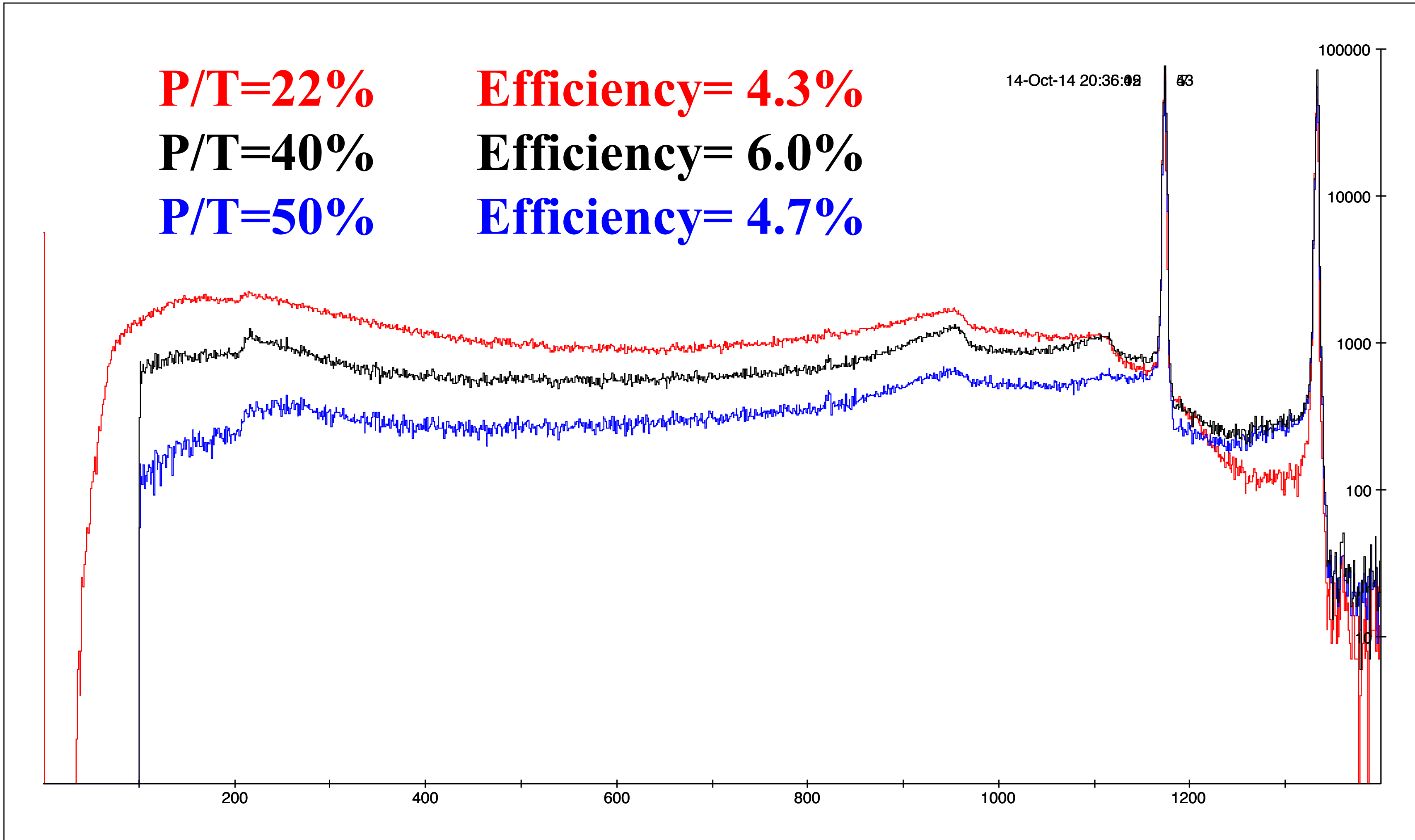
Measured FWHM of 1.00% consistent with a spatial resolution of σ ≈ 2mm

38

2 Be)

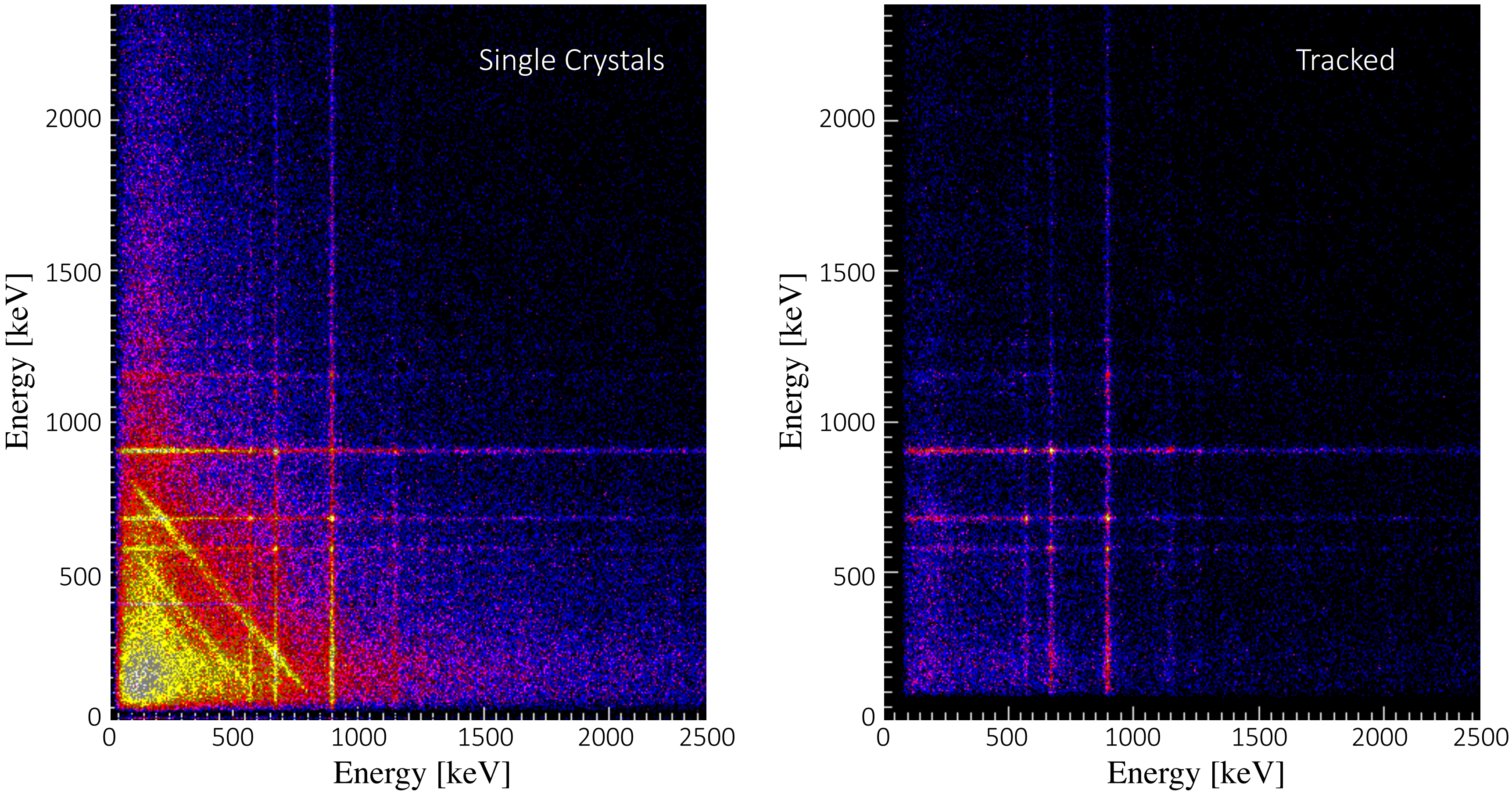
Efficiency and P/T: ^{60}Co source

Singles Clustered Tracked



Tracking improves signal/background

^{64}Ge populated in knockout from ^{65}Ge



Reduction of Compton background by tracking allows – for the first time – gamma **spectroscopy with fast beams** with spectral quality **comparable to arrays with anti-Compton shields**.

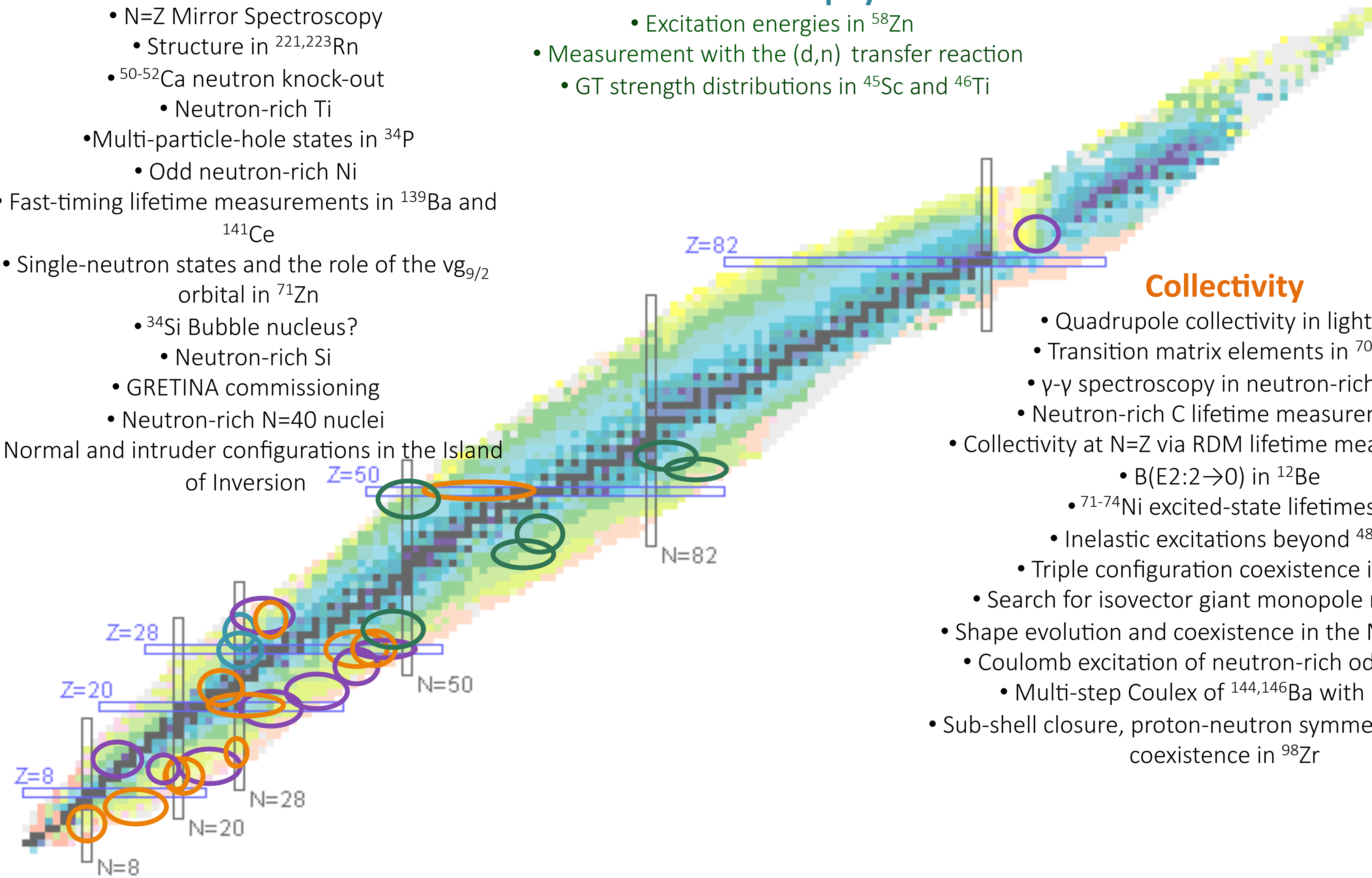
Physics campaigns: NSCL(2012/13) and ATLAS(2014/15)

Nuclear Shell Evolution

- N=Z Mirror Spectroscopy
- Structure in ^{221,223}Rn
- $^{50-52}$Ca neutron knock-out
- Neutron-rich Ti
- Multi-particle-hole states in ^{34}P
- Odd neutron-rich Ni
- Fast-timing lifetime measurements in ^{139}Ba and ^{141}Ce
- Single-neutron states and the role of the $\nu g_{9/2}$ orbital in ^{71}Zn
- ^{34}Si Bubble nucleus?
- Neutron-rich Si
- GRETINA commissioning
- Neutron-rich N=40 nuclei
- Normal and intruder configurations in the Island of Inversion

Nuclear Astrophysics

- Excitation energies in ^{58}Zn
- Measurement with the (d,n) transfer reaction
- GT strength distributions in ^{45}Sc and ^{46}Ti



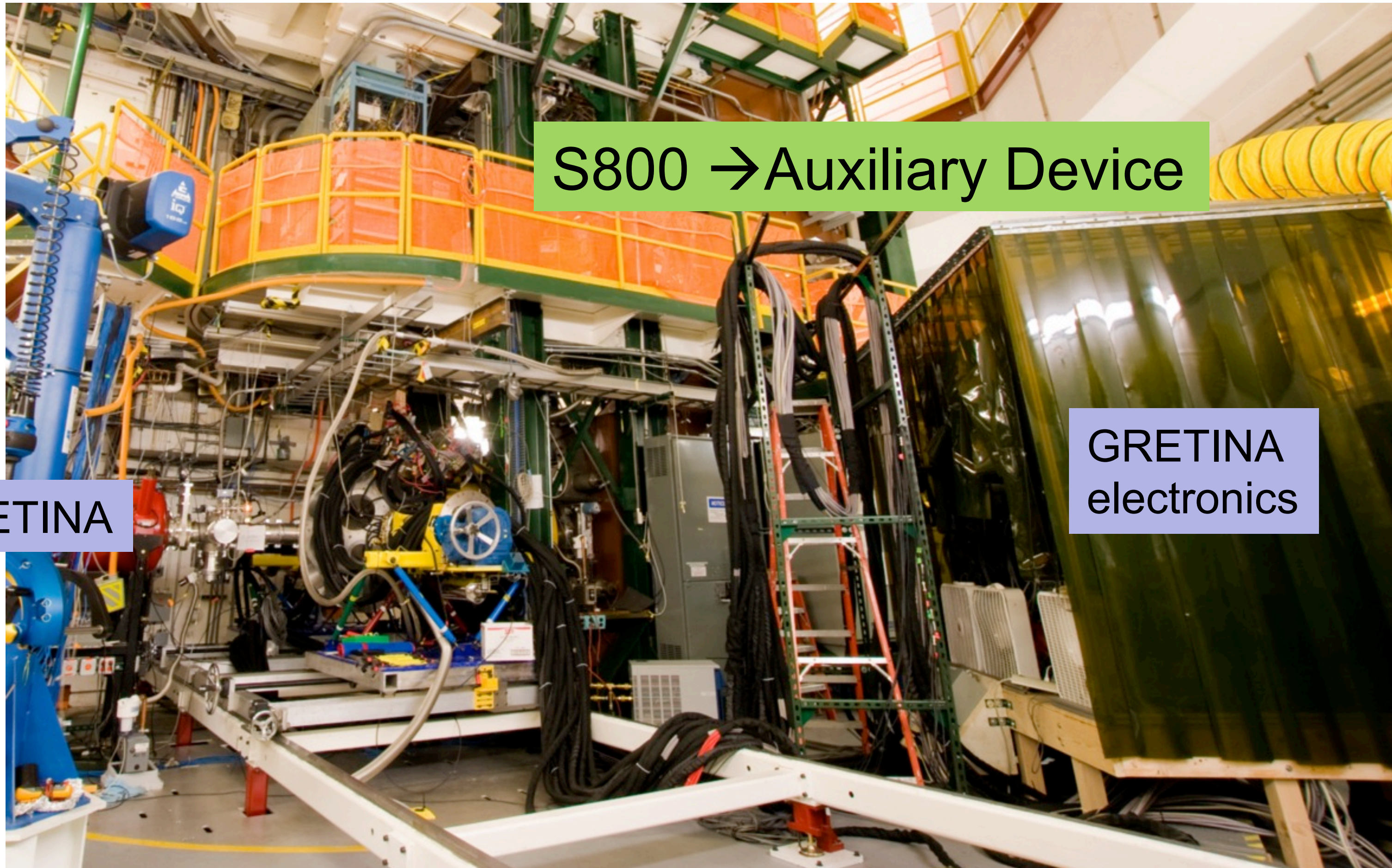
Collectivity

- Quadrupole collectivity in light Sn
- Transition matrix elements in ^{70,72}Ni
- γ-γ spectroscopy in neutron-rich Mg
- Neutron-rich C lifetime measurement
- Collectivity at N=Z via RDM lifetime measurements
- B(E2:2→0) in ^{12}Be
- $^{71-74}$Ni excited-state lifetimes
- Inelastic excitations beyond ^{48}Ca
- Triple configuration coexistence in ^{44}S
- Search for isovector giant monopole resonance
- Shape evolution and coexistence in the Mo-Ru region
- Coulomb excitation of neutron-rich odd-odd ^{98m}Y
- Multi-step Coulex of ^{144,146}Ba with CARIBU
- Sub-shell closure, proton-neutron symmetry and shape coexistence in ^{98}Zr

Heather Crawford

Science campaign at NSCL: July 2012 – June 2013

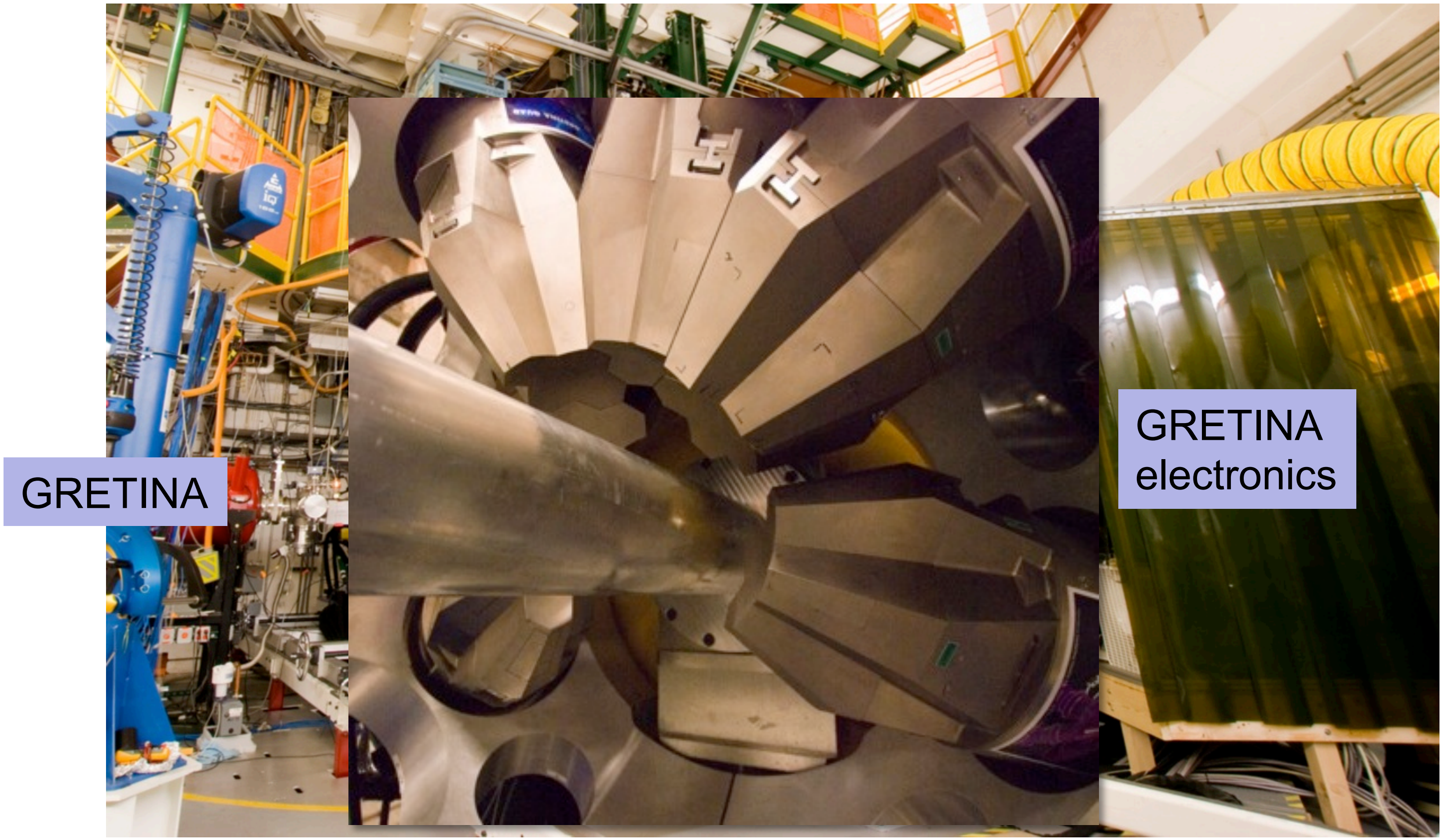
- **23 experiments approved: 3360 hours**



GRETINA at target position of S800 spectrograph

Science campaign at NSCL: July 2012 – June 2013

- **23 experiments approved: 3360 hours**



GRETINA at target position of S800 spectrograph

PRL 113, 032502 (2014) PHYSICAL REVIEW LETTERS week ending 18 JULY 2014

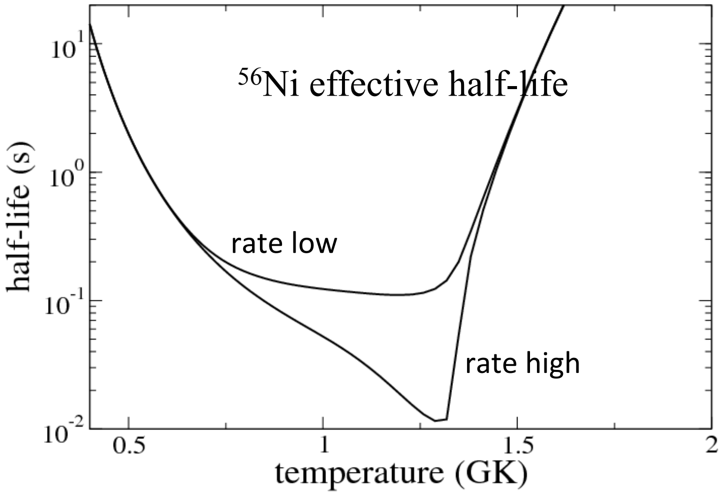
Determining the *rp*-Process Flow through ^{56}Ni: Resonances in ^{57}Cu$(p,\gamma)^{58}$Zn Identified with GRETINA

C. Langer,[1,2,*] F. Montes,[1,2] A. Aprahamian,[3] D. W. Bardayan,[4,†] D. Bazin,[1] B. A. Brown,[1,5] J. Browne,[1,2,5] H. Crawford,[6] R. H. Cyburt,[1,2] C. Domingo-Pardo,[7] A. Gade,[1,5] S. George,[8,‡] P. Hosmer,[9] L. Keek,[1,2,5] A. Kontos,[1,2] I-Y. Lee,[6] A. Lemasson,[1] E. Lunderberg,[1,5] Y. Maeda,[10] M. Matos,[11] Z. Meisel,[1,2,5] S. Noji,[1] F. M. Nunes,[1,5] A. Nystrom,[3] G. Perdikakis,[12,1,2] J. Pereira,[1,2] S. J. Quinn,[1,2,5] F. Recchia,[1] H. Schatz,[1,2,5] M. Scott,[1,2,5] K. Siegl,[3] A. Simon,[1,2,§] M. Smith,[3] A. Spyrou,[1,2,5] J. Stevens,[1,2,5] S. R. Stroberg,[1,5] D. Weisshaar,[1] J. Wheeler,[1,2,5] K. Wimmer,[12,1] and R. G. T. Zegers[1,2,5]

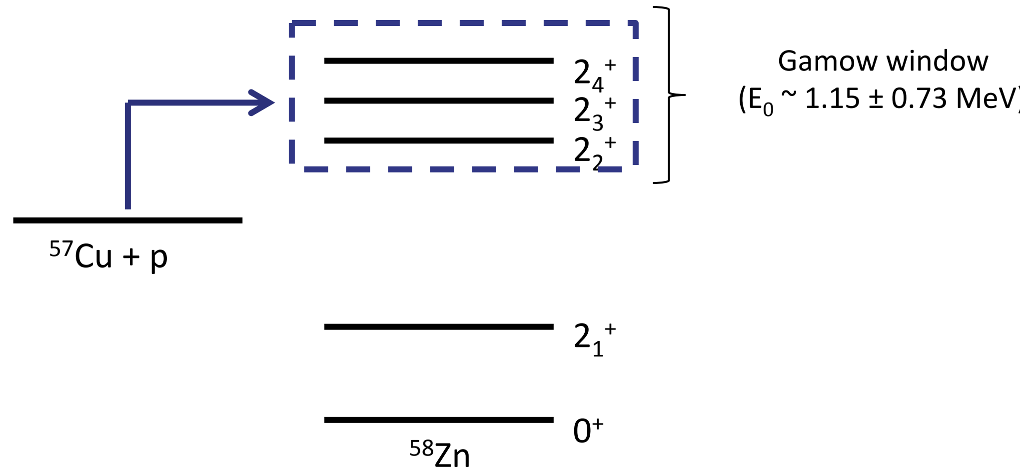
[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[4]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[5]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[6]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[7]*IFIC, CSIC-University of Valencia, E-46071 Valencia, Spain*
[8]*Ernst-Moritz-Arndt-Universität, 17487 Greifswald, Germany*
[9]*Department of Physics, Hillsdale College, Hillsdale, Michigan 49242, USA*
[10]*Department of Applied Physics, University of Miyazaki, Miyazaki, Miyazaki 889-2192, Japan*
[11]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803-4001, USA*
[12]*Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*

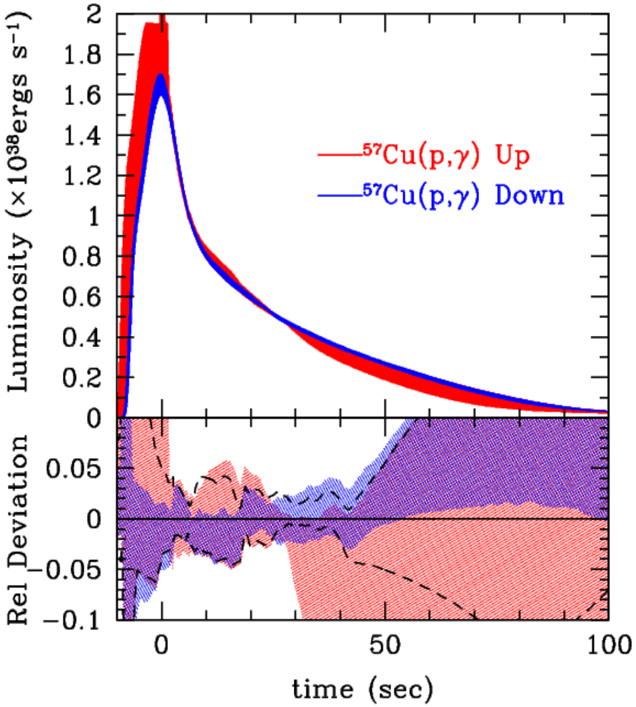
The ^{57}Cu(p,γ)^{58}Zn stellar reaction rate has a significant effect in the light-curve emitted in X-ray bursts. ^{58}Zn excitation energies are not known experimentally.

The effective lifetime of ^{56}Ni determines the amount of A =56 material in the neutron star crust.



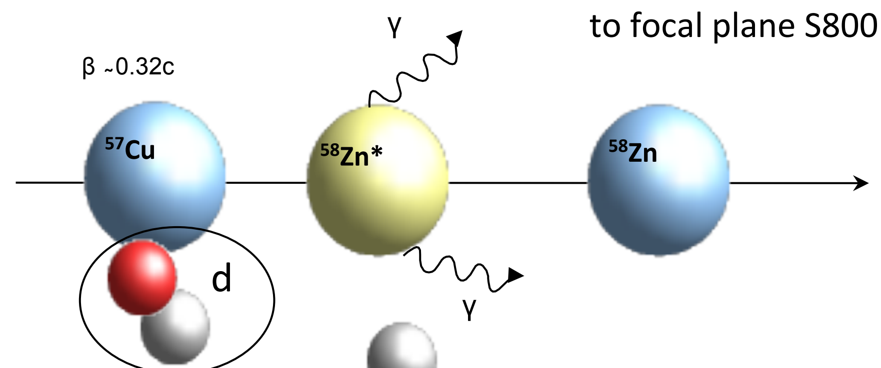
Reaction rate dominated by 2^+ resonances





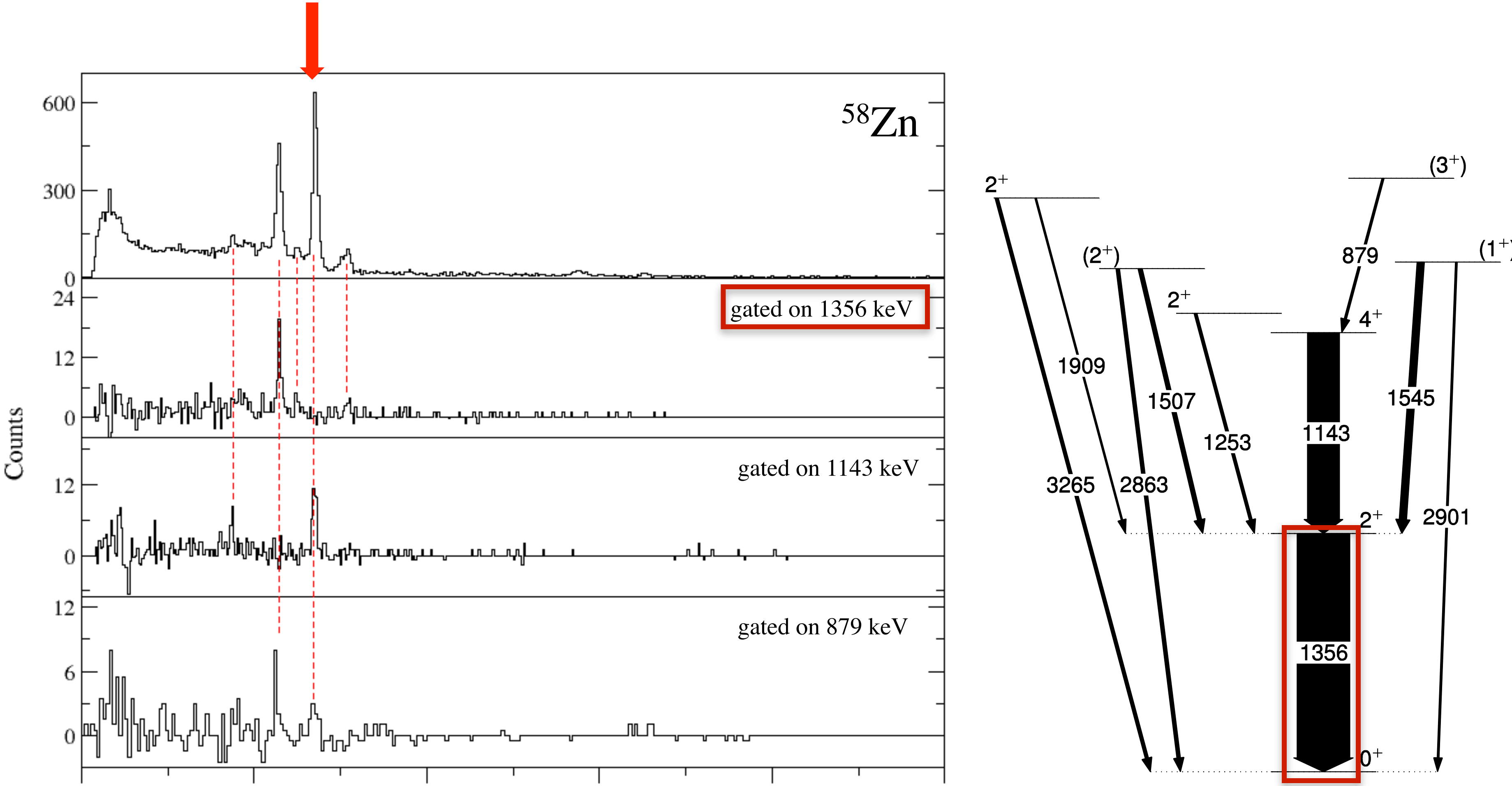
Cyburt et al. (to be published)

^{57}Cu beam ~ 3 10^4 pps produced from stable ^{58}Ni @160 MeV/u

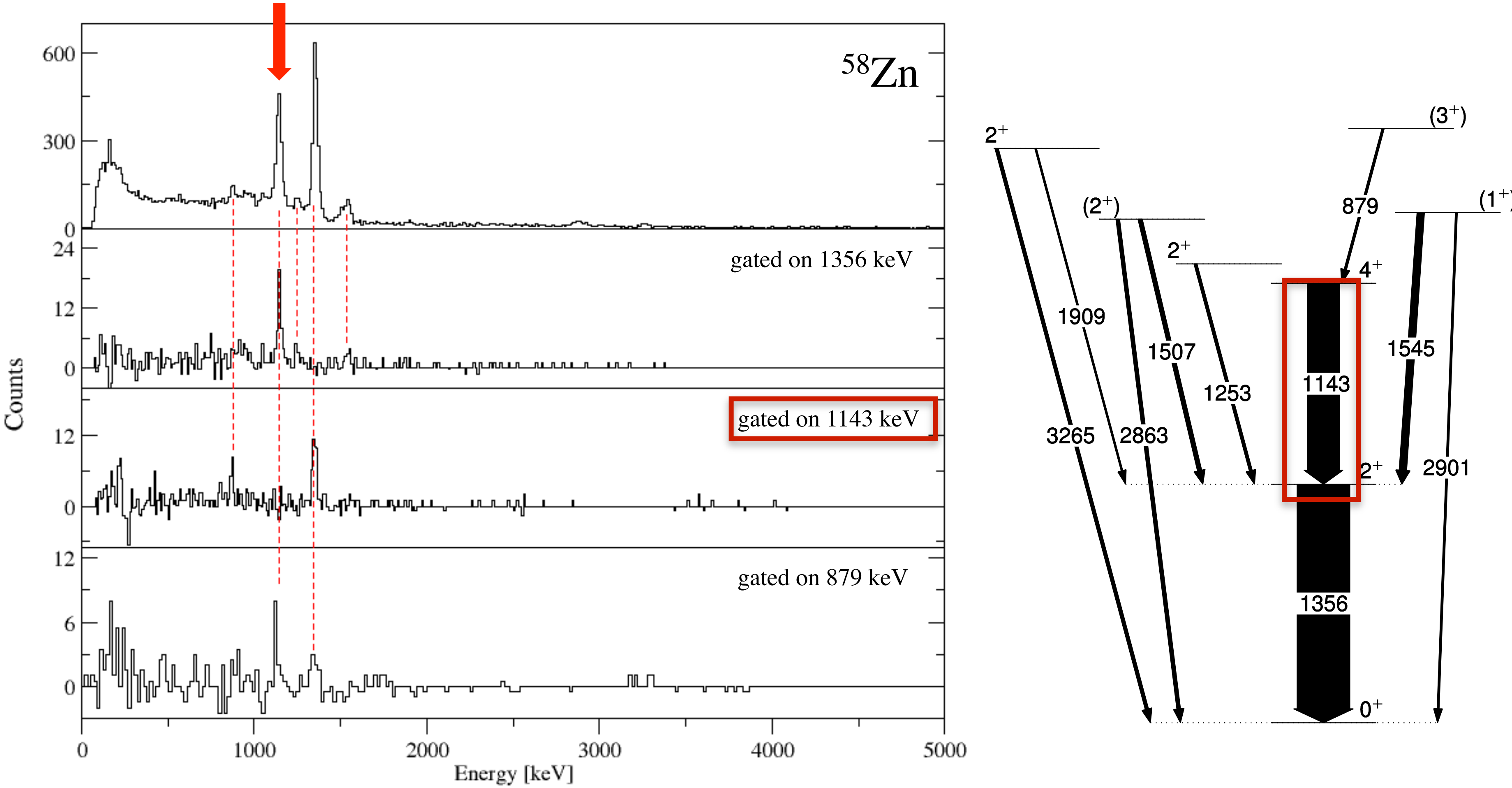


CD_2 of 225 mg/cm^2

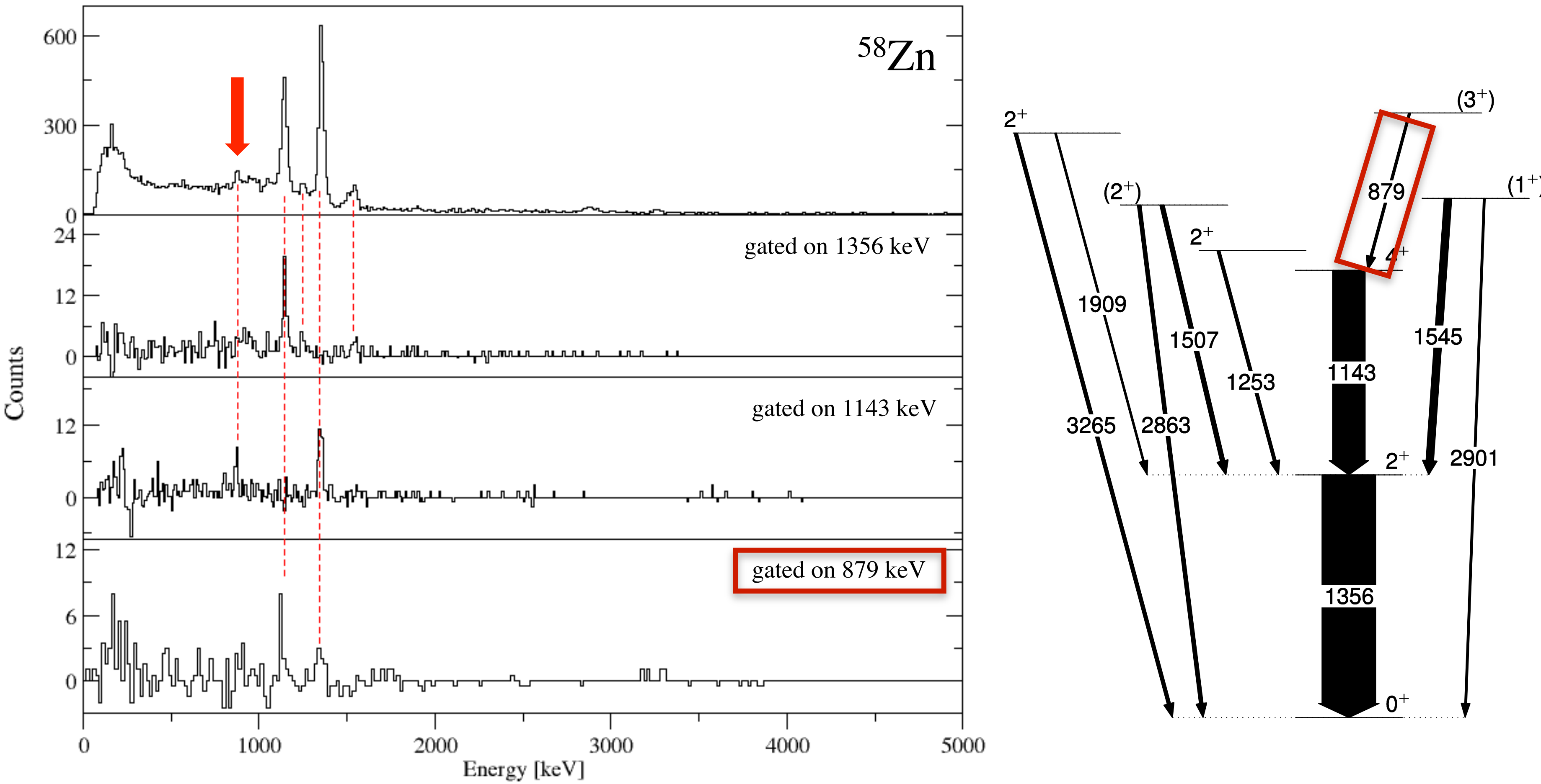
Coincidence Analysis

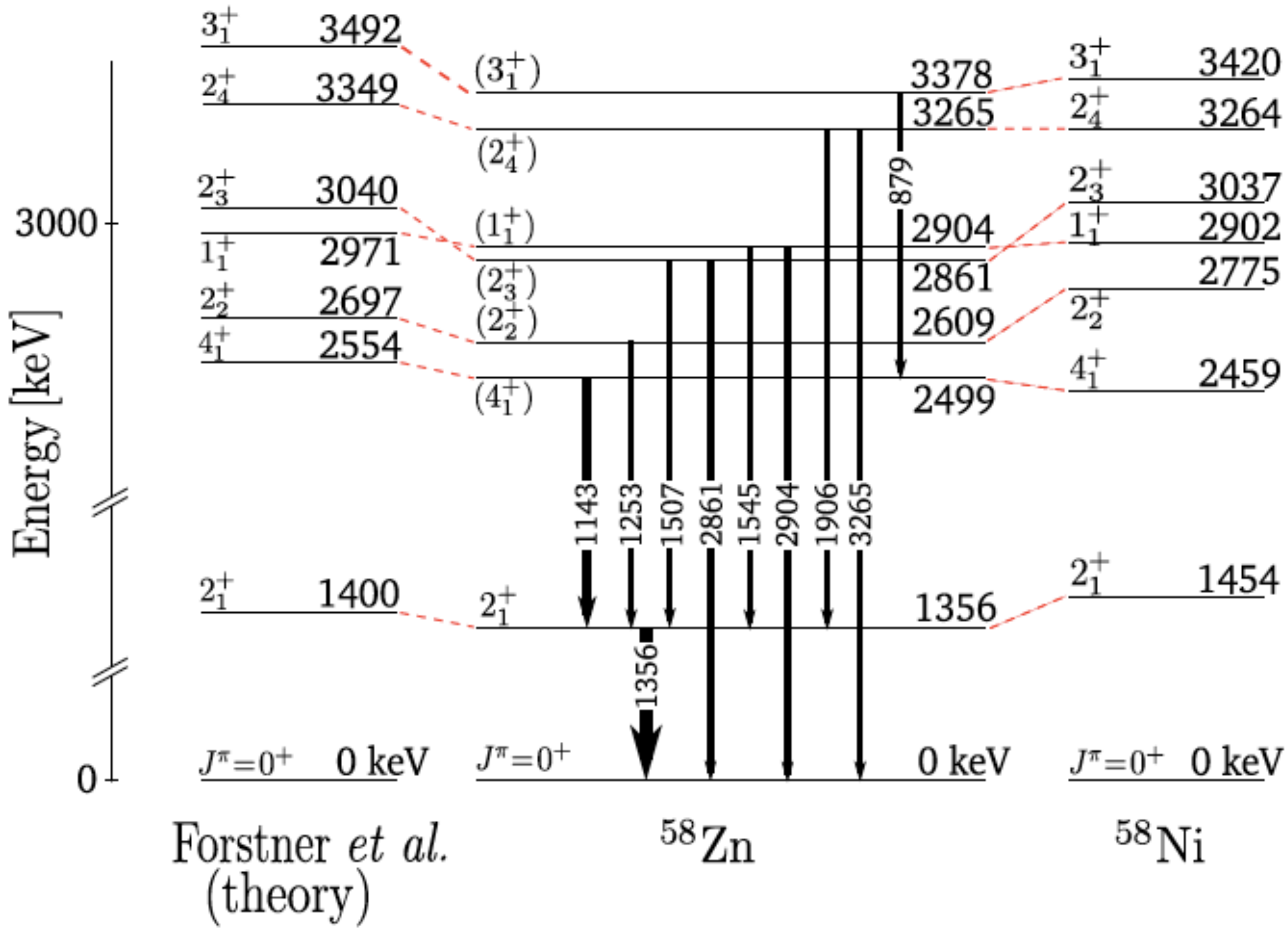


Coincidence Analysis

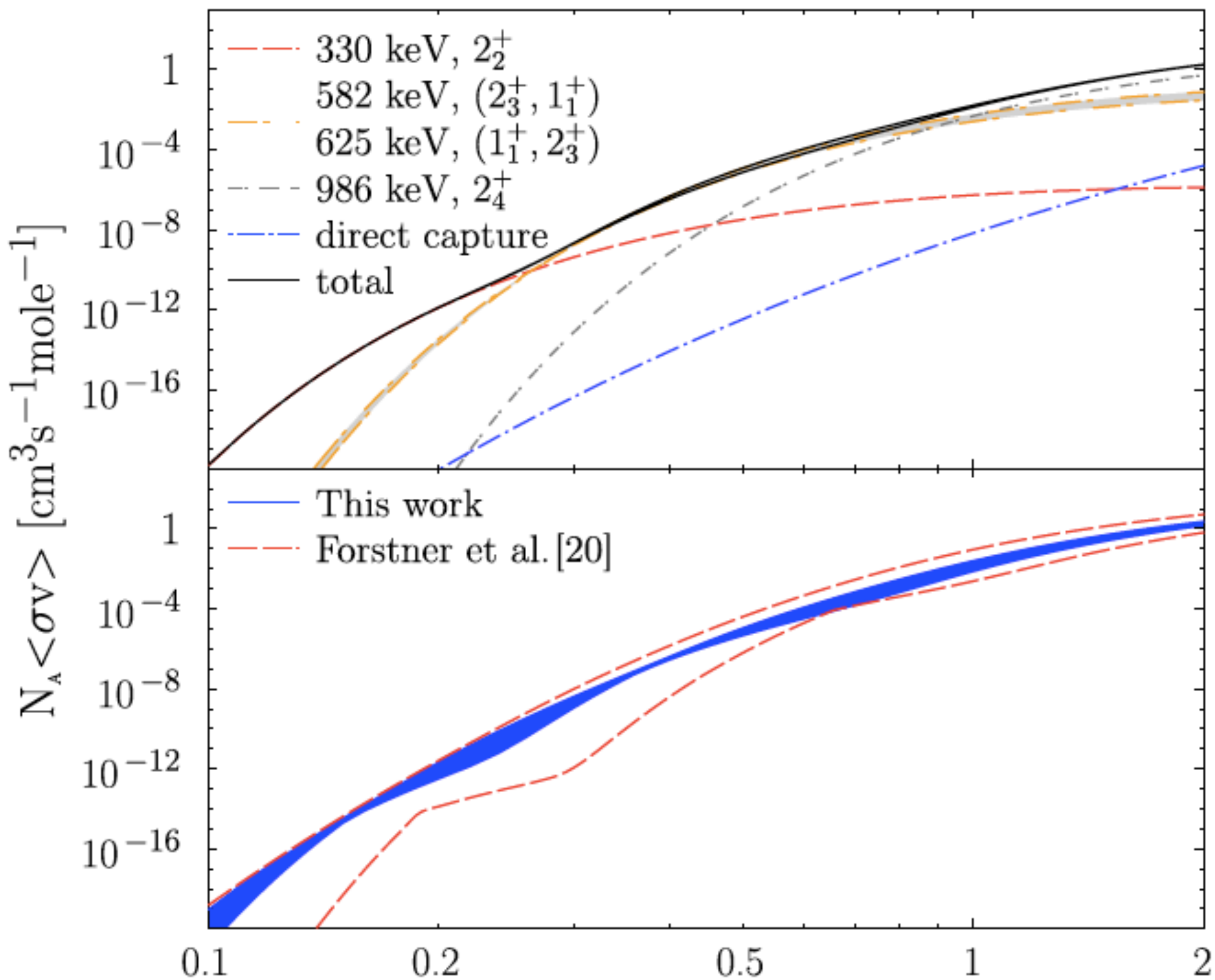


Coincidence Analysis





Mirror Symmetry



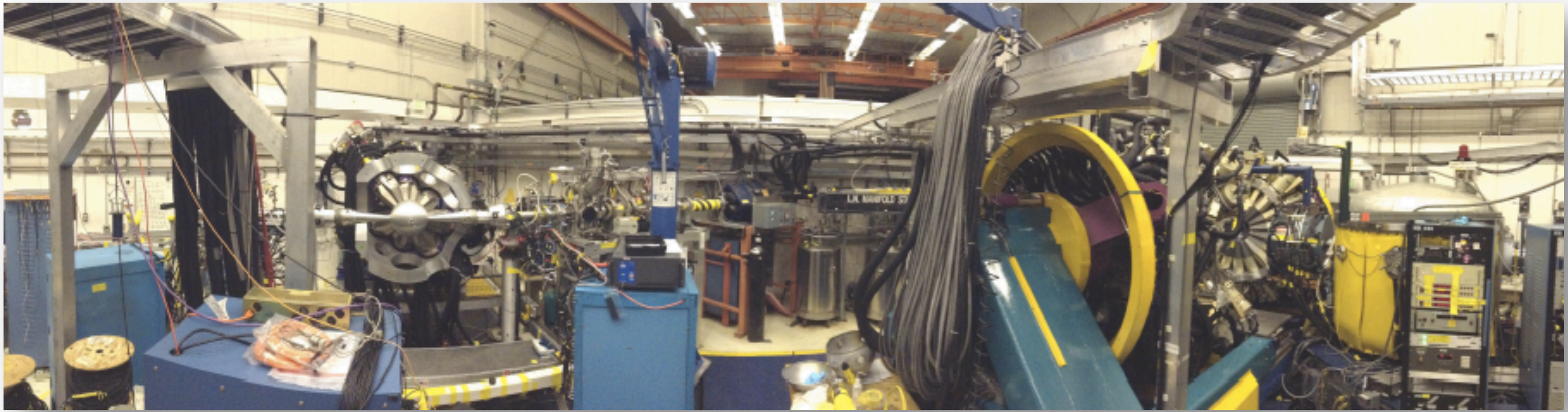
$^{57}Cu(p,\gamma)^{58}Zn$ rate uncertainty highly reduced

→ Reliable prediction of A=56 in ashes

The uncertainty in A = 56 nuclei production was reduced (from just this reaction) from a factor of 2 to about 20%.

At ATLAS/ANL March 2014 – June 2015

- **23 experiments approved: 3350 hours**



Position Resolution

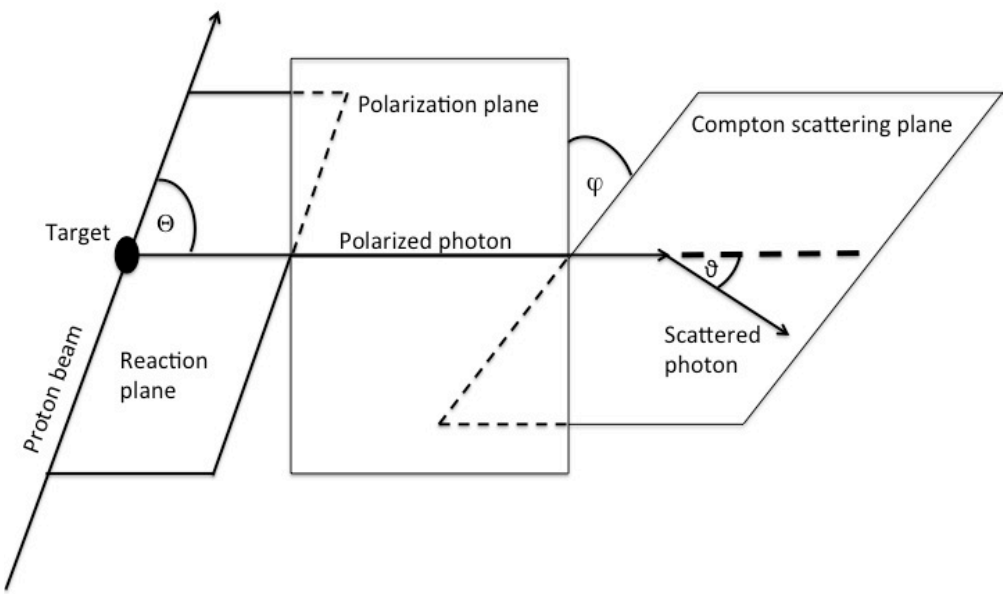
Good response for high-energy gammas

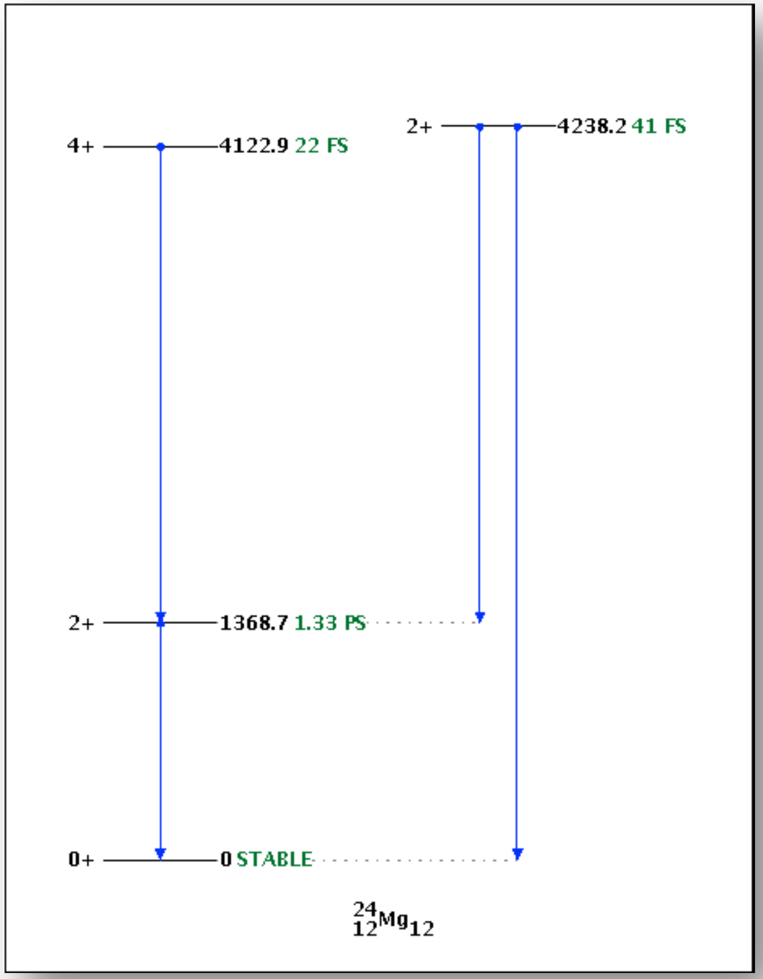
Polarization sensitivity

Neutron-rich nuclei – CARIBU beams

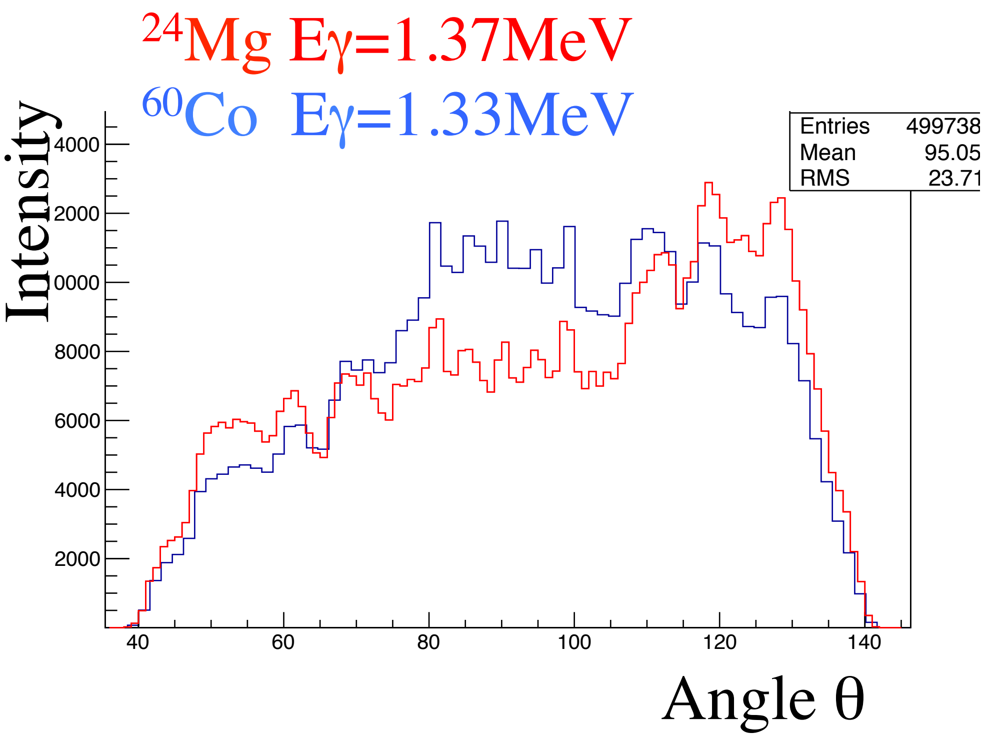
Polarization

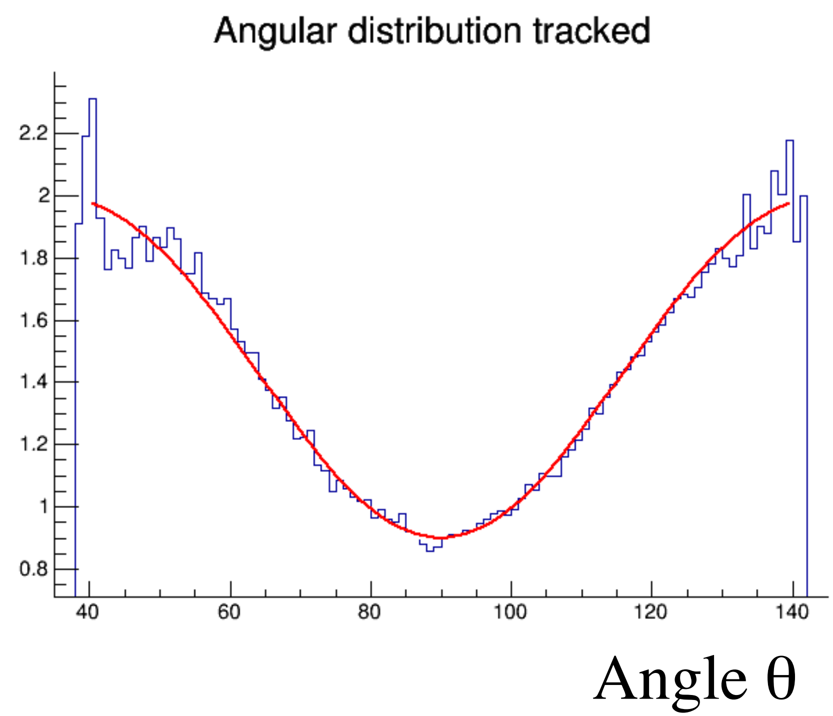
ANL ATLAS Experiment 1520x, A. Wiens *et al.*
$^{24}Mg(p,p'\gamma)^{24}Mg$, E_p = 2.6 and 6 MeV





Angular distributions



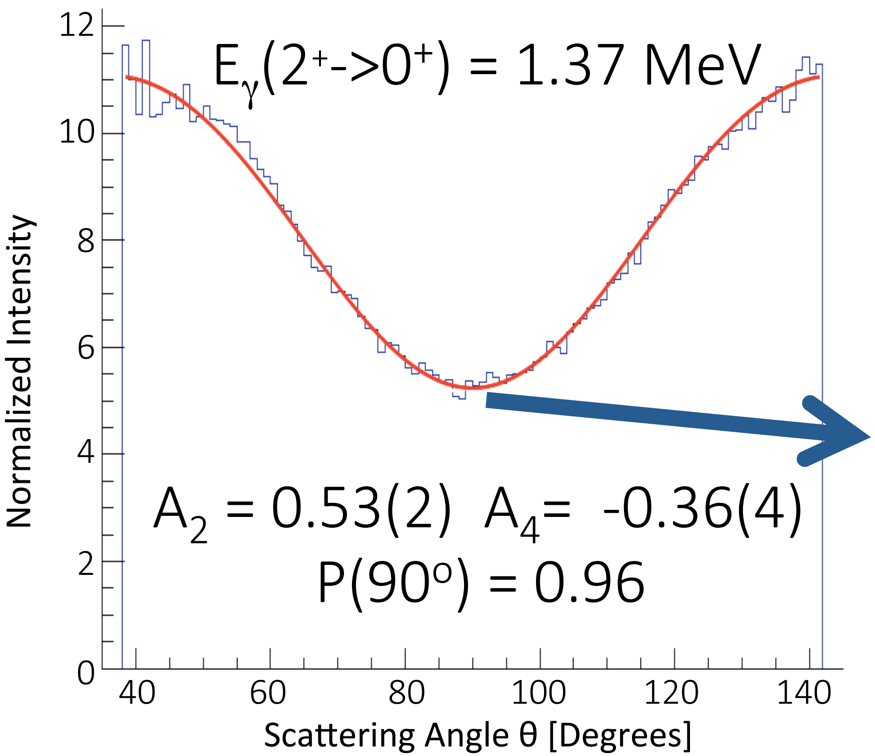


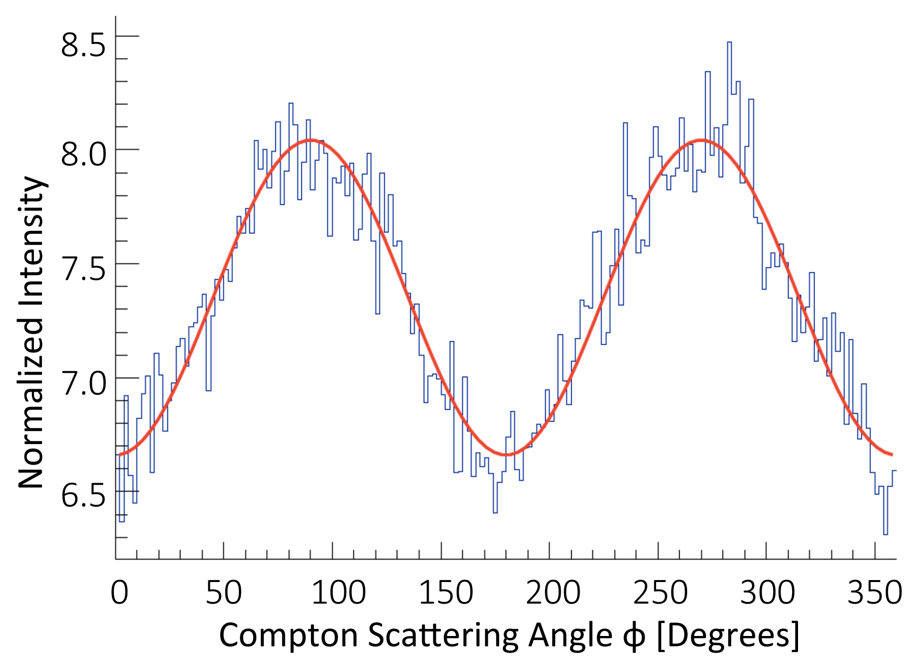
$A_2 = 0.53(2)$ $A_4 = -0.36(4)$

P(M=0) ~ 100%   P(M=1) ~ few %

$$\frac{d\sigma}{d\Omega}(\vartheta,\varphi) = \frac{r_0^2}{2}\left(\frac{E_{\gamma'}}{E_\gamma}\right)^2\left[\frac{E_{\gamma'}}{E_\gamma} + \frac{E_\gamma}{E_{\gamma'}} - 2\sin^2\vartheta\cos^2\varphi\right]$$

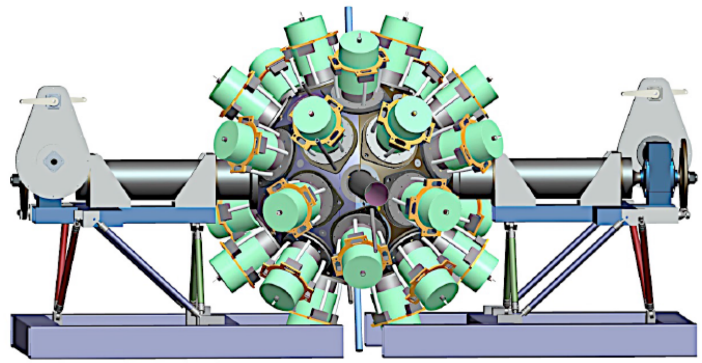
Event by event polarization information





THE GAMMA-RAY ENERGY TRACKING ARRAY

GRETA

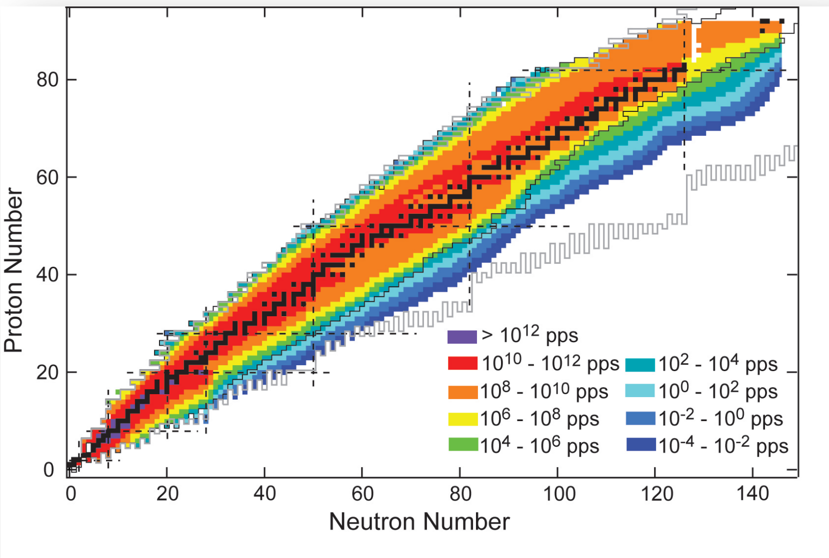


Whitepaper submitted to the Nuclear
Astrophysics and Low Energy Nuclear
Physics Town Meeting August 2014

www.greta.lbl.gov

Physics Opportunities (from the White Paper)

FRIB beams will provide access to thousands of nuclei



"GRETA will fully utilize and maximize the physics opportunities at FRIB, using both fast-fragmentation and reaccelerated beams."
–2014 GRETA Whitepaper

2.1 How does subatomic matter organize itself and what phenomena emerge?

Evolution of shell structure far from stability

Calcium isotopes – a prototypical example of structural evolution

Shape and configuration coexistence across the nuclear chart

Spin-isospin response of nuclei

At the dripline – physics in the regime of weak binding

At the limits of mass, charge, and spin

2.2 How did visible matter come into being and how does it evolve?

Explosive scenarios and the rp-process

The origin of the elements heavier than Iron – the r-process

Benchmarking electron-capture rates – towards understanding supernovae and processes in neutron stars

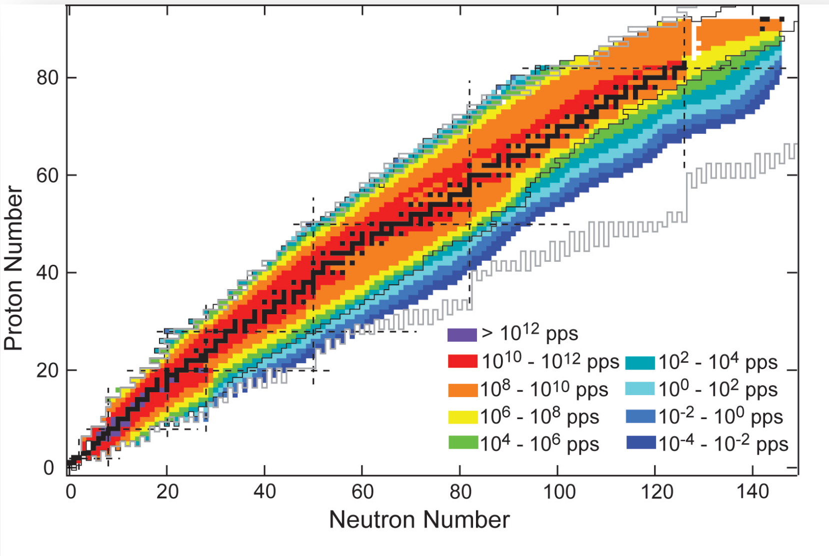
2.3 Are the fundamental interactions that are basic to the structure of matter fully understood?

Studies of octupole collectivity to guide searches for physics beyond the Standard Model

2.4 How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

Physics Opportunities (from the White Paper)

FRIB beams will provide access to thousands of nuclei



"GRETA will fully utilize and maximize the physics opportunities at FRIB, using both fast-fragmentation and reaccelerated beams."
–2014 GRETA Whitepaper

2.1 How does subatomic matter organize itself and what phenomena emerge?

Evolution of shell structure far from stability

Calcium isotopes – a prototypical example of structural evolution

Shape and configuration coexistence across the nuclear chart

Spin-isospin response of nuclei

At the dripline – physics in the regime of weak binding

At the limits of mass, charge, and spin

2.2 How did visible matter come into being and how does it evolve?

Explosive scenarios and the rp-process

The origin of the elements heavier than Iron – the r-process

Benchmarking electron-capture rates – towards understanding supernovae and processes in neutron stars

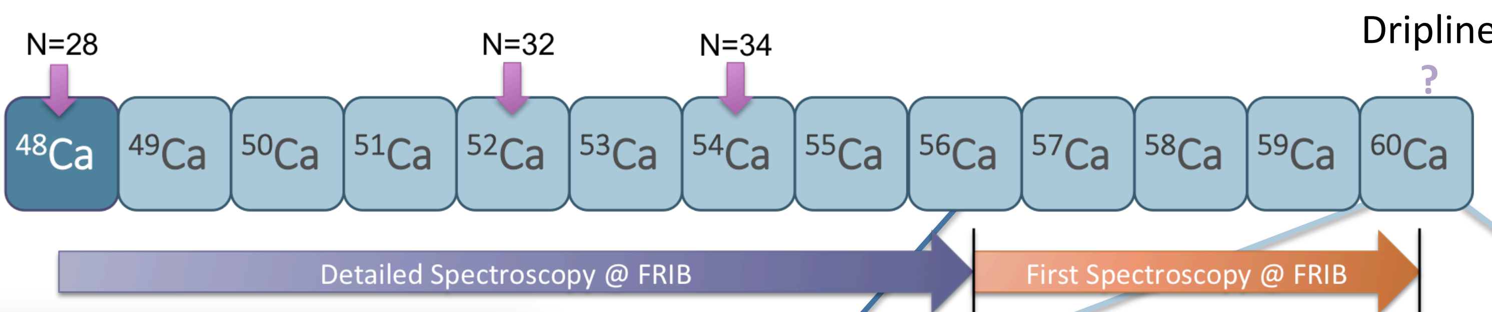
2.3 Are the fundamental interactions that are basic to the structure of matter fully understood?

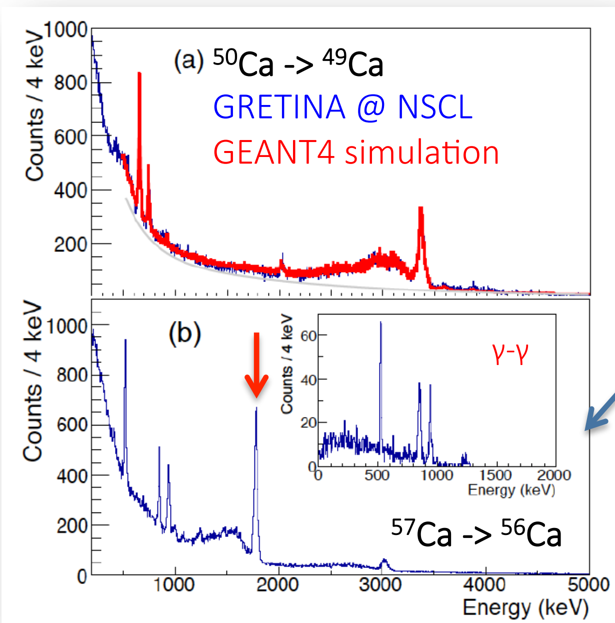
Studies of octupole collectivity to guide searches for physics beyond the Standard Model

2.4 How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

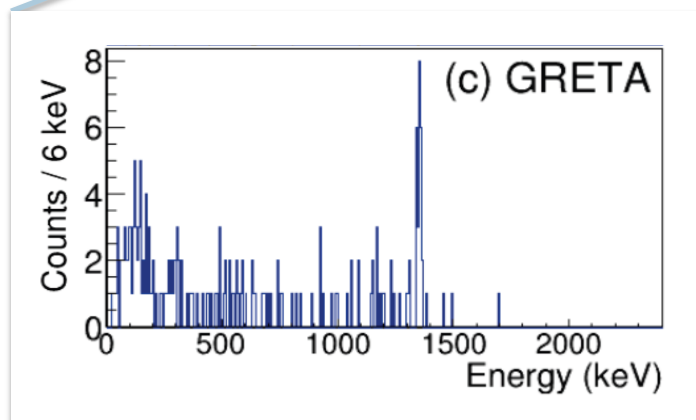
GRETA + High-Rigidity Spectrometer at FRIB

- The neutron-rich Ca isotopes beyond ^{48}Ca provide dramatic examples of shell evolution
- Microscopic calculations suggest a sensitivity of the detailed structure to the inclusion of 3N forces





- Detailed studies of single particle structure, provide a critical test of effective interactions and 3N forces
- The structure around ^{60}Ca informs the location of the dripline at Z = 20



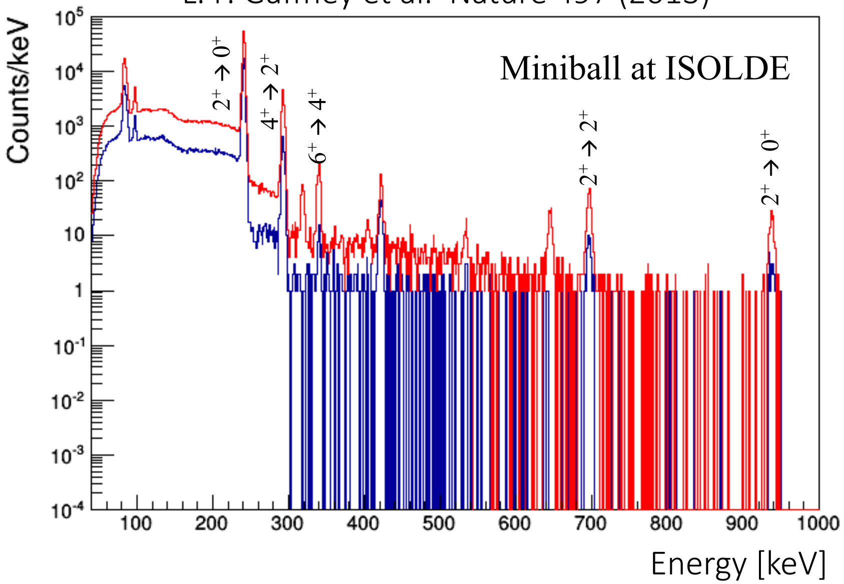
GRETA will have superior resolving power for fast-beam experiments compared to any other γ-ray detector

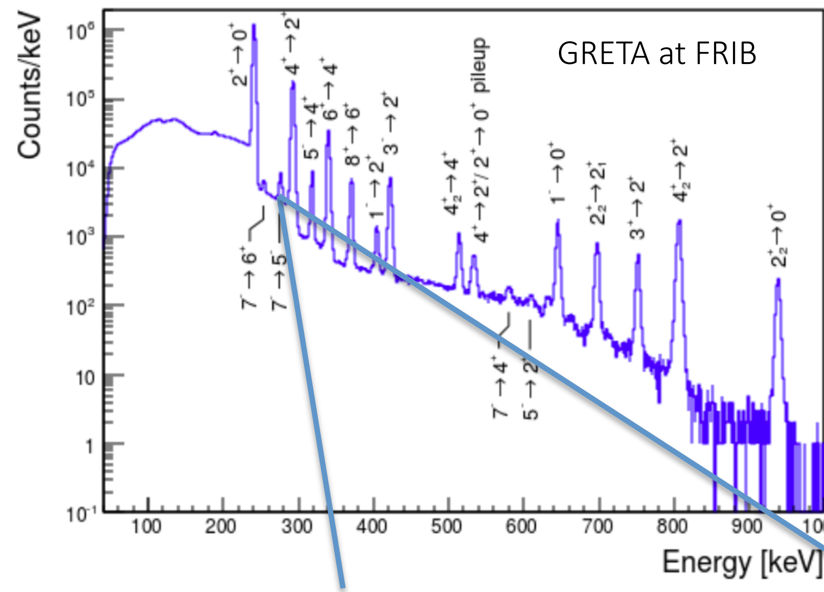
GRETA and re-accelerated beams

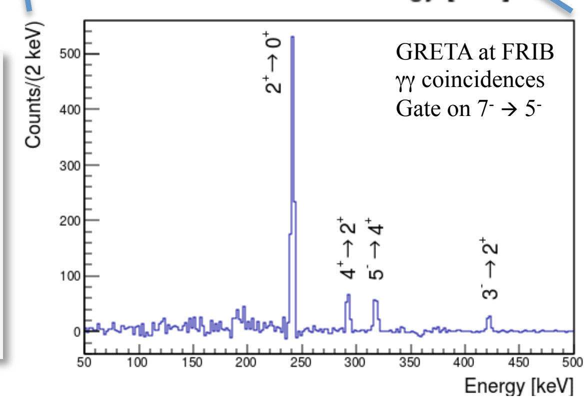
Studies of octupole collectivity to guide searches for physics beyond the Standard Model

Coulomb Excitation of ^{220}Rn on ^{120}Sn

L. P. Gaffney et al. Nature 497 (2013)



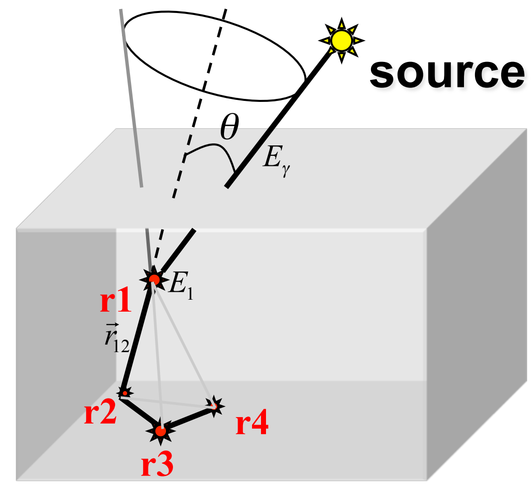




4π GRETA combined with the FRIB reaccelerated beam intensity and energy provide a 100-fold or more increase in the intensity of transitions characterizing higher-spin states

Unprecedented discovery potential for identification and characterization of octupole-collective candidate nuclei for EDM searches.

Applications of imaging gamma-rays



High energy astrophysics

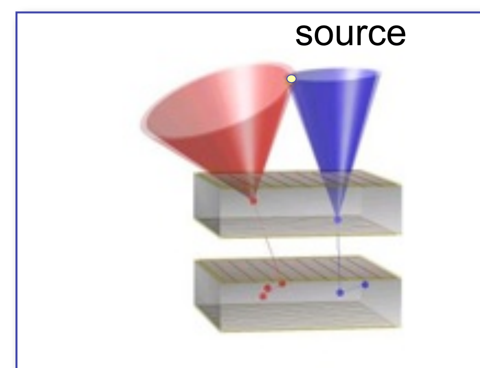
Correlate the detected photon to the source object as known from more precise observations in other wavelengths

Biomedical research

Precise localization of radioactive tracers in the body
Cancer diagnosis
Molecular targeted radiation therapy
Monitor changes in the tracer distribution -> dynamical studies

National security

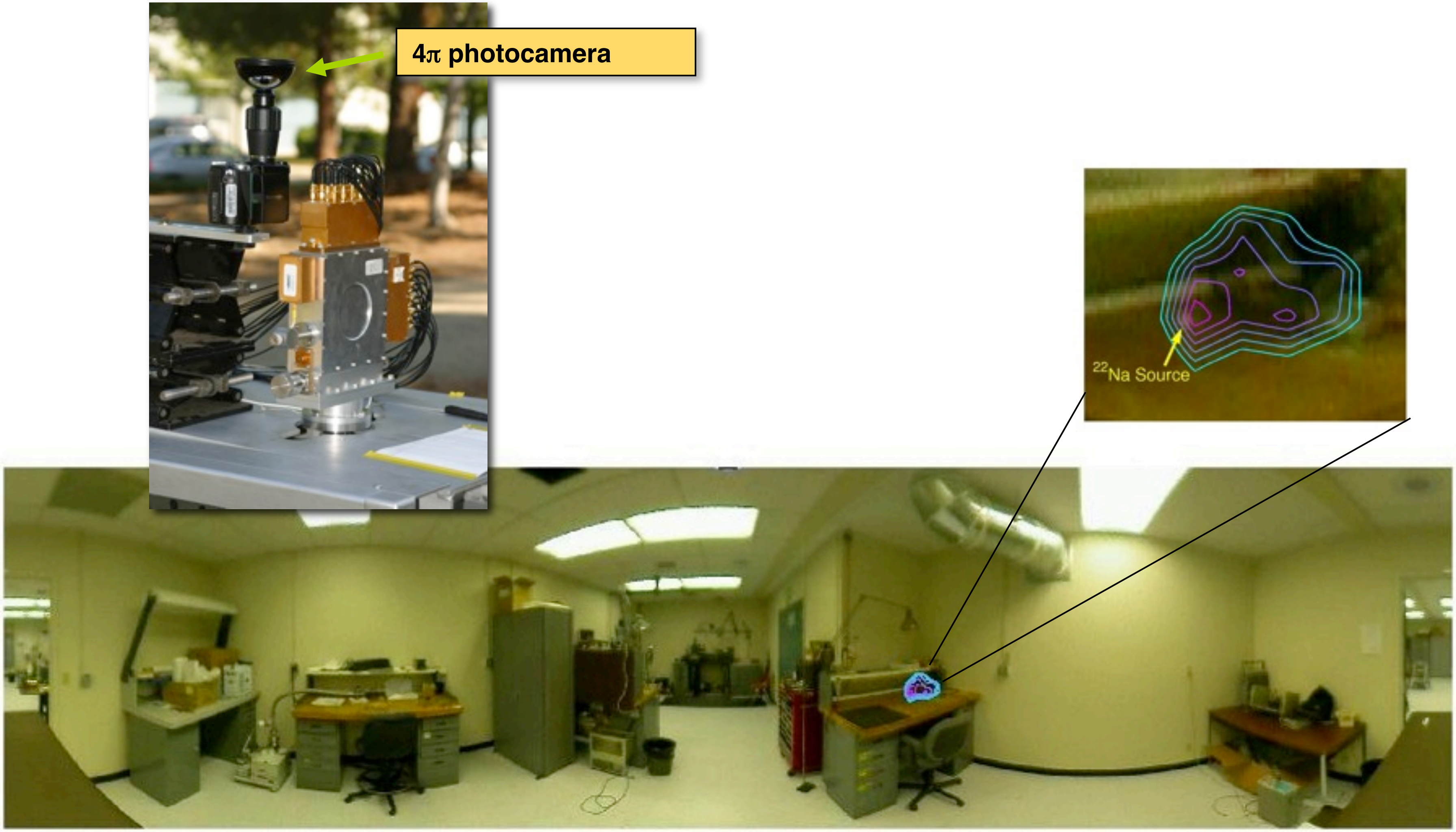
Nuclear non-proliferation/ nuclear counter terrorism
Contraband detection
Stockpile stewardship
Nuclear waste monitoring and management



Industrial non-destructive assessments

Determination of the material density distribution between the source and detector

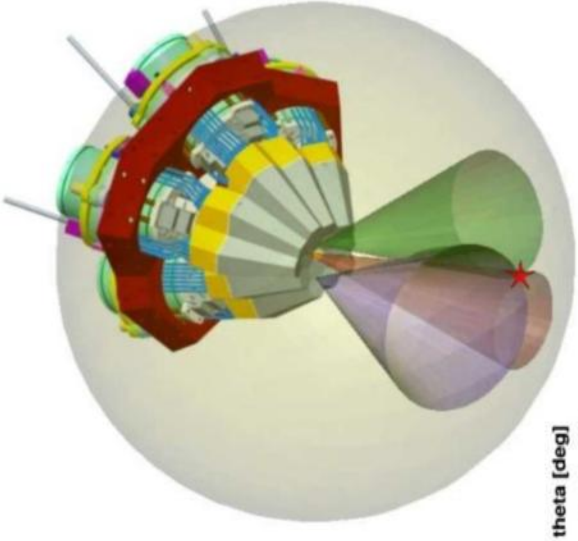
4π gamma-ray imaging



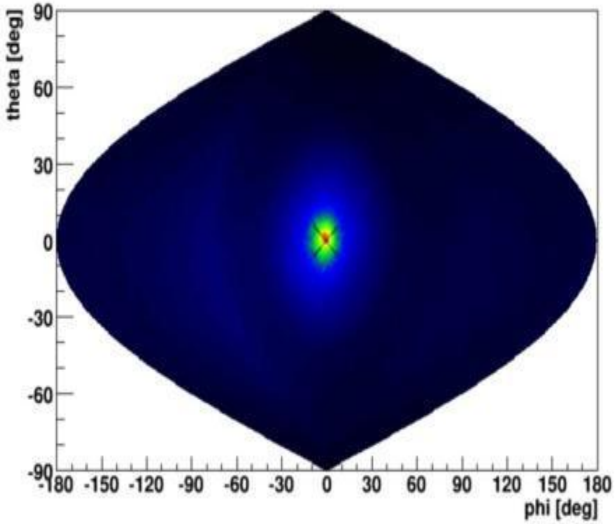
K.Vetter et al.

Imaging of E_γ=1332 keV gamma rays

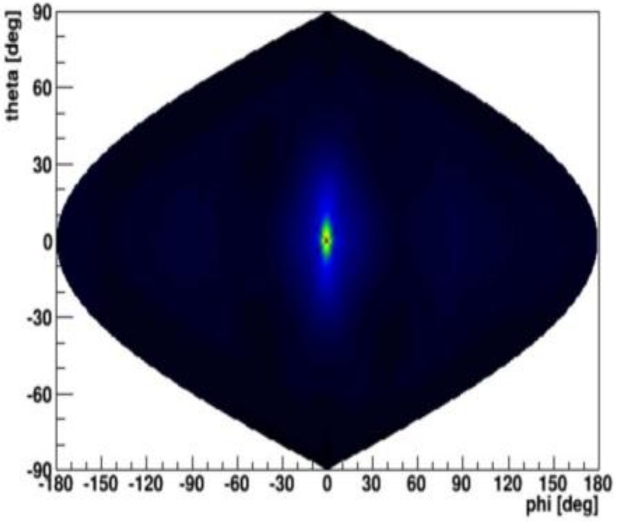
AGATA used as a big Compton Camera



Source at 51 cm ➔ Δx ~Δy ~2 mm Δz ~2 cm



All 9 detectors



One detector

F. Recchia, Padova

Acknowledgements

Construction and commissioning:

The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA

S. Paschalis [a,*], I.Y. Lee [a,**], A.O. Macchiavelli [a], C.M. Campbell [a], M. Cromaz [a], S. Gros [a], J. Pavan [a], J. Qian [a], R.M. Clark [a], H.L. Crawford [a], D. Doering [a], P. Fallon [a], C. Lionberger [a], T. Loew [a], M. Petri [a], T. Stezelberger [a], S. Zimmermann [a], D.C. Radford [b], K. Lagergren [b], D. Weisshaar [c], R. Winkler [c], T. Glasmacher [c], J.T. Anderson [d], C.W. Beausang [e]

[a] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[b] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[c] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[d] *Argonne National Laboratory, Argonne, IL 60439, USA*
[e] *Department of Physics, University of Richmond, 28 Westhampton Way, Richmond, VA 23173, USA*

Operation at NSCL:

NSCL: D. Weisshaar, A Gade, F. Recchia, T. Baugher, C. Langer, E. Lunderberg, A. Lemasson, S. Noji, M. Scott, D. Smalley, K. Wimmer, R.Zegers
R. Fox (NSCL DAQ) and D. Bazin, S. Williams (S800)

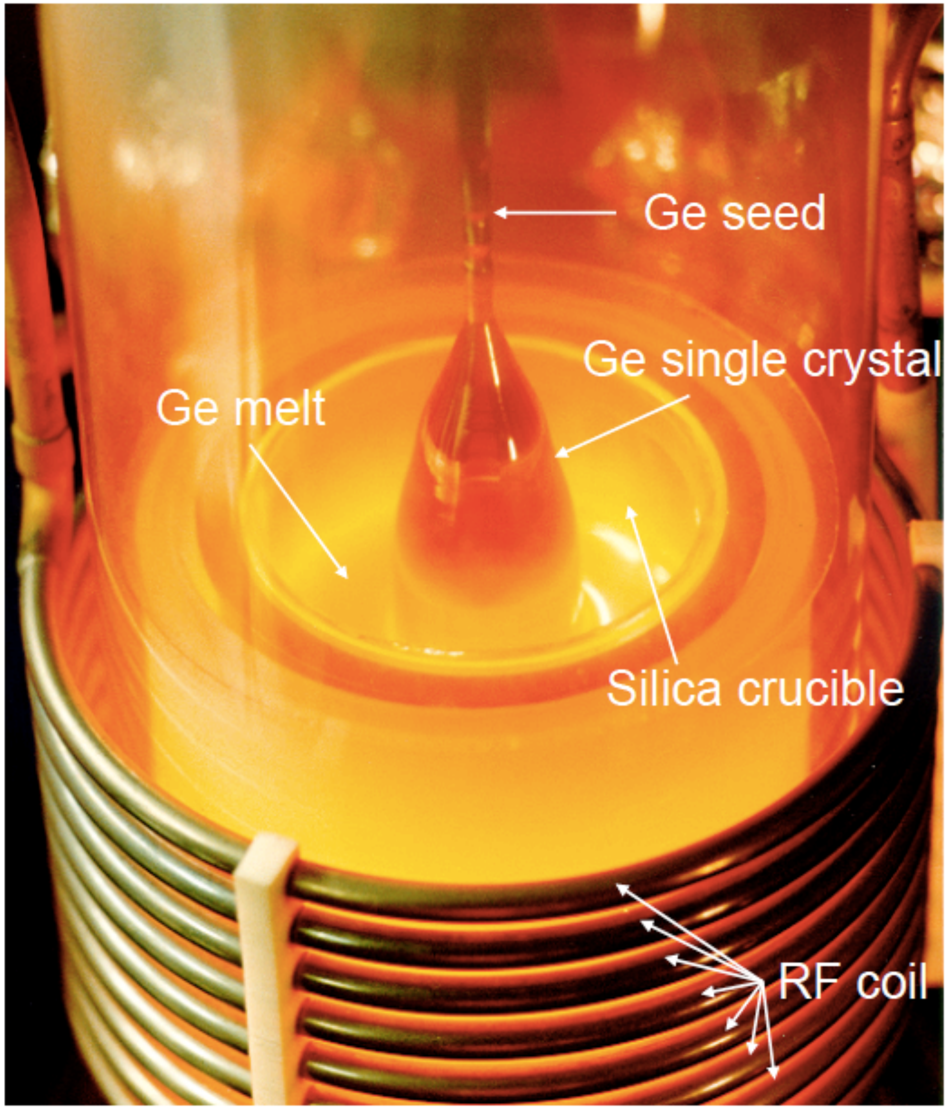
ORNL: D. Radford, J. M. Allmond

LBNL: I.Y. Lee, C.M. Campbell, H. Crawford, M. Cromaz, P.Fallon, C. Lionberger, A. Wiens

GRETINA was funded by the US DOE - Office of Science. Operation of the array at NSCL is supported by NSF under PHY-1102511(NSCL) and DOE under grant DE-AC02-05CH11231(LBNL).

Thank You!

EXTRA MATERIAL



An ultra-pure Germanium single crystal is being “pulled” from a melt contained in a silica crucible at 936ºC. The atmosphere is pure Hydrogen. Heat is supplied by the water cooled radiofrequency (RF) coil surrounding the silica envelope. This bulk crystal growth technique carries the name of it’s inventor, “Jan Czochralski.”

Compton scattering: More Details

Compton formula:

$$E' = \frac{E}{1 + \frac{E}{m_0 c^2}(1 - \cos\theta)}$$

Special case for $E >> m_0c^2$:
gamma-ray energy after 180° scatter is approximately

$$E' = \frac{m_0 c^2}{2} = 256 \text{ keV}$$

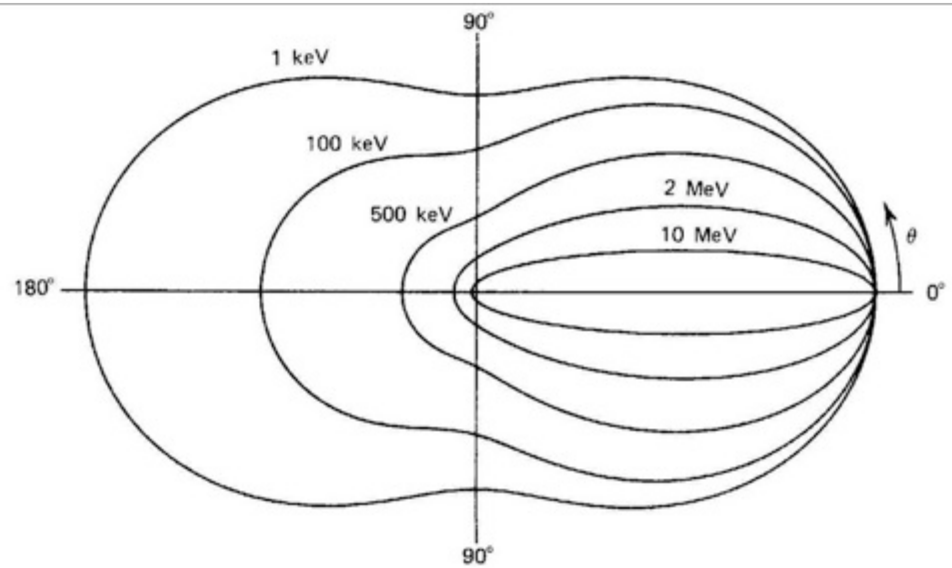
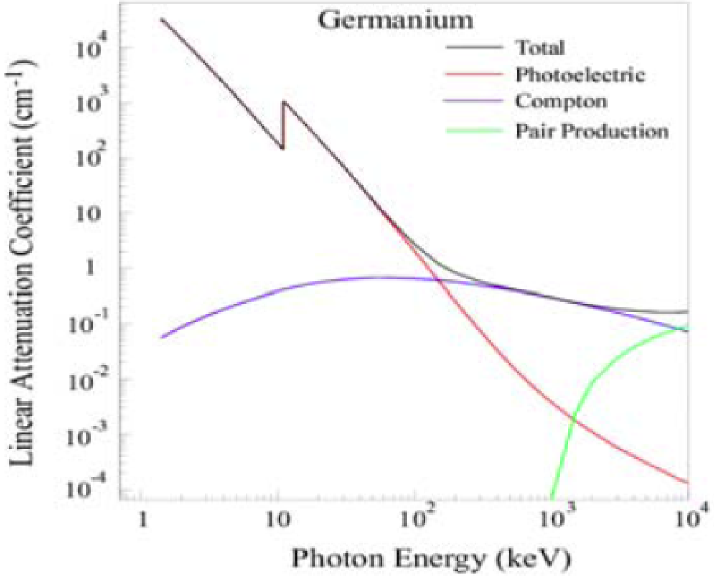


Figure 2-19 A polar plot of the number of photons (incident from the left) Compton scattered into a unit solid angle at the scattering angle θ. The curves are shown for the indicated initial energies.

The angle dependence of Compton scattering is expressed by the **Klein-Nishina Formula**

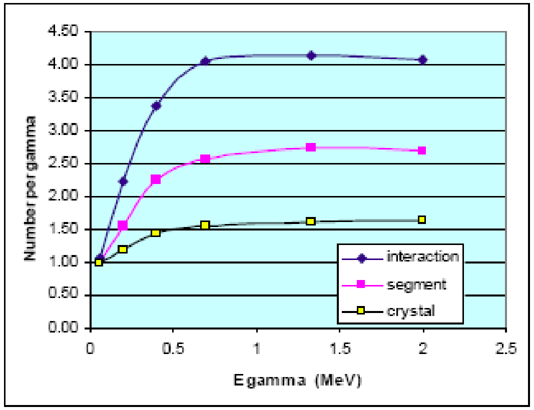
Forward scattering
(θ small) is dominant for E>100keV

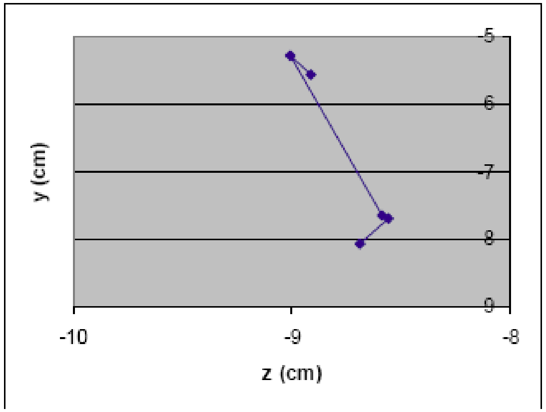
Tracking - Use properties of γ-ray interaction with Ge to determine the γ-ray scattering sequence

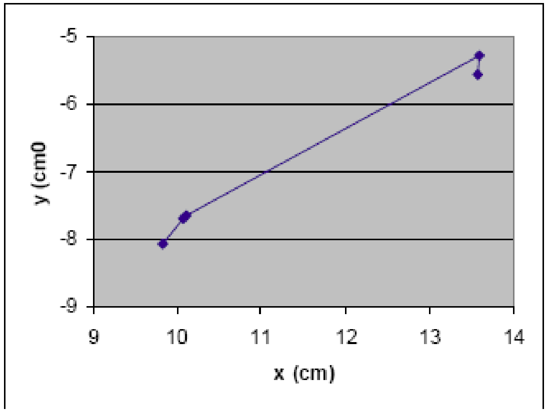


Example; 1.33 MeV
5 interactions: 4 Compton, 1 photo
Separation of interactions: 0.5 – 5 cm

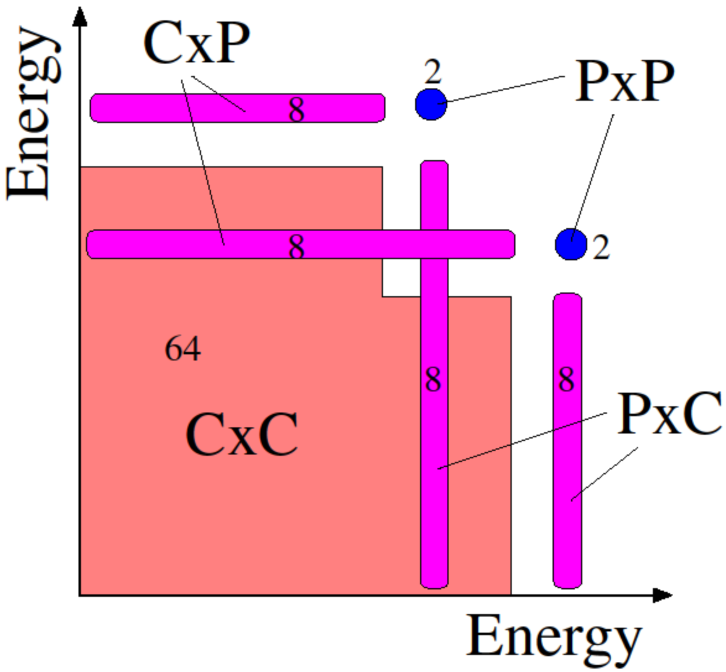
x (cm)	y (cm)	z (cm)	E (MeV)
9.82	-8.07	-8.69	1.0184
10.07	-7.68	-8.56	0.0418
10.11	-7.65	-8.59	0.0044
13.58	-5.27	-9.01	0.1202
13.57	-5.55	-8.91	0.1452







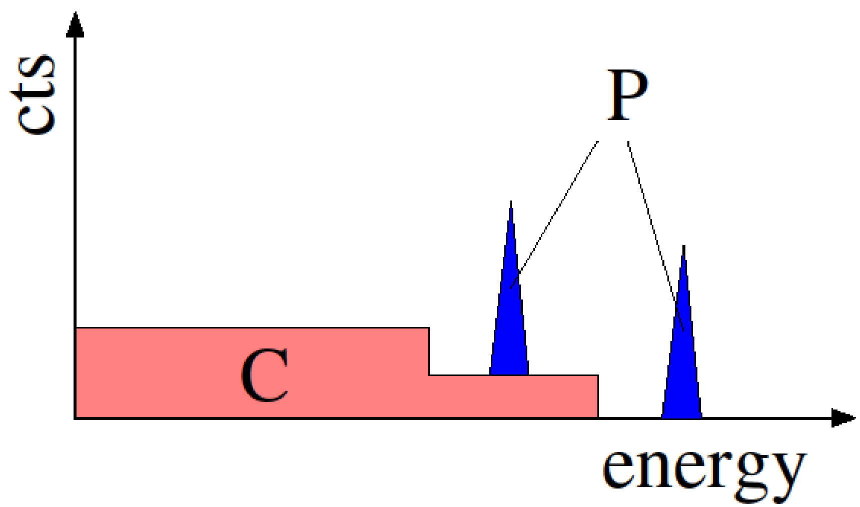
….what we have to pay:



P/T: Probability to count a detected gamma in the Peak and NOT in the Compton plateau

Example: P/T=0.2, two gammas, 100 events

Detecting both in peak	PxP: 4%
1 in Peak, 1 as Compton	PxC:16%
1 as Compton, 1 in Peak	CxP:16%
Both as Compton	CxC:64%



In projection we have 10 events in peak, but in a corresponding δE cut only 2 (10 x P/T)

Conclusion: We **lose factor P/T** in peak intensity each time we increase Fold F.

Signal Generation

- **Electric field**

$$\vec{E} = \vec{\nabla} V$$

$$\nabla^2 V = \rho \qquad \rho : impurity\ concentration$$

Boundary condition : applied bias voltage

- **Weighting potential for segment *k***

$$\nabla^2 V_k = 0$$

Boundary condition : 1 V on the segment k
0 V on all other segments

Signal Generation

- **Trajectory : for electrons and holes**

$$\vec{v} = \vec{v}(\vec{E})$$

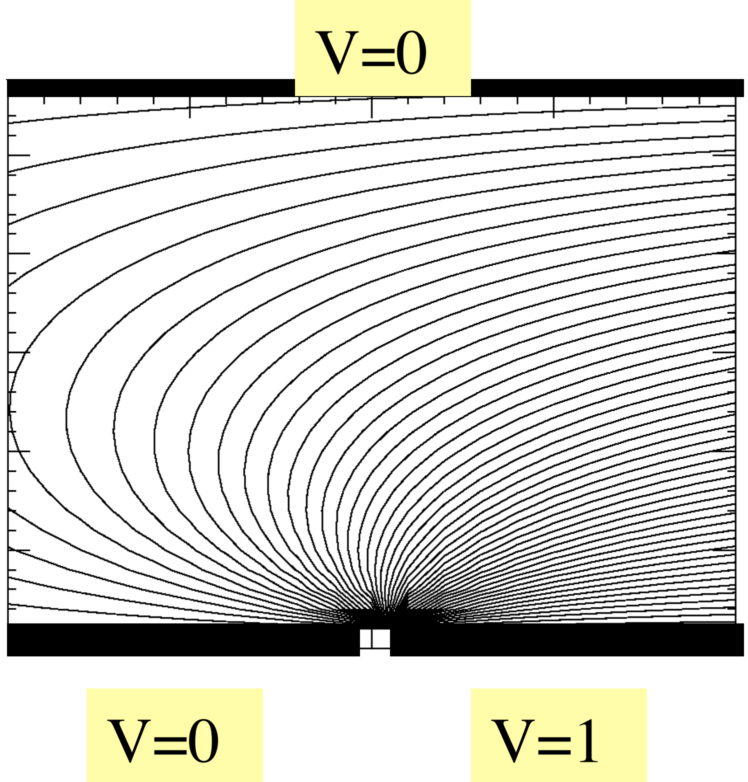
anisotropic

$$\vec{x}(t) = \vec{x}_0 + \int_0^t \vec{v}\, dt$$

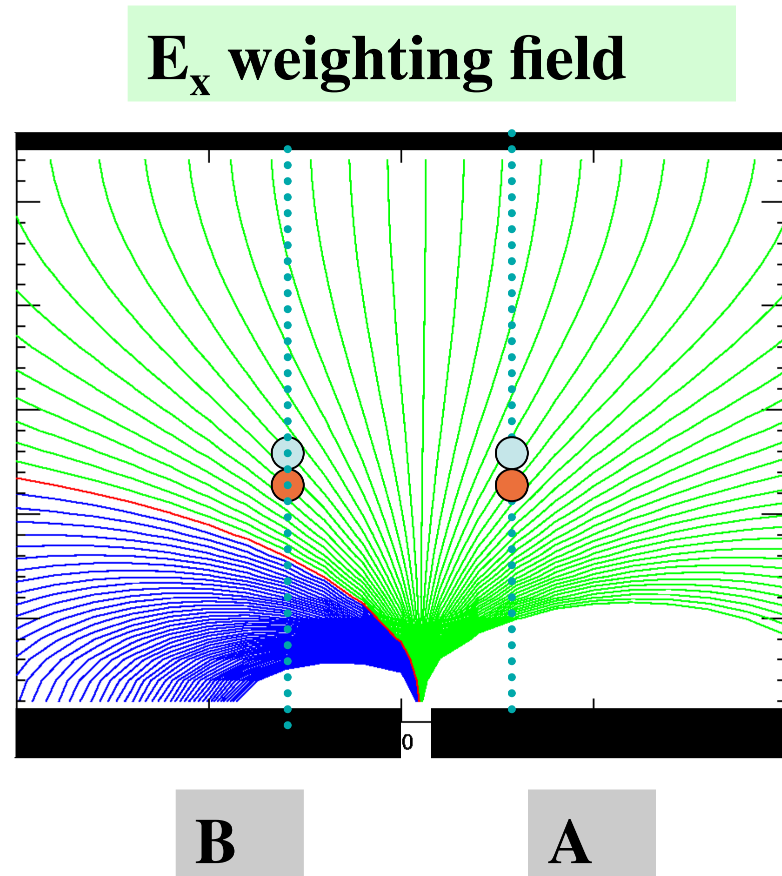
- **Induced charge** **(S. Ramo, Proc. IRE 27(1939)584)**

If a charge q moves from position x_1 to position x_2, then the induced charge on electrode k is

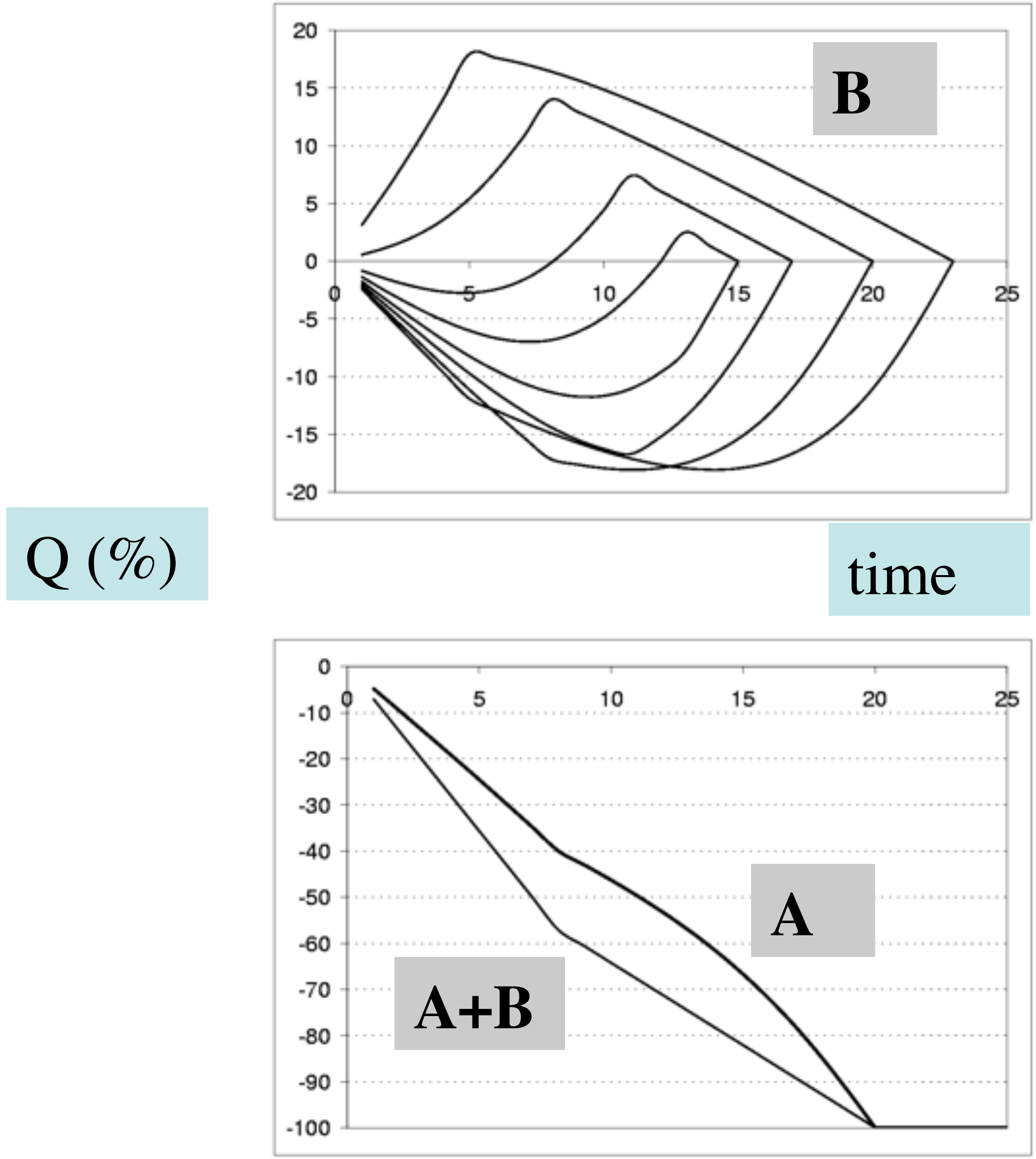
$$\Delta Q_k = q\left(V_k(\vec{x}_2) - V_k(\vec{x}_1)\right)$$



weighting potential

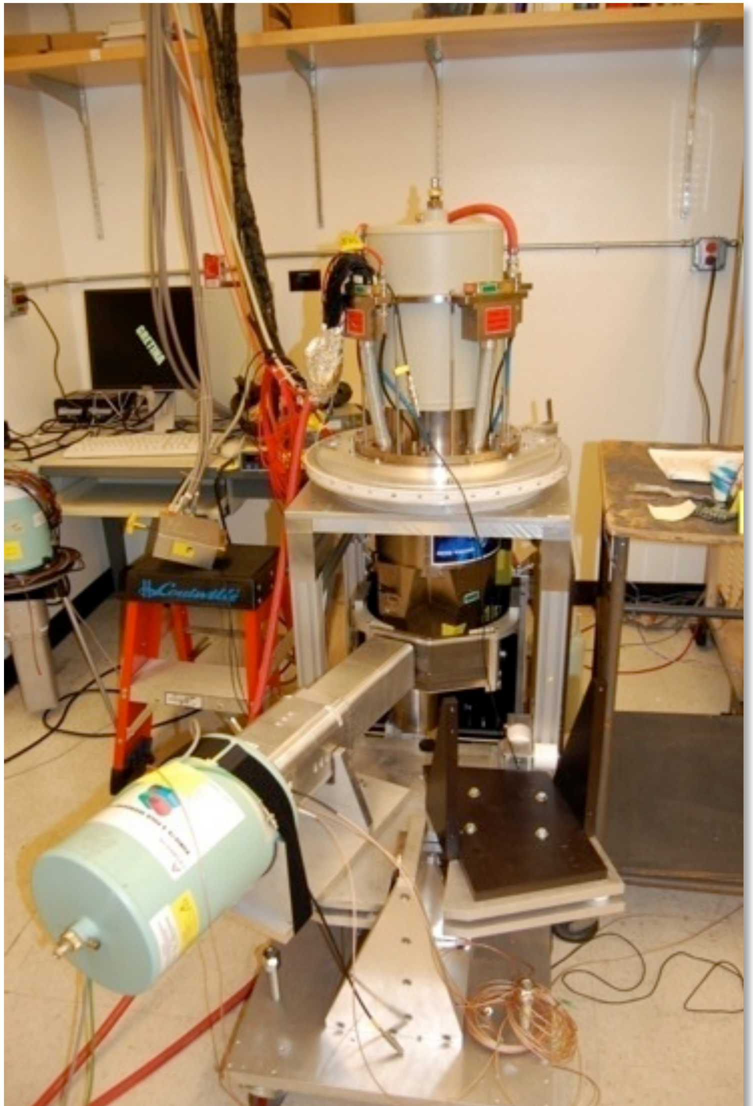


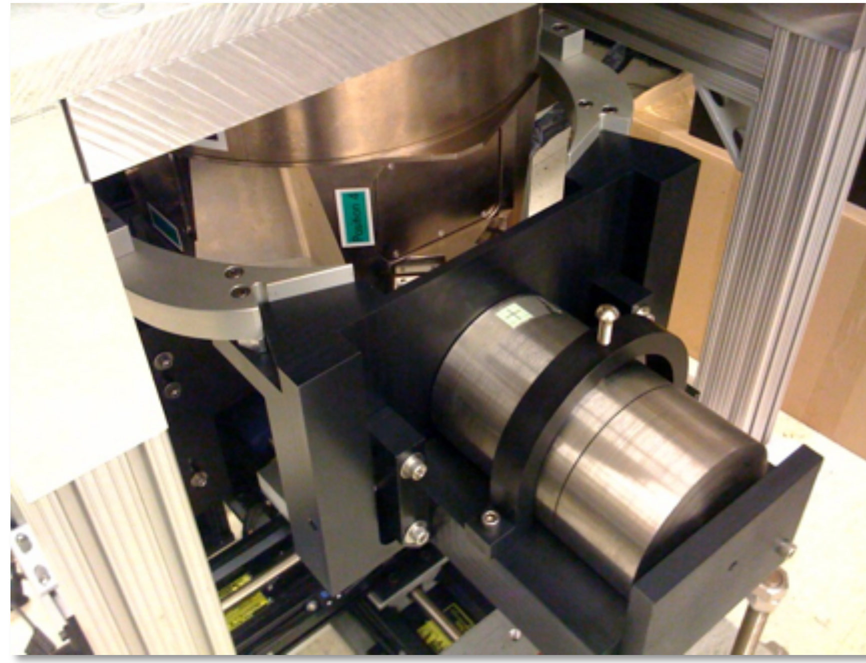
$$\Delta Q \propto \vec{E} \bullet \vec{v} \Delta t = E_x v \Delta t$$



B
20
15
10
5
0
-5
-10
-15
-20
0
5
10
15
20
25
Q (%)
time
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
A
A+B

Characterization





$140\mu Ci$ Am source (60keV)

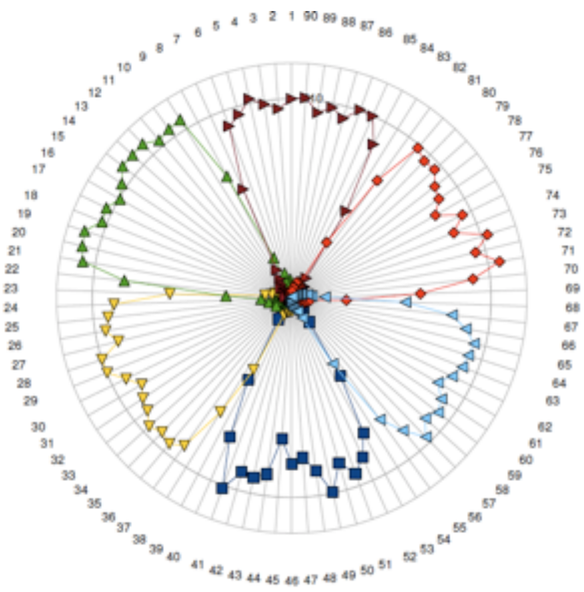
1 mCi ^{137}Cs source (662keV)

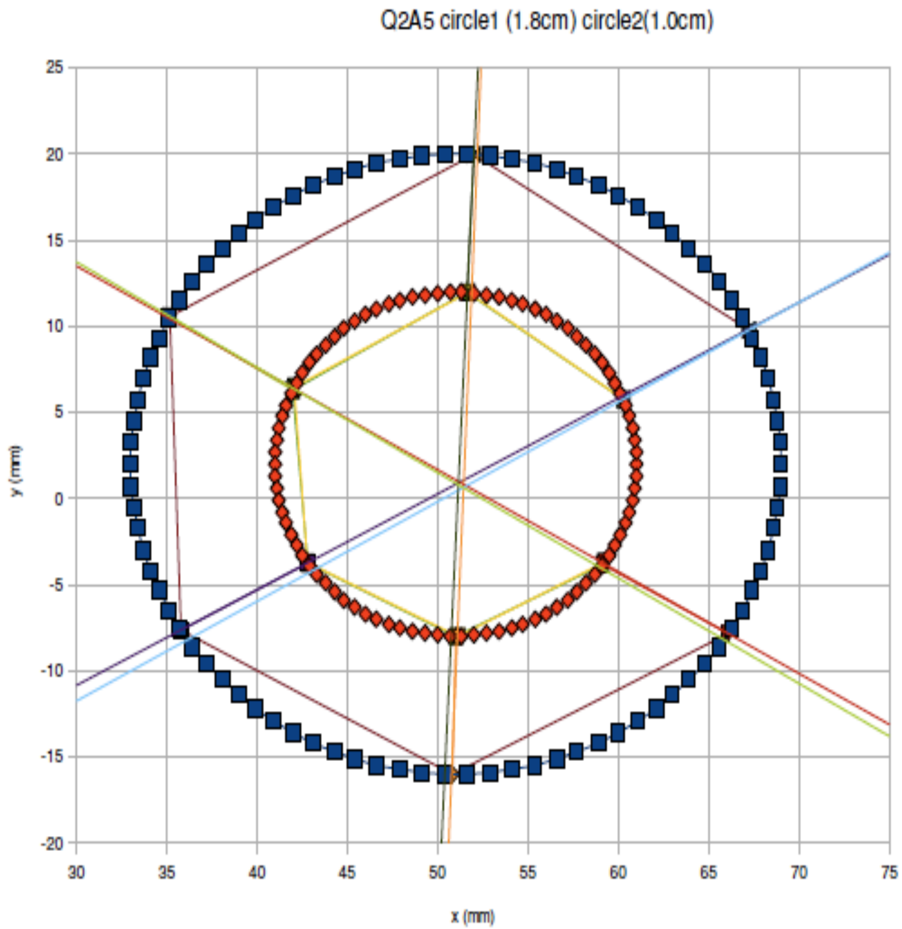
Vertical, horizontal and slit collimators (1, 2 mm) to define x, y and z

Stepping motors in x, y, z (LabView Control)

Automatic scans.

Am Surface scans





- Front segmentation lines are within 0.2 mm
- Accuracy of measurement is 0.15 mm
- Reproducibility after crystal replacement is 0.2 mm

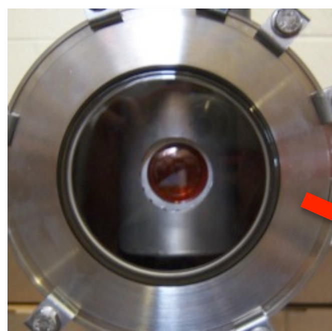
Inverse-kinematics proton scattering on ^{50}Ca: determining effective charges using complementary probes

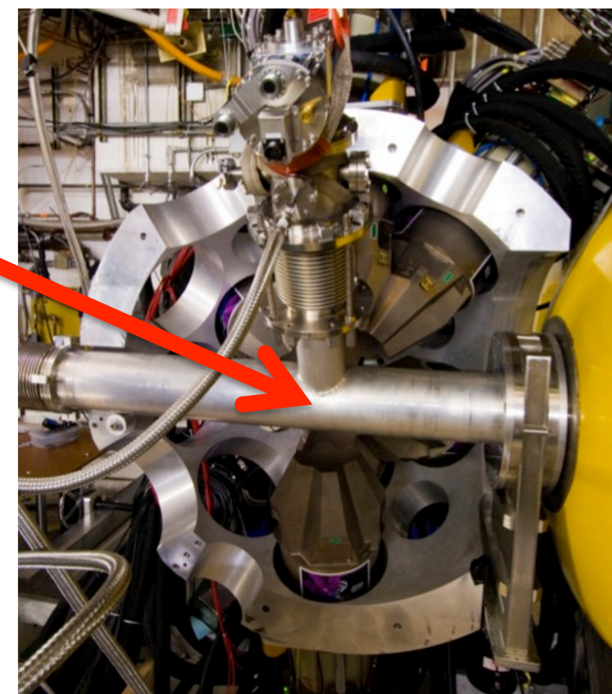
L. A. Riley,[1] M. L. Agiorgousis,[1] T.R. Baugher,[2] D. Bazin,[2] M. Bowry,[2] P. D. Cottle,[3] F. G. DeVone,[1] A. Gade,[2] M. T. Glowacki,[1] K. W. Kemper,[3] E. Lunderberg,[2] D. M. McPherson,[3] S. Noji,[2] F. Recchia,[2,*] B. V. Sadler,[1] M. Scott,[2] D. Weisshaar,[2] and R. G. T. Zegers[2,4]

[1]*Department of Physics and Astronomy, Ursinus College, Collegeville, PA 19426, USA*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, 48824, USA*
[3]*Department of Physics, Florida State University, Tallahassee, FL 32306, USA*
[4]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA*

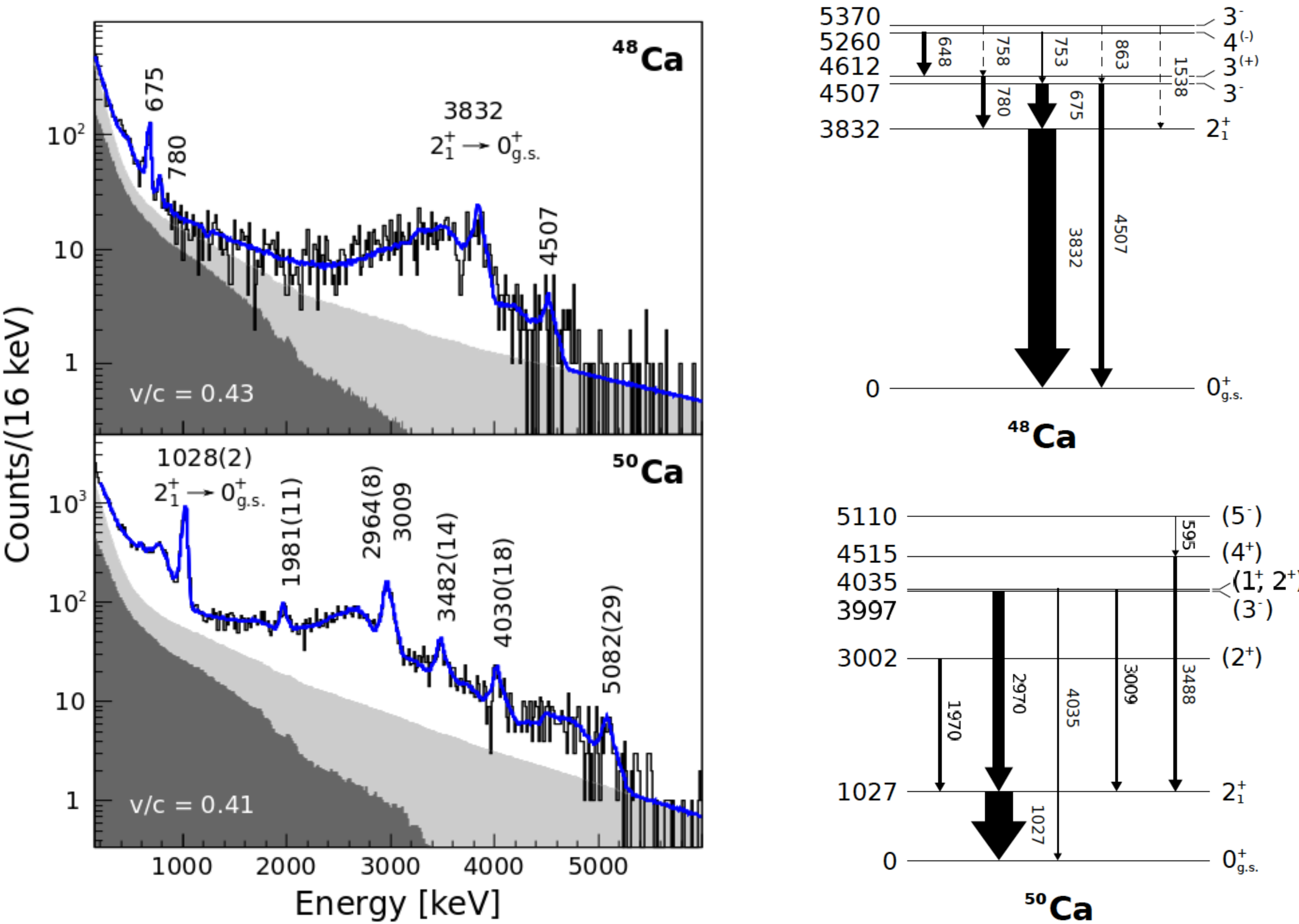
(Dated: July 16, 2014)

~50mg/cm^2 LH$_2$





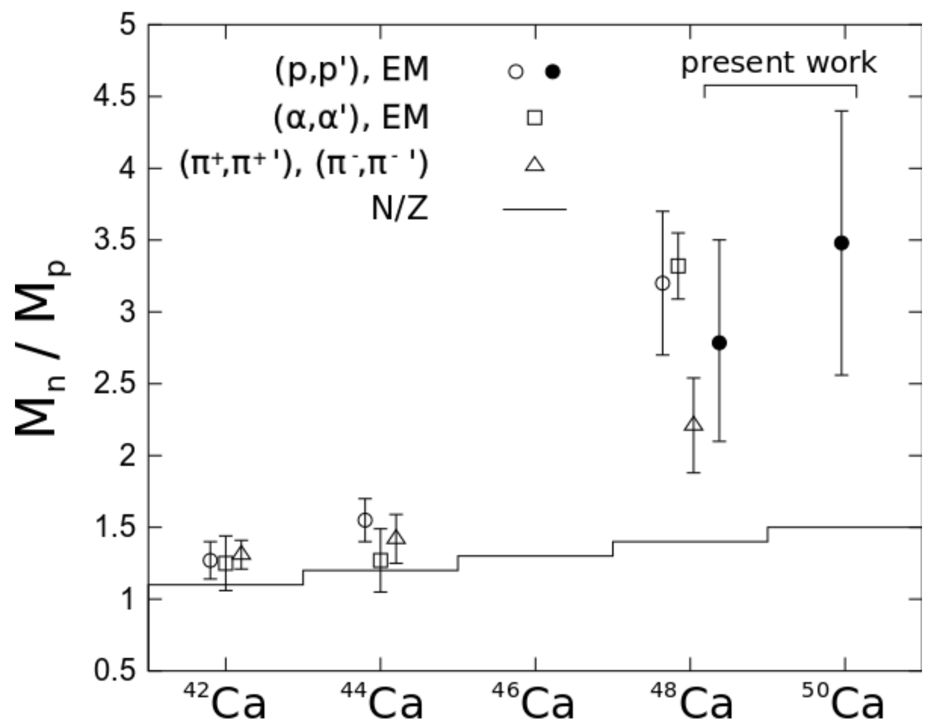
Liquid Hydrogen target and GRETINA
L. Riley, Ursinus College and R.G.T. Zegers, NSCL



48Ca
675
780
3832
$2^+_1 \rightarrow 0^+_{g.s.}$
4507
v/c = 0.43
50Ca
1028(2)
$2^+_1 \rightarrow 0^+_{g.s.}$
1981(11)
2964(8)
3009
3482(14)
4030(18)
5082(29)
v/c = 0.41
Counts/(16 keV)
Energy [keV]
5370
5260
4612
4507
3832
0
648
758
753
863
1538
780
675
3832
4507
3^-
$4^{(-)}$
$3^{(+)}$
3^-
2^+_1
$0^+_{g.s.}$
48Ca
5110
4515
4035
3997
3002
1027
0
595
1970
2970
4035
3009
3488
1027
(5^-)
(4^+)
$(1^+, 2^+)$
(3^-)
(2^+)
2^+_1
$0^+_{g.s.}$
50Ca

(p,p’) cross-sections are used to extract proton-scattering deformation lengths

Comparison with lifetime measurements determine the Mn/Mp ratios



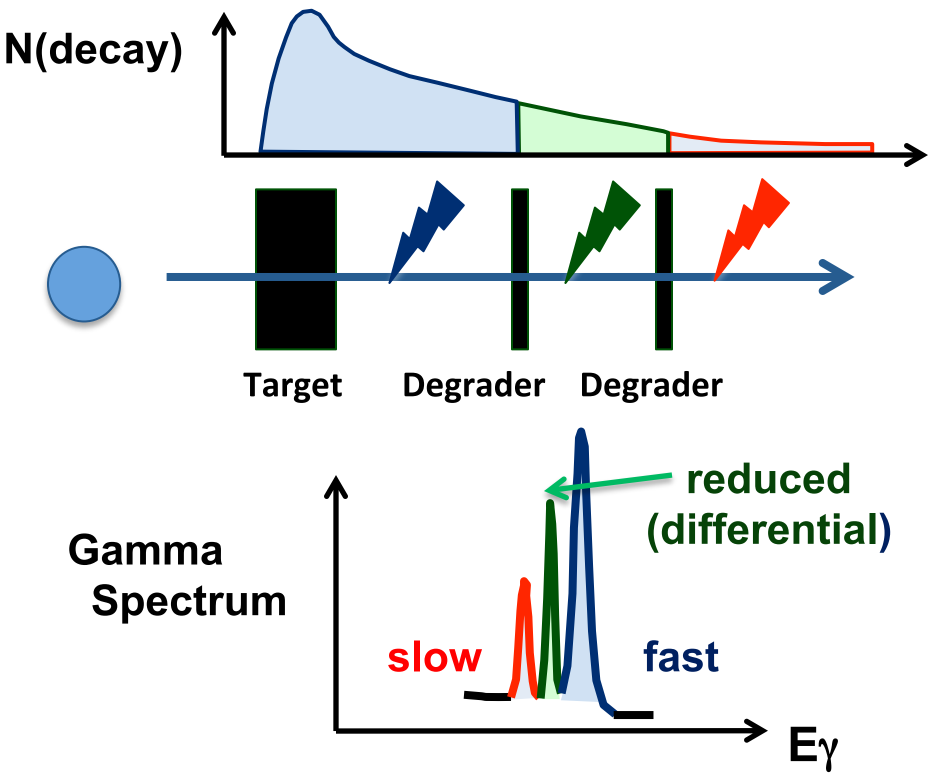
$$\frac{e_p}{e_n} = \frac{M_n}{M_p} = 3.5(9)$$

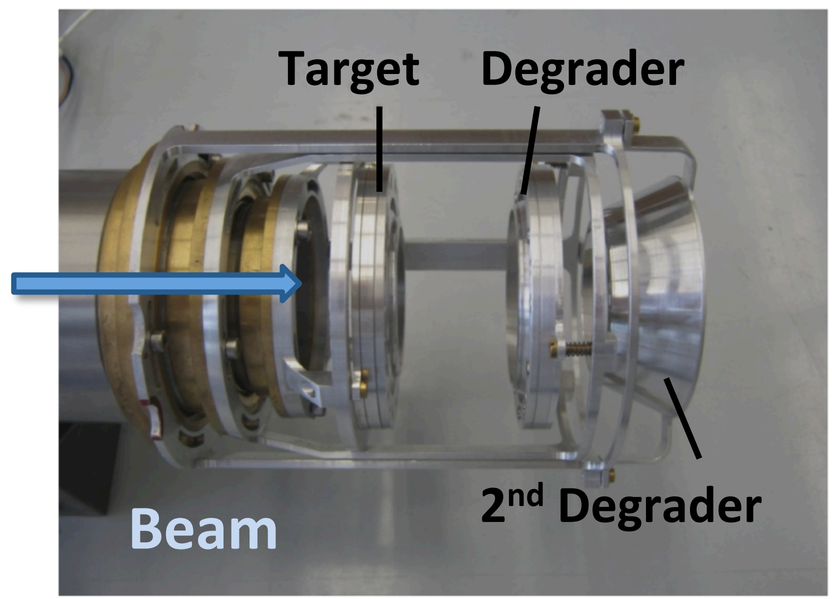
M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Phys. Rev. C 69, 034335 (2004). GXPF1

J. J. Valiente-Dobon, et al. Phys. Rev. Lett. 102, 242502 (2009).

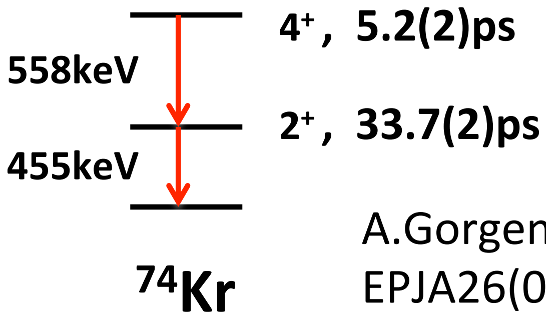
TRIPLEX (TRIple PLUNGER for EXOTIC BEAMS)

Hiro Iwasaki, *et al.*

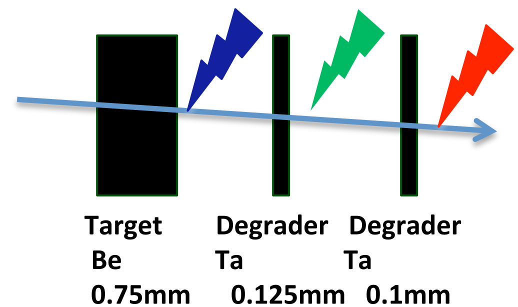


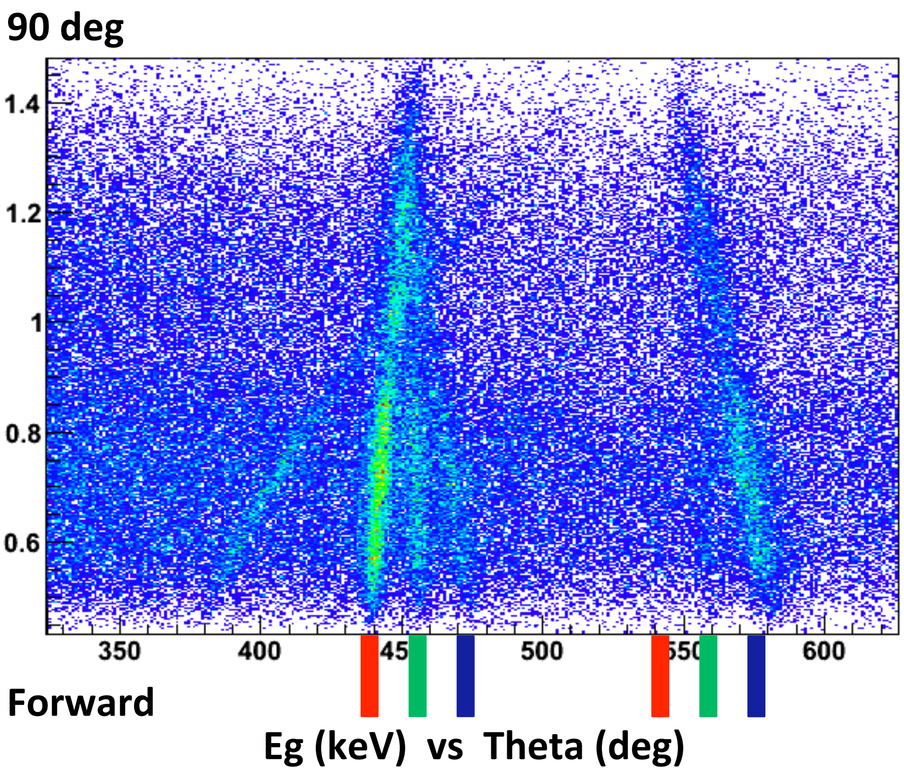


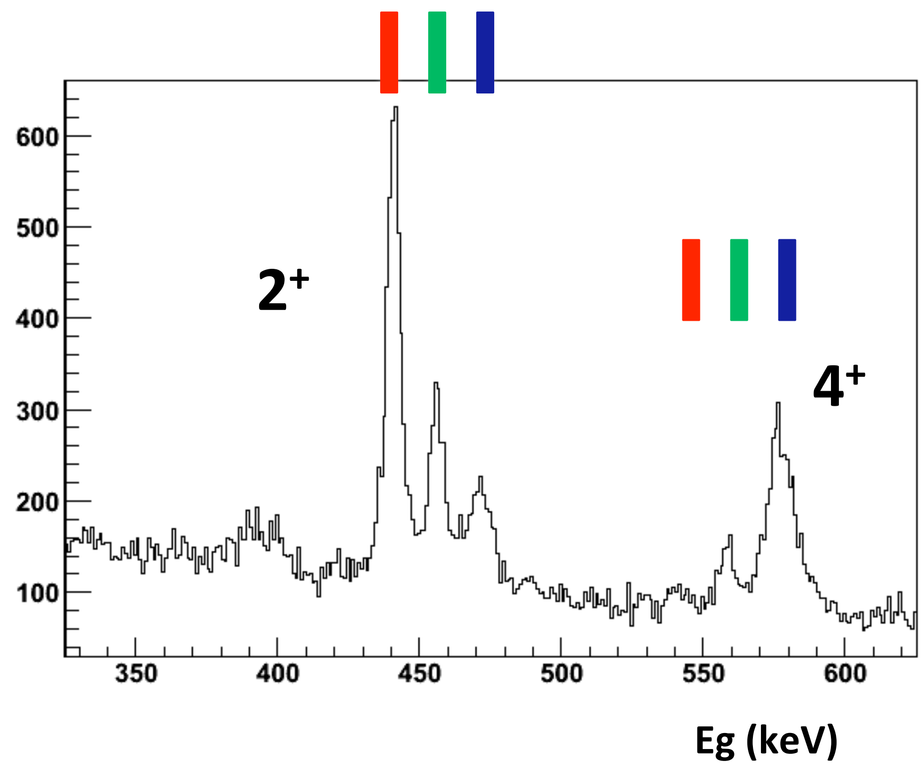
H. Iwasaki, A. Lemasson, *et al.* PRL 112, 142502 (2014)



A.Gorgen et al.
EPJA26(05)153







PRL 112, 112503 (2014) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2014

Nuclear Structure Towards $N = 40$ ^{60}Ca: In-Beam γ-Ray Spectroscopy of ^{58,60}Ti

A. Gade,[1,2] R. V. F. Janssens,[3] D. Weisshaar,[1] B. A. Brown,[1,2] E. Lunderberg,[1,2] M. Albers,[3] V. M. Bader,[1,2] T. Baugher,[1,2] D. Bazin,[1] J. S. Berryman,[1] C. M. Campbell,[4] M. P. Carpenter,[3] C. J. Chiara,[5,3] H. L. Crawford,[4,*] M. Cromaz,[4] U. Garg,[6] C. R. Hoffman,[3] F. G. Kondev,[7] C. Langer,[1,8] T. Lauritsen,[3] I. Y. Lee,[4] S. M. Lenzi,[9] J. T. Matta,[6] F. Nowacki,[10] F. Recchia,[1,†] K. Sieja,[10] S. R. Stroberg,[1,2] J. A. Tostevin,[11] S. J. Williams,[1] K. Wimmer,[12,1] and S. Zhu[3]

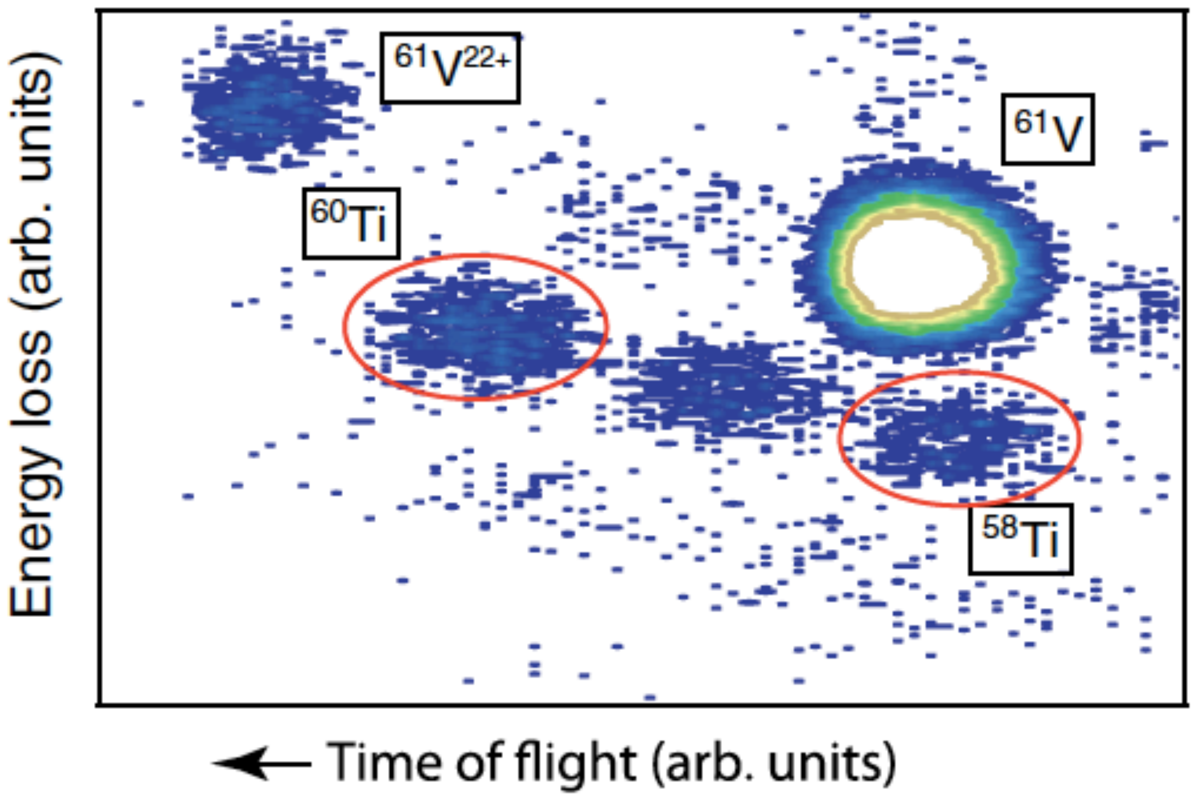
[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[5]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[6]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[7]*Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[8]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[9]*Dipartimento di Fisica e Astronomia dell'Università and INFN, Sezione di Padova, I-35131 Padova, Italy*
[10]*IPHC, IN2P3-CNRS et Université de Strasbourg, F-67037 Strasbourg, France*
[11]*Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, United Kingdom*
[12]*Department of Physics, Central Michigan University, Mt. Pleasant, Michigan 48859, USA*

(Received 31 December 2013; published 21 March 2014)

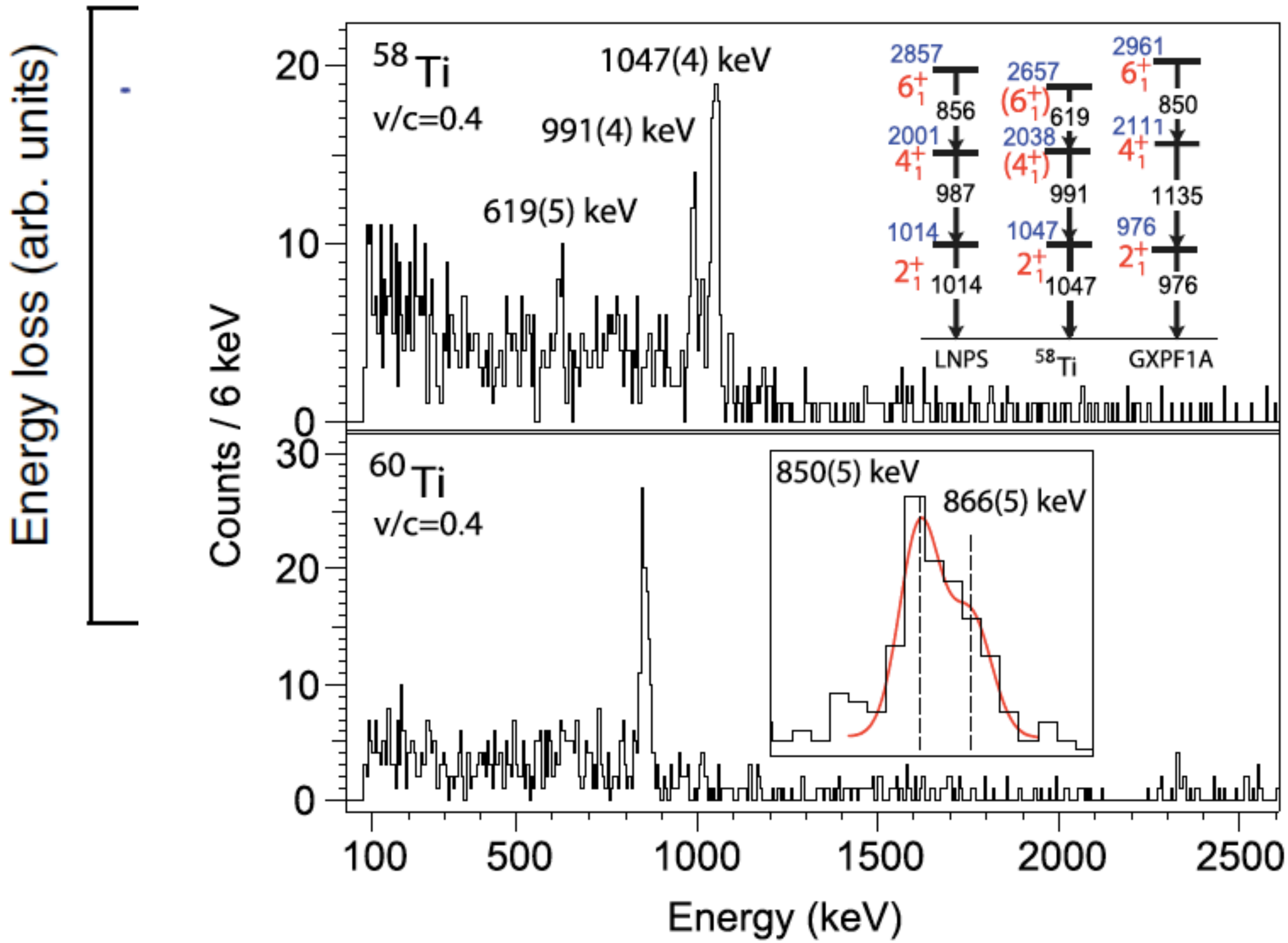
- Region around n-rich nuclei approaching N=40 is subject of rapid shell evolution
- Neutron-rich ^{58,60}Ti are a good testing ground to study shell evolution and unravel the driving forces
- Maybe the closest extrapolation points toward ^{60}Ca

^{58}Ti and ^{60}Ti were produced in the nucleon removal from ^{61}V on a ^{9}Be target

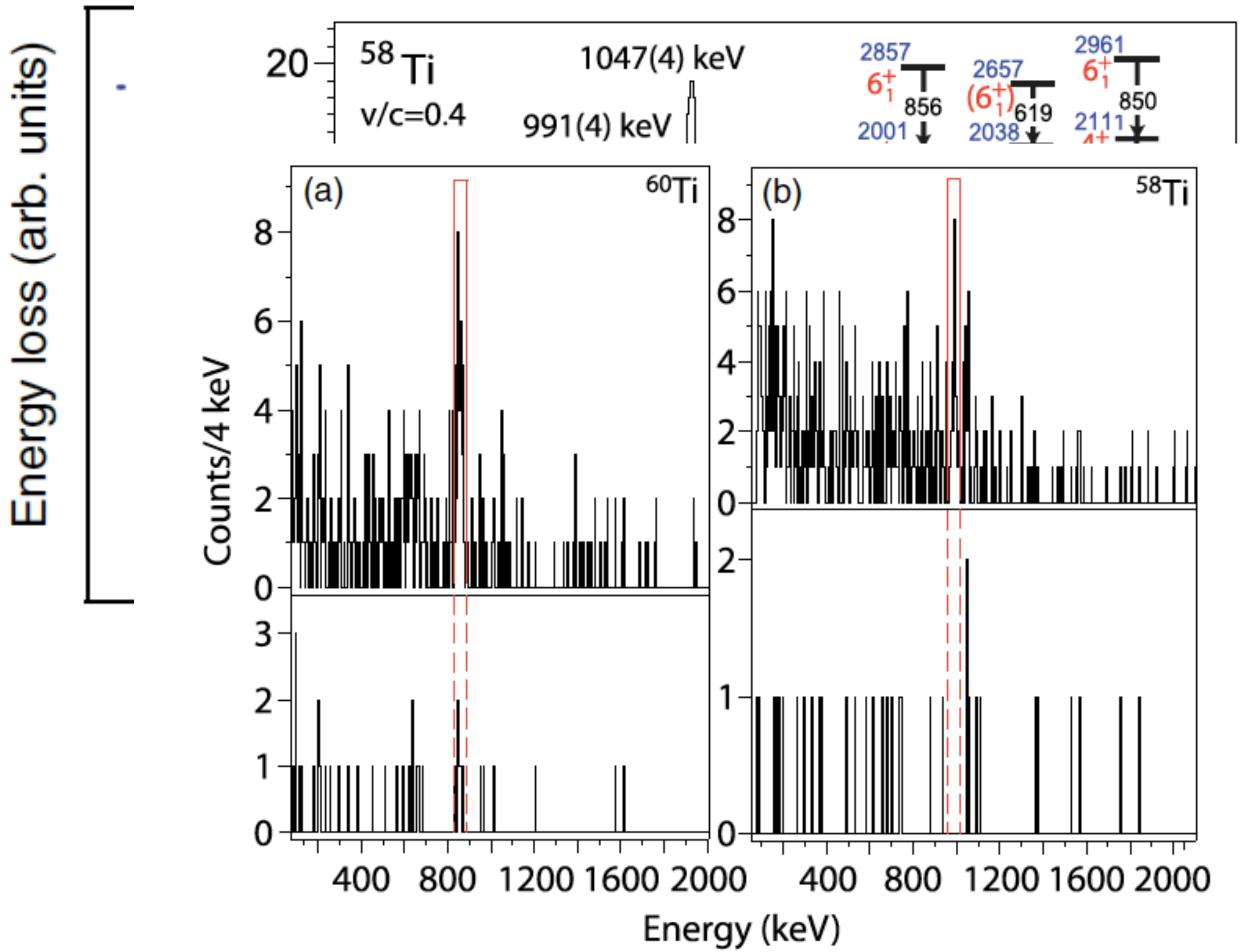
The ^{61}V ions were produced from a 140-MeV/u primary beam of ^{82}Se

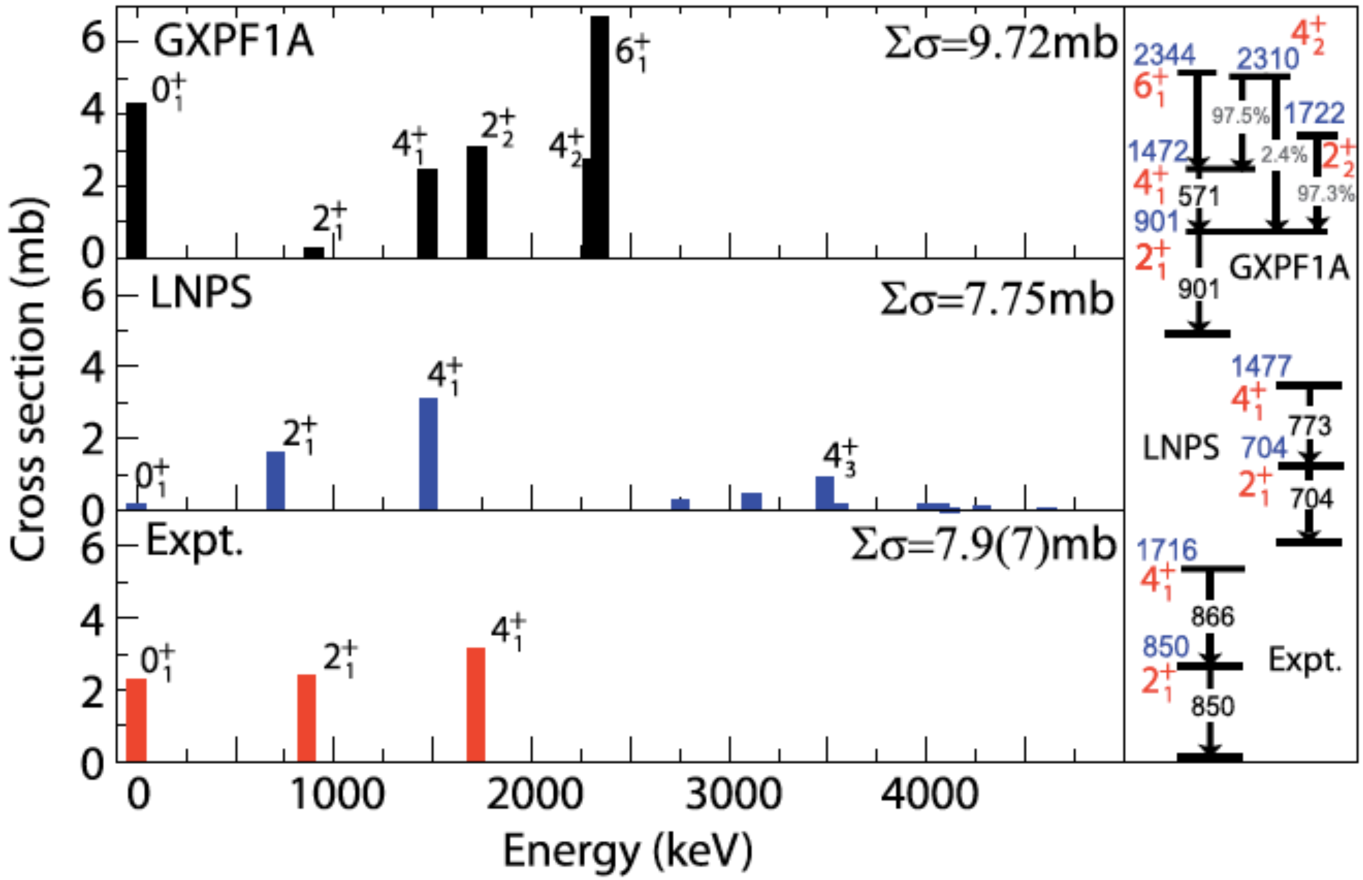


^{58}Ti and ^{60}Ti were produced in the nucleon removal from ^{61}V on a ^{9}Be target

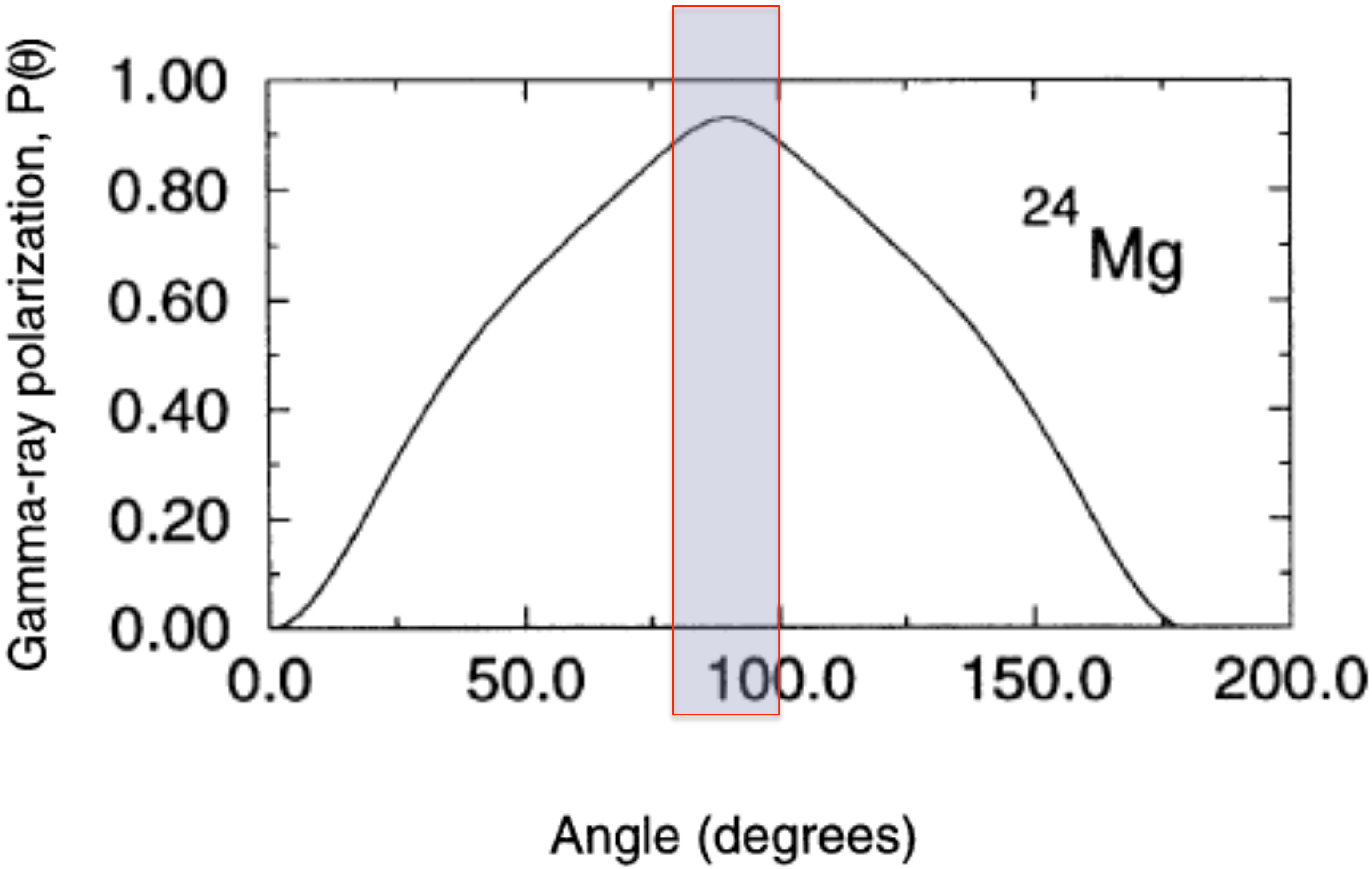


^{58}Ti and ^{60}Ti were produced in the nucleon removal from ^{61}V on a ^{9}Be target

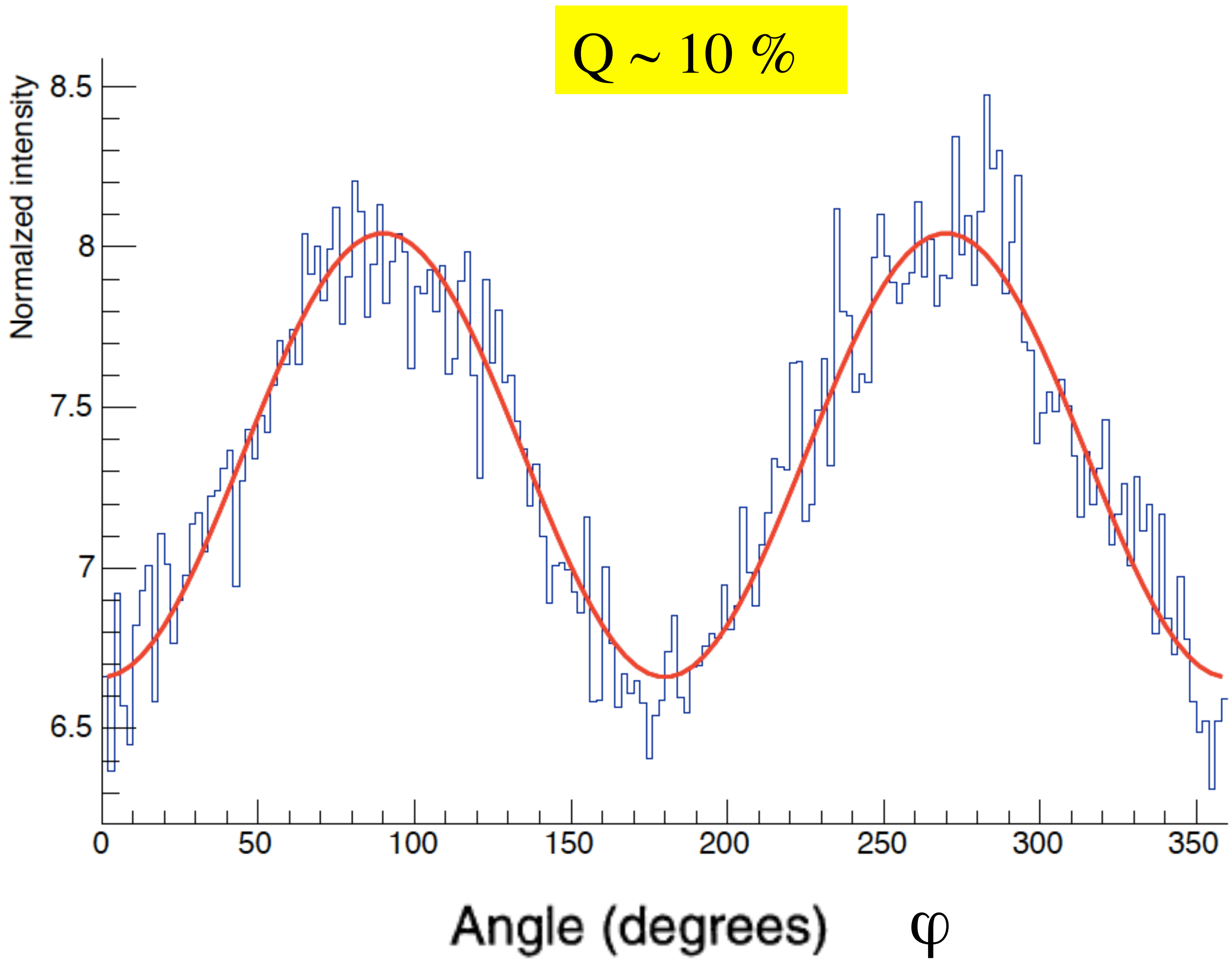


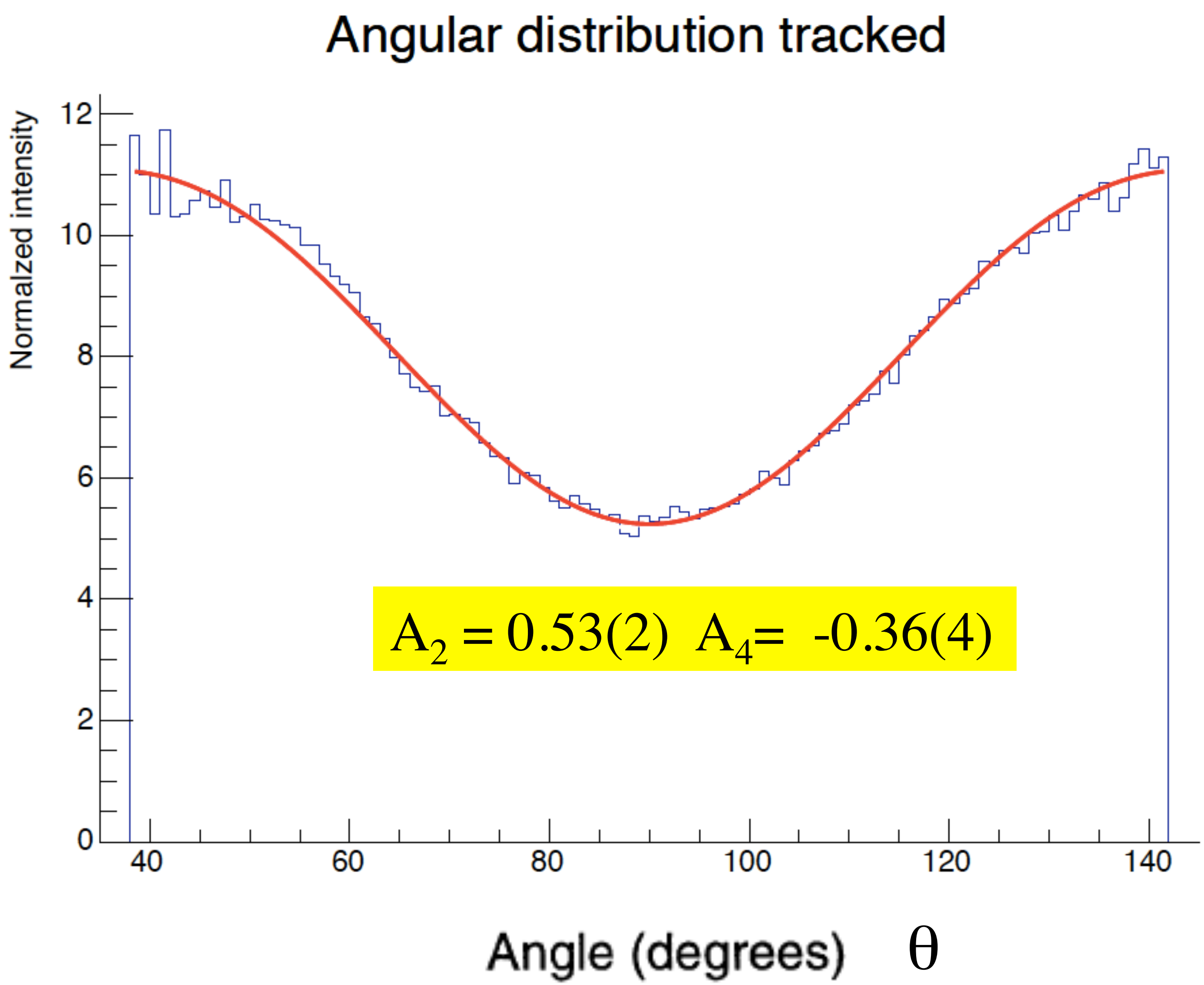


- Calculations restricted to the *fp* shell for neutrons predict many states to be populated in $^{9}Be(^{61}V,^{60}Ti)X$
- Only the shell model calculations with the largest neutron model space correctly predict the strong population of two excited states only
- Excited states in ^{60}Ti and knockout cross sections are closets benchmark yet to ^{60}Ca


Gamma-ray polarization, P(θ)
1.00
0.80
0.60
0.40
0.20
0.00
0.0
50.0
100.0
150.0
200.0
24 Mg
Angle (degrees)

P(90)= 0.956


Q ~ 10 %
Normalzed intensity
8.5
8
7.5
7
6.5
0
50
100
150
200
250
300
350
Angle (degrees) φ


Angular distribution tracked
Normalzed intensity
12
10
8
6
4
2
0
40
60
80
100
120
140
A2 = 0.53(2) A4= -0.36(4)
Angle (degrees) θ

From the Demonstrator to AGATA 1π

Plans for the next few years

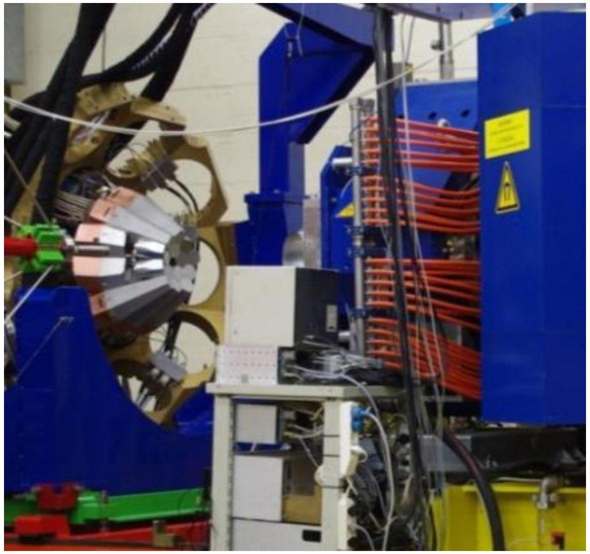
LNL: 2010-2011
15 crystals (5TC)
Total Eff. ~6%

➡

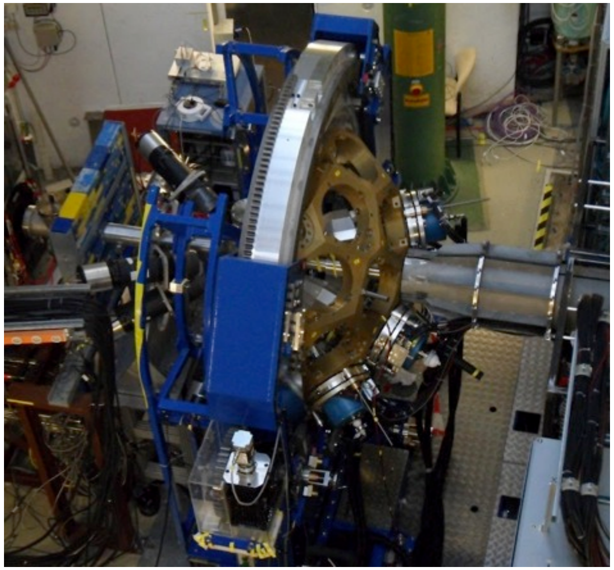
GSI: 2012-2013
25 crystals (5DC+5TC)
Total Eff.~10%

➡

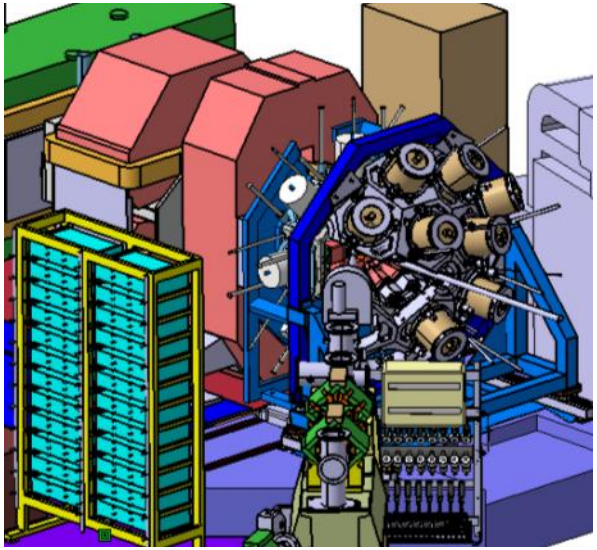
GANIL: 2014-2015
45 crystals (15 TC)
Total Eff. ~15%



Demonstrator + PRISMA



AGATA + FRS



AGATA+VAMOS

Courtesy of Dino Bazzacco