Gamma-ray detection for experiments with fast beams

T. Glasmacher

Michigan State University

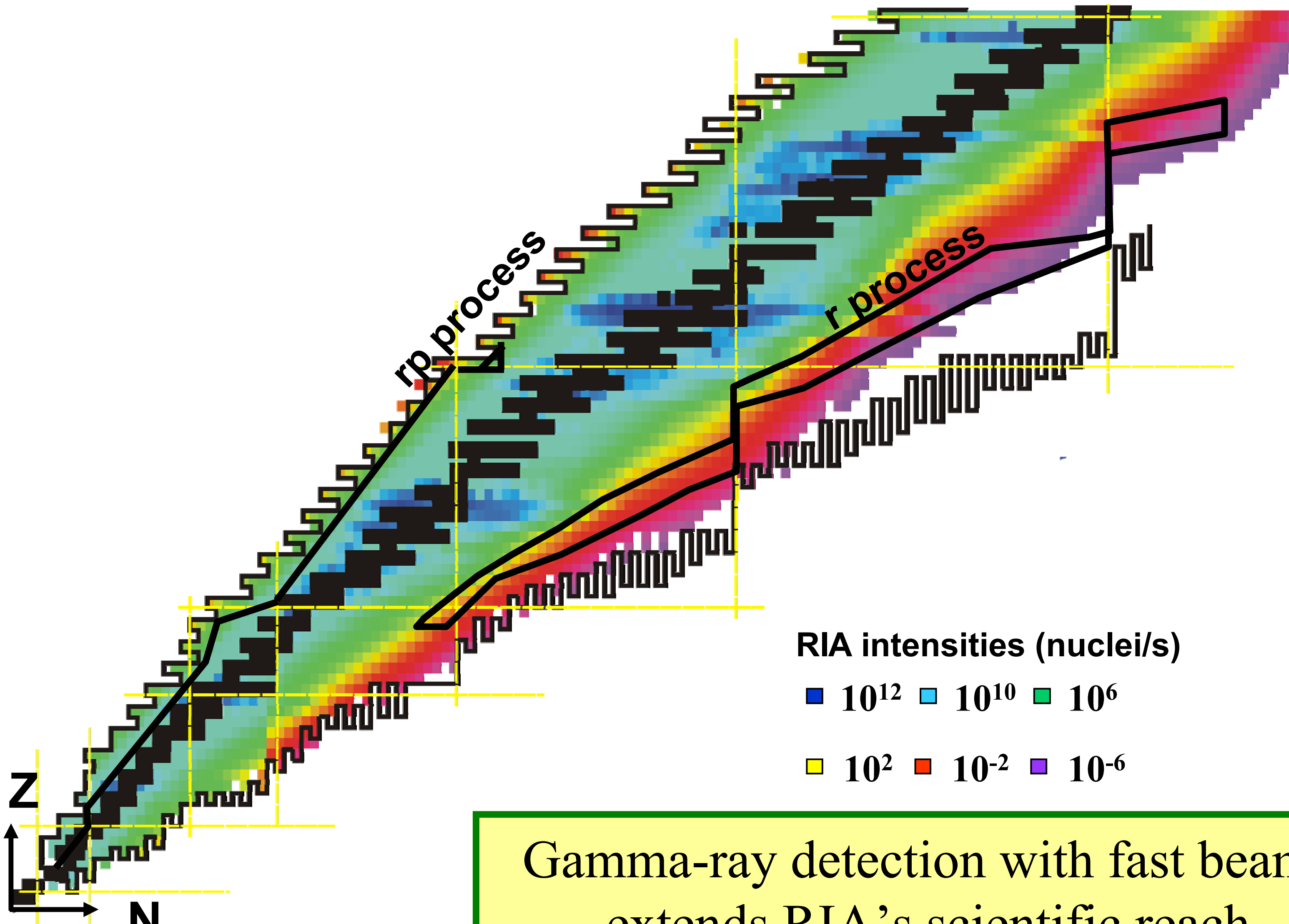
Three “crucial questions”

in the chapter “Atomic Nuclei: Structure and Stability” of the 2002 Long-Rang Plan for Nuclear Science (p. 38)

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

Experiments detecting gamma-rays from fast exotic beams will contribute to answering two of them

The Scientific Reach of RIA



Gamma-ray detection with fast beams extends RIA's scientific reach

Reactions with fast beams and thick targets

Need to optimize $N_{reactions} = \sigma \cdot N_{target} \cdot N_{beam}$

Cross section σ

• Coulex (A=40)	20–100 mbarn
• Coulex (A=150)	100–1000 mbarn
• Proton scattering	2-20 mbarn
• 1-nucleon knockout	10-30 mbarn
• 2-nucleon knockout	1-5 mbarn

N_{beam}

All there is	0.1 Hz – 100 Hz

N_{target}

• Hydrogen	$1.32 \cdot 10^{23} – 6.6 \cdot 10^{23}$ (200-1000 mg/cm^2)
• Gold	$6.7 \cdot 10^{20} – 3.35 \cdot 10^{21}$ (200-1000 mg/cm^2)

New spectroscopy methods developed for fast beams

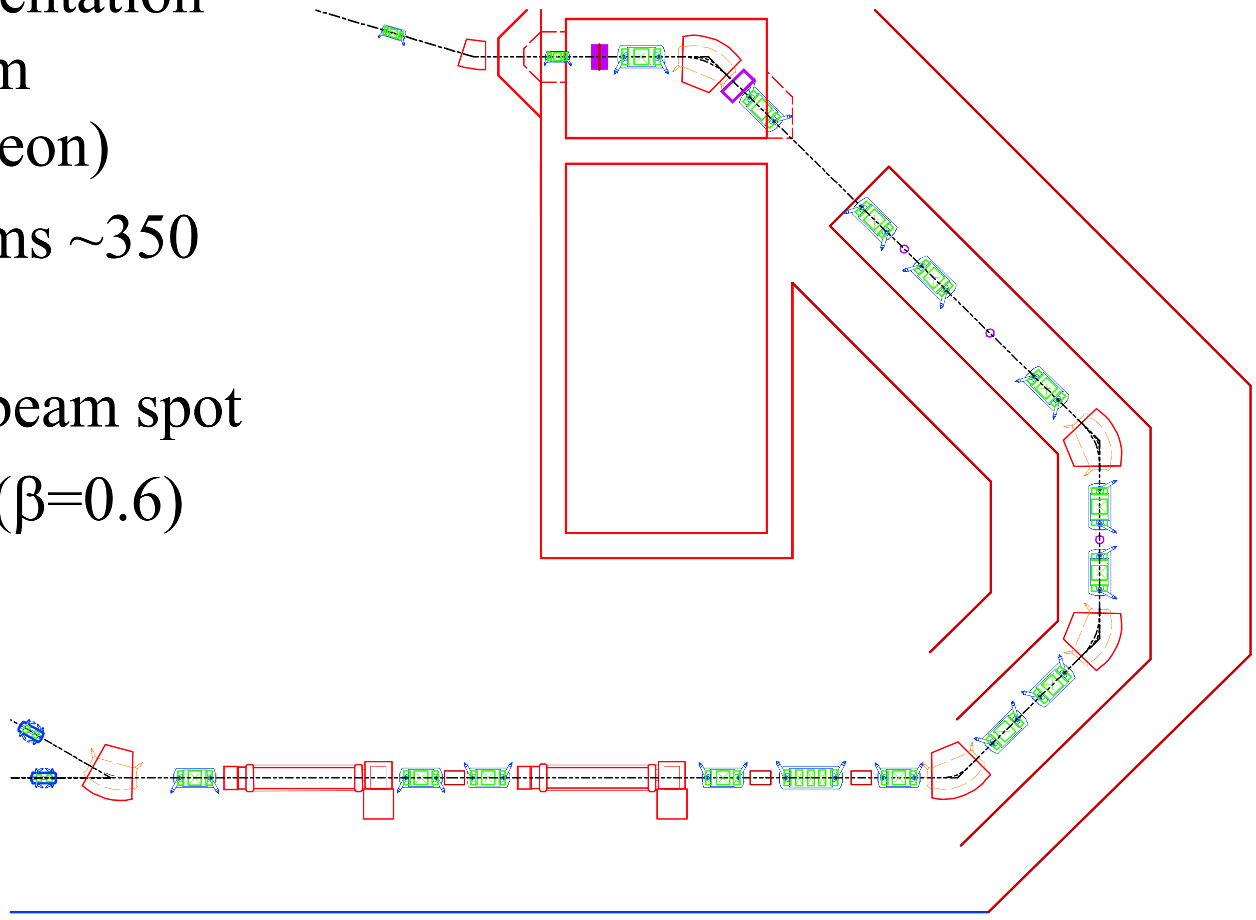
- Inelastic scattering in inverse kinematics
  - Coulomb excitation
  - Proton scattering
  - Alpha scattering
  - ➢ Excited state energies, reduced transition matrix elements
- In-beam fragmentation
  - ➢ Excited state energies
- One- and two-nucleon-knockout reactions as spectroscopy tools
  - ➢ Spectroscopic factors

Need modular detector to accommodate particle detectors

Fast exotic beams

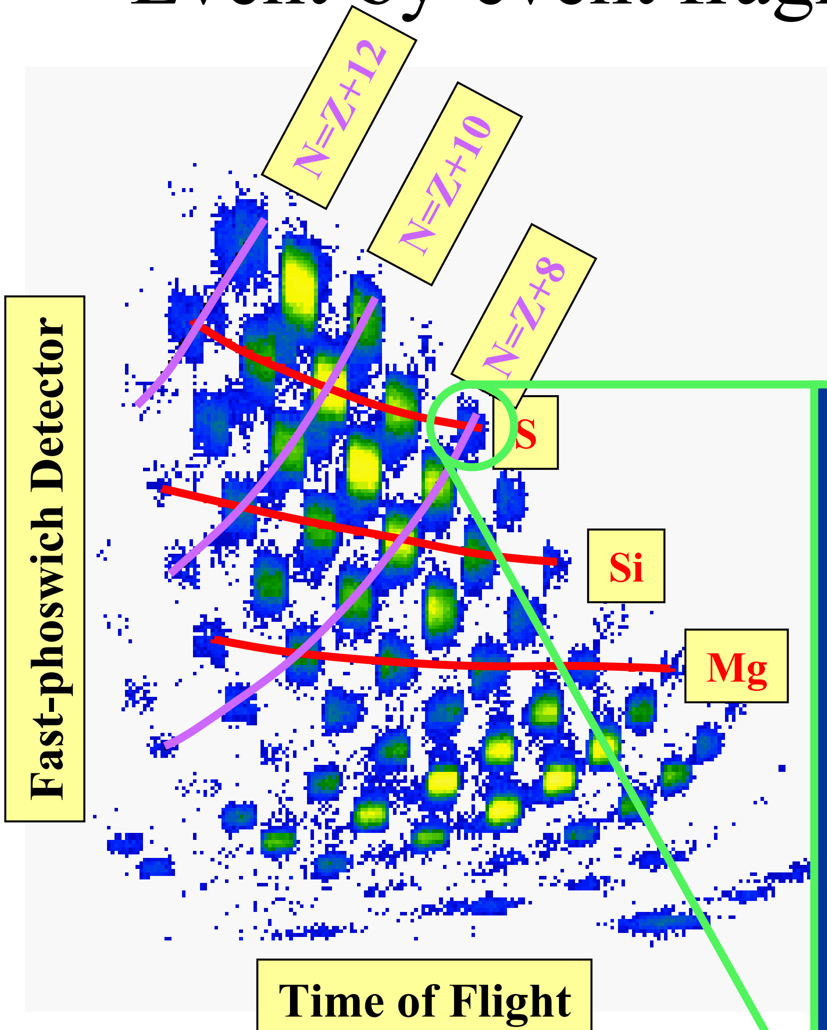
Separation by physical means

- Made by fragmentation of primary beam (400 MeV/nucleon)
- Secondary beams ~350 MeV/nucleon
- Possibly large beam spot
- Large velocity (β=0.6)
- Event-by-event identification
- Energy spread ($\Delta p/p$ = 6%)

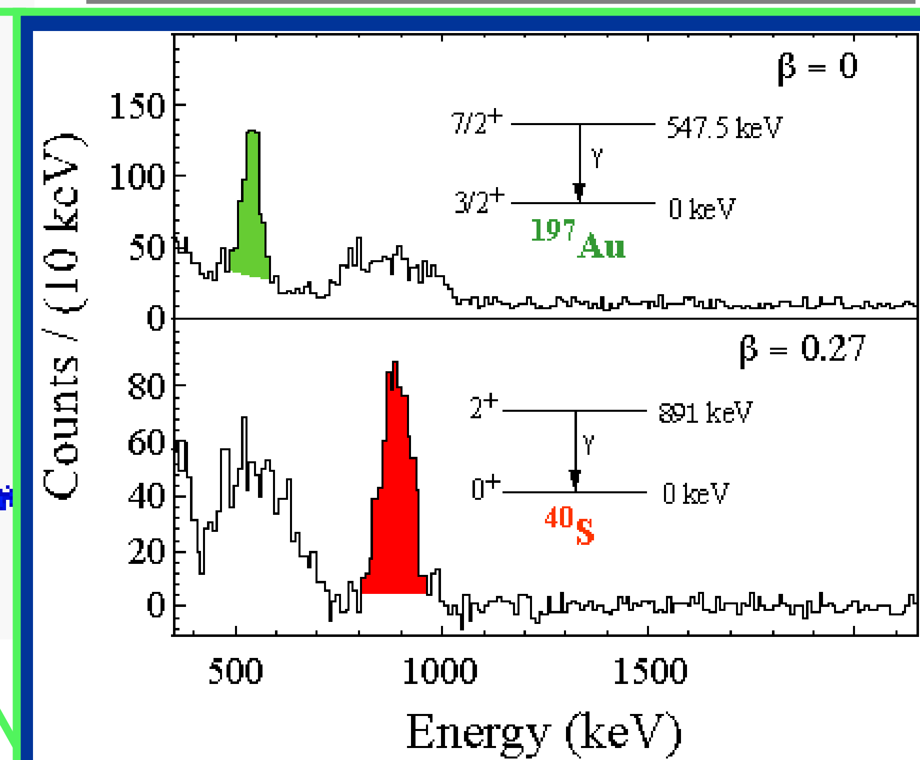


Need modular gamma detector to accommodate beam profile

Event-by-event fragment identification



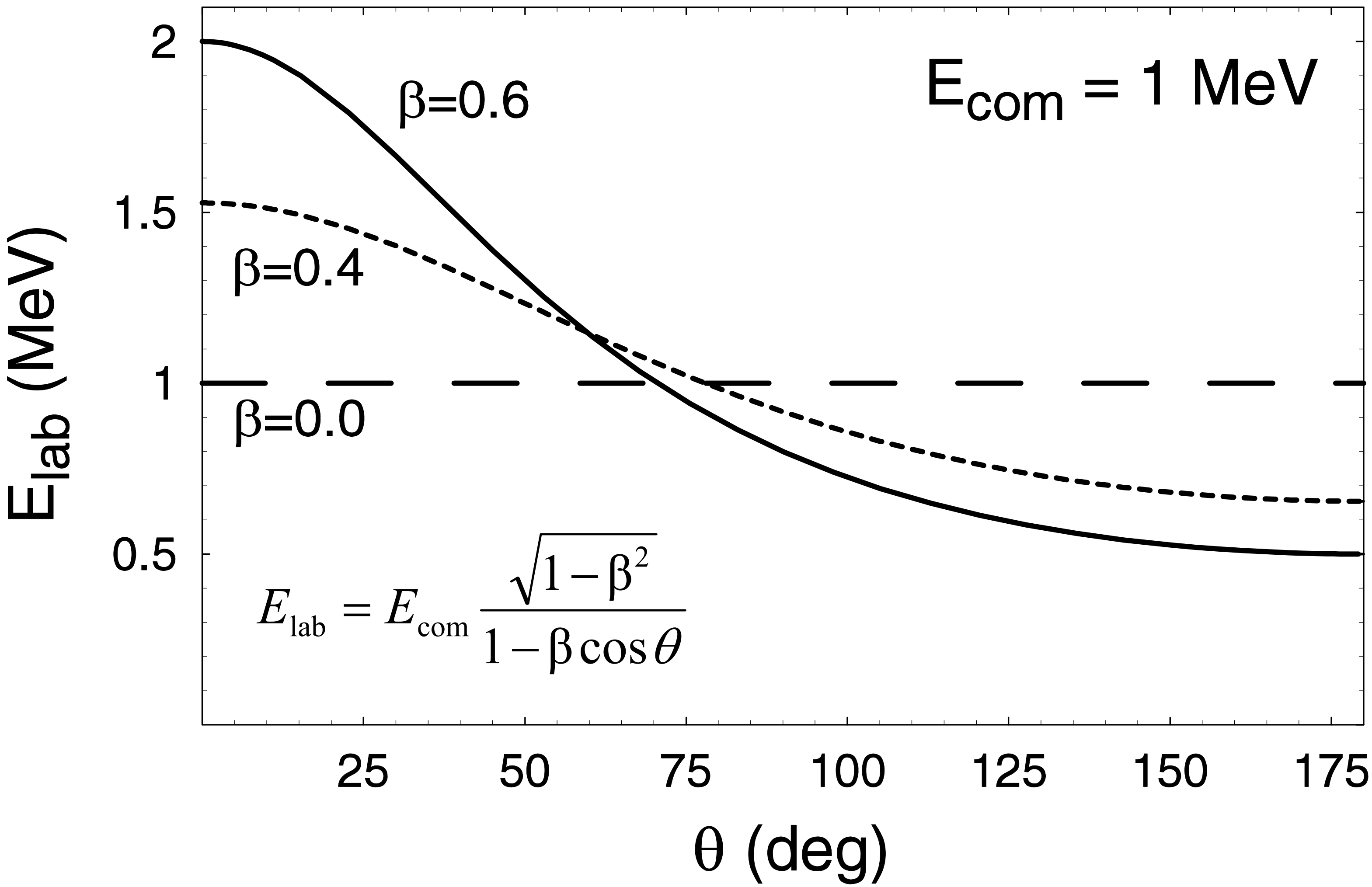
- $^{48}Ca^{12+}$, 70 MeV/nucl.
- Targets:
  - production ^{9}Be 285 mg/cm^2
  - secondary ^{197}Au 537 mg/cm^2
- $\Delta p/p = 1\%$



H. Scheit et al. Phys. Rev. Lett. 77 (1996) 3967.

Need fragment-gamma coincidence: the better—the cleaner

Large beam velocity Significant Dopplershift



Need twice the dynamic range compared to low-energy beams

Contributions to achievable energy resolution

Four major contributions to final energy resolution of photon spectrum emitted from a fast ($\beta \approx 0.4$) source:

a) Intrinsic energy resolution of detector
   $\rightarrow$ detector material

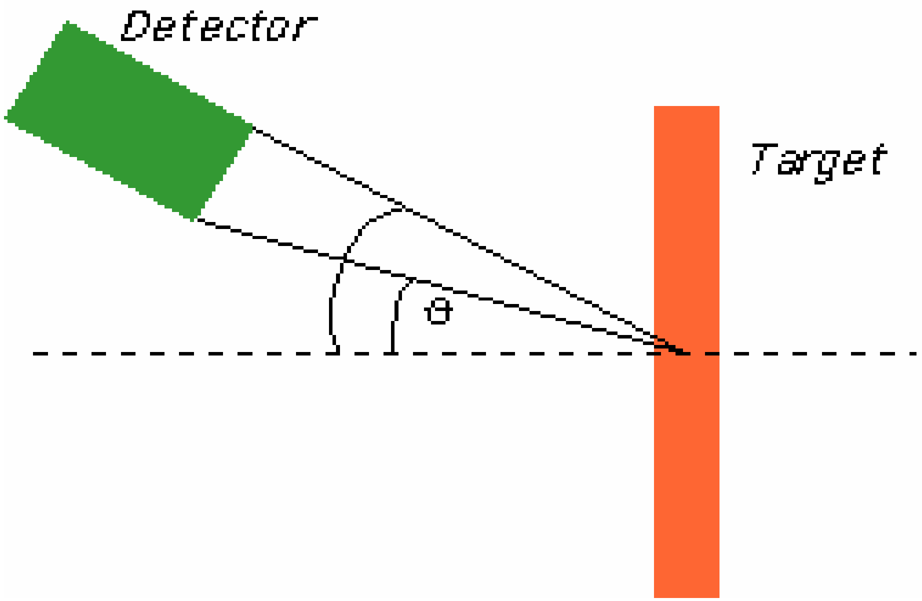
b) Doppler broadening due to finite opening angle of detector
   $\rightarrow$ detector granularity and distance from target

c) Doppler broadening due to slowing down of projectile in target
   $\rightarrow$ target thickness (and element)

d) Doppler broadening due to angular spread of projectile caused by scattering in target
   $\rightarrow$ target thickness (and element)

Doppler broadening due to finite opening angle of detector

$$E_\gamma = E_\gamma^{proj} \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$



Doppler broadening due to slowing down of projectile in target

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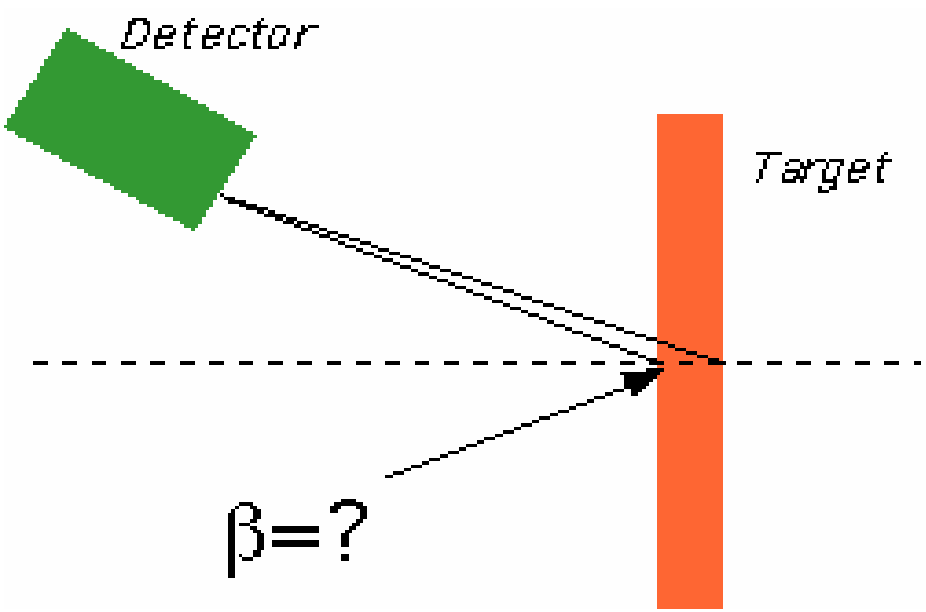


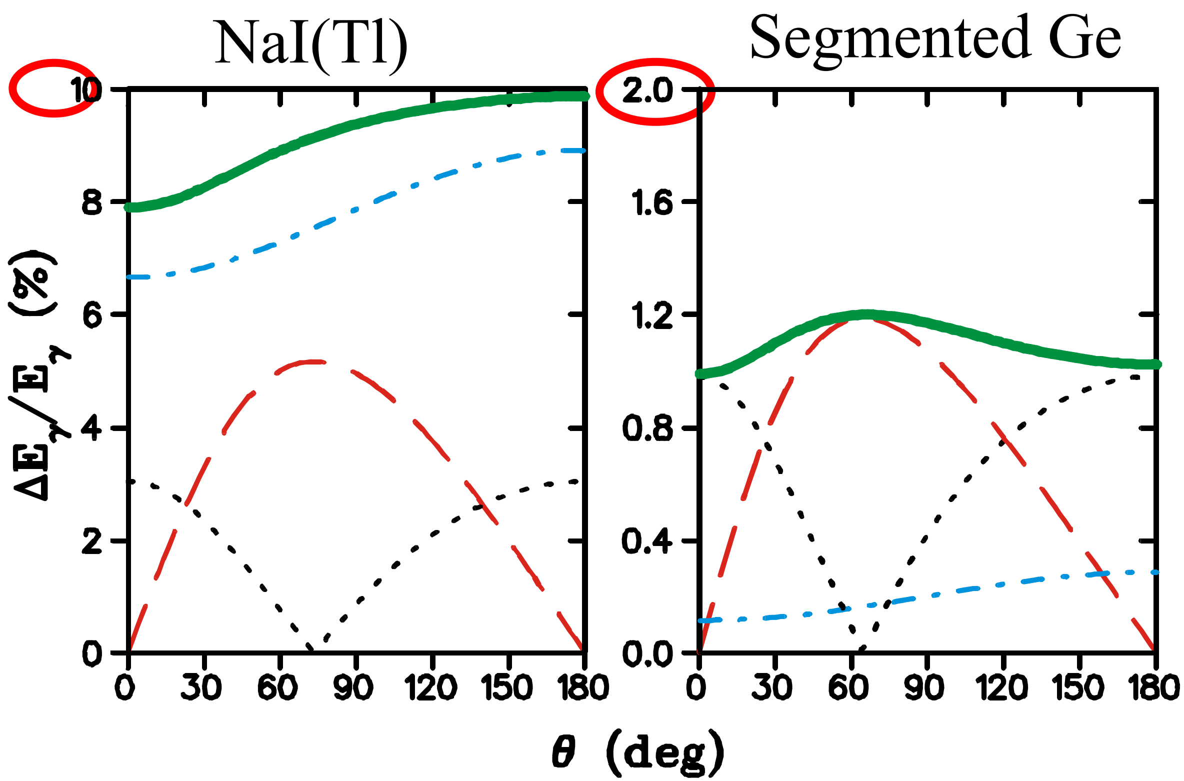
Limits on achievable energy resolution

$$\left(\frac{\Delta E_\gamma}{E_\gamma}\right)^2 = \left(\frac{\beta \sin\theta}{1-\beta\sin\theta}\right)^2 (\Delta\theta)^2 + \left(\frac{\cos\theta - \beta}{(1-\beta^2)(1-\beta\cos\theta)}\right)^2 (\Delta\beta)^2 + \left(\frac{\Delta E_{intr}}{E_\gamma}\right)^2$$

- $\Delta\theta$ is determined by detector's ability to reconstruct first γ-ray interaction point
- $\Delta\beta$ is determined by target thickness
- ΔE is determined by detector
- Old new paradigm for fast beam experiments with non-4π γ-ray detectors:
  Experimenter trades energy resolution ($\Delta\theta$) versus efficiency

For RIA, build large-coverage detector with sufficient spatial and energy resolution

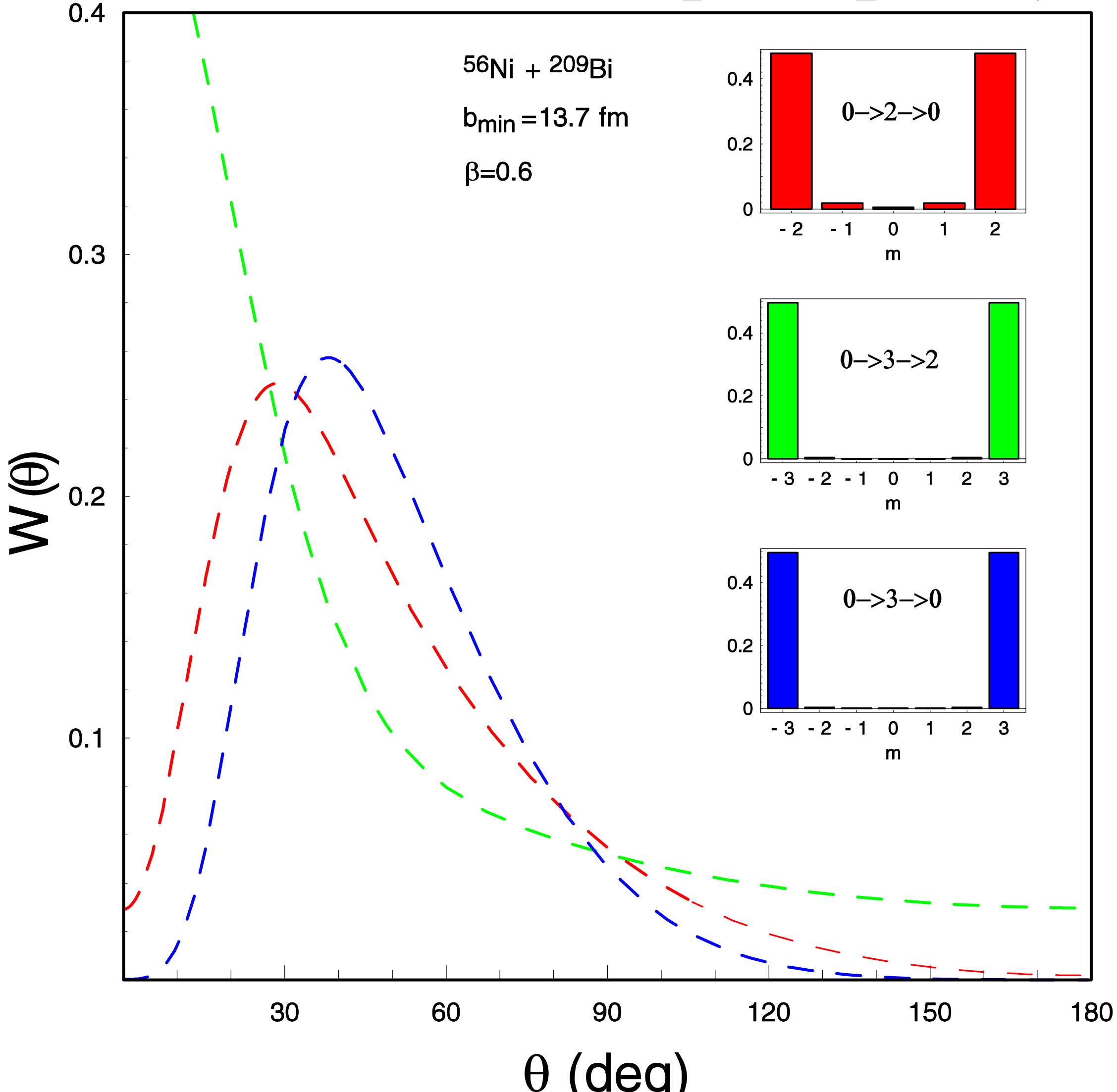
Segmented Ge Detectors vs NaI(Tl)



Resolution comparison:
Total
ΔE in target
Opening angle
Intrinsic

Final energy resolution is of the order of 1% with target of order few 100 mg/cm^2
→ detector should have similar or better resolution
→ Energy resolution of ~1% or better
→ Angular resolution of ~ 10 mrad

Angular distribution of dipole and qudrupole γ-rays

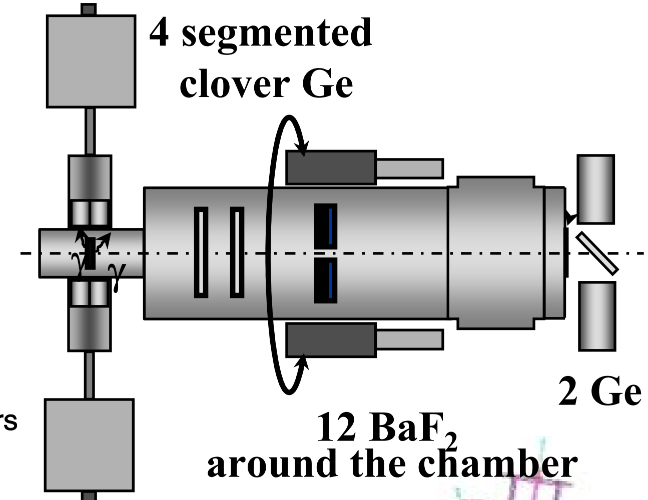


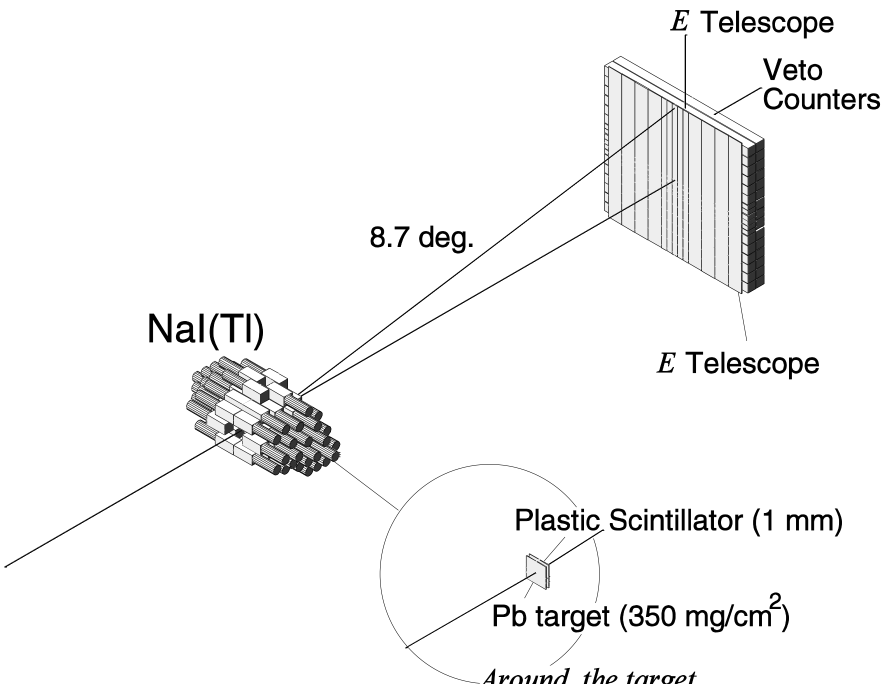
- Example: Coulomb excitation

Gamma-ray flux is forward focused, need high 2-3π detector with granularity in front.

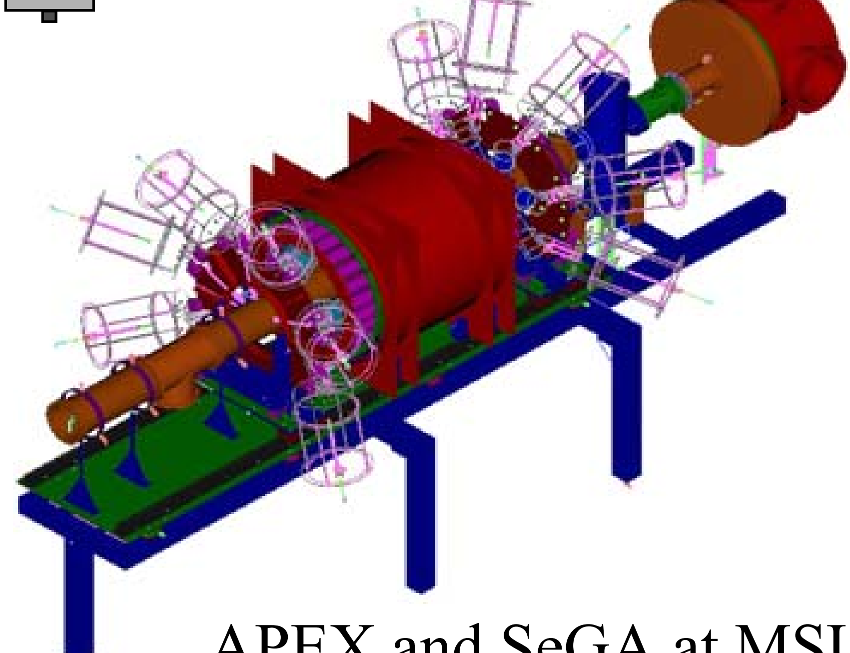
Examples of existing (scintillation) detectors

GANIL





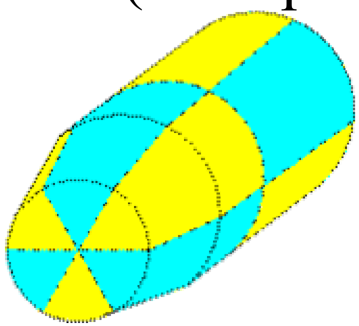
DALI at RIKEN



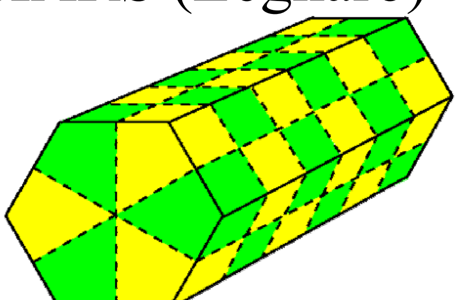
APEX and SeGA at MSU

Some 3-D segmented Germanium detectors

- GRETA (Lawrence Berkeley Laboratory)
- PT6x2 (Liverpool)

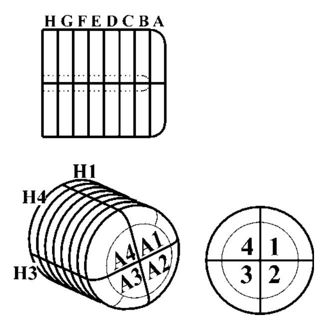


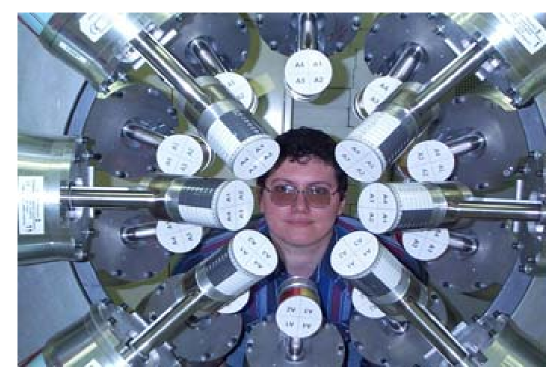
- MARS (Legnaro)



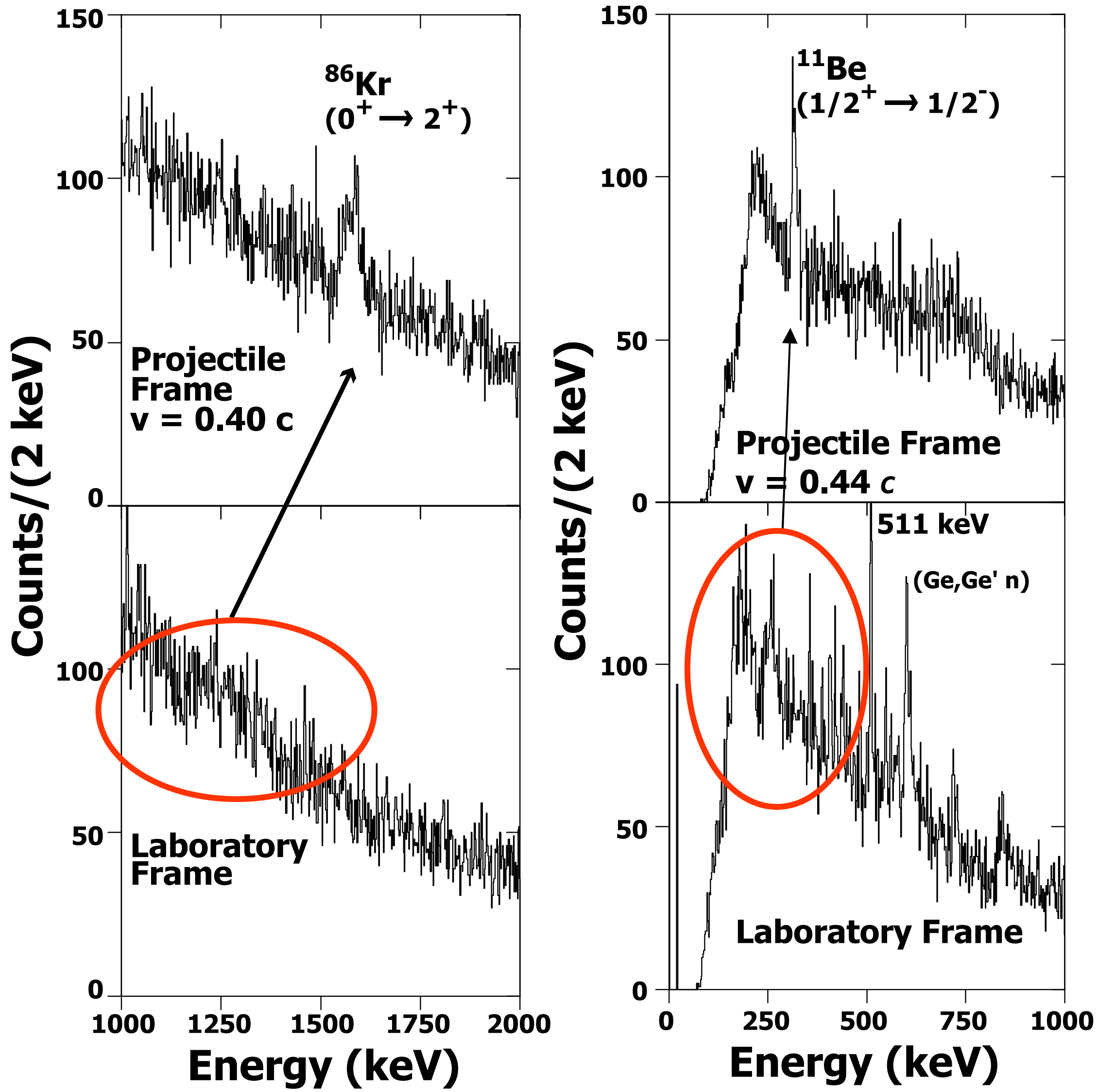
- Cluster (Germany/Belgium)

- 32-fold (SeGA at MSU)





Fast beams and Germanium detectors work together
Example SeGA: ^{86}Kr and ^{11}Be

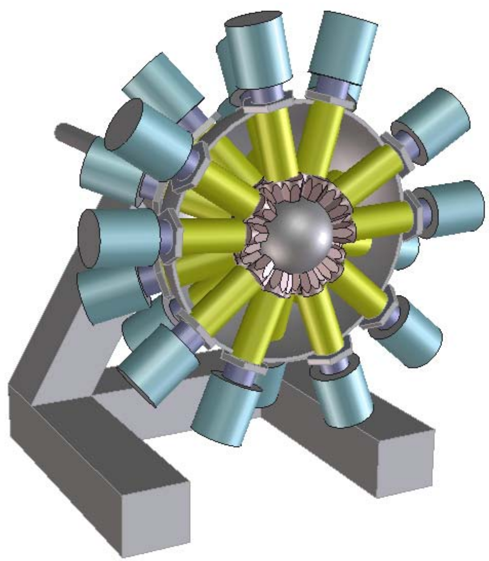


- Six detectors at 109° 14 cm from target
- Details for ^{86}Kr
  - 12.04 GeV primary beam degraded to 7.1 GeV
  - Gold secondary target; 184 mg/cm^2
  - 4.5 hours
- Details for ^{11}Be
  - 2.24 GeV primary beam
  - Gold secondary target 968 mg/cm^2
  - 6.5 hours

Summary

- Detector requirements
  - Efficiency, dynamic range, energy resolution, angular resolution, timing characteristics, modularity, coverage

HPGe based GRETA



Well-developed concept

Array of room-temperature semiconductor detectors

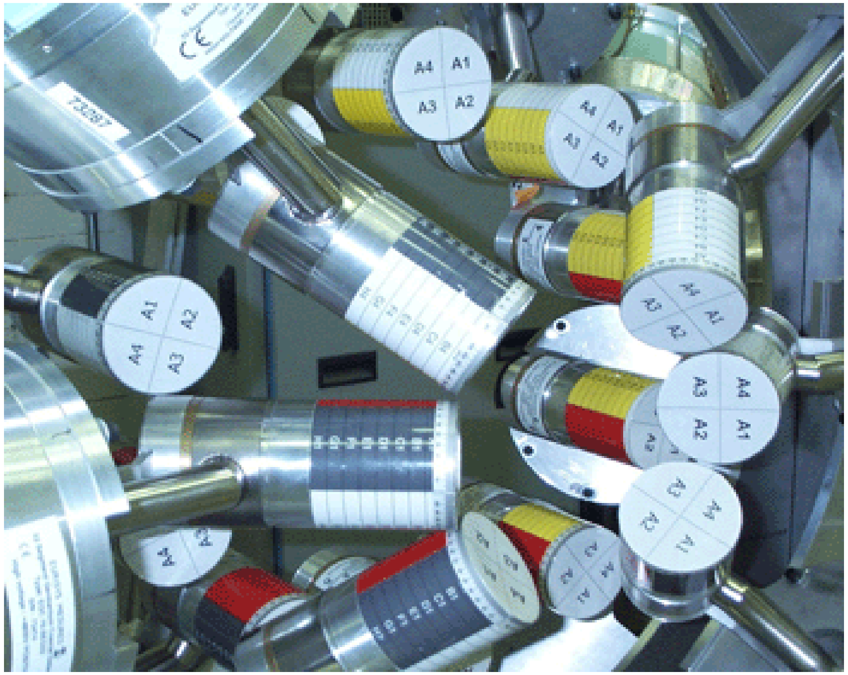
CZT (2.5 times as efficient as NaI)

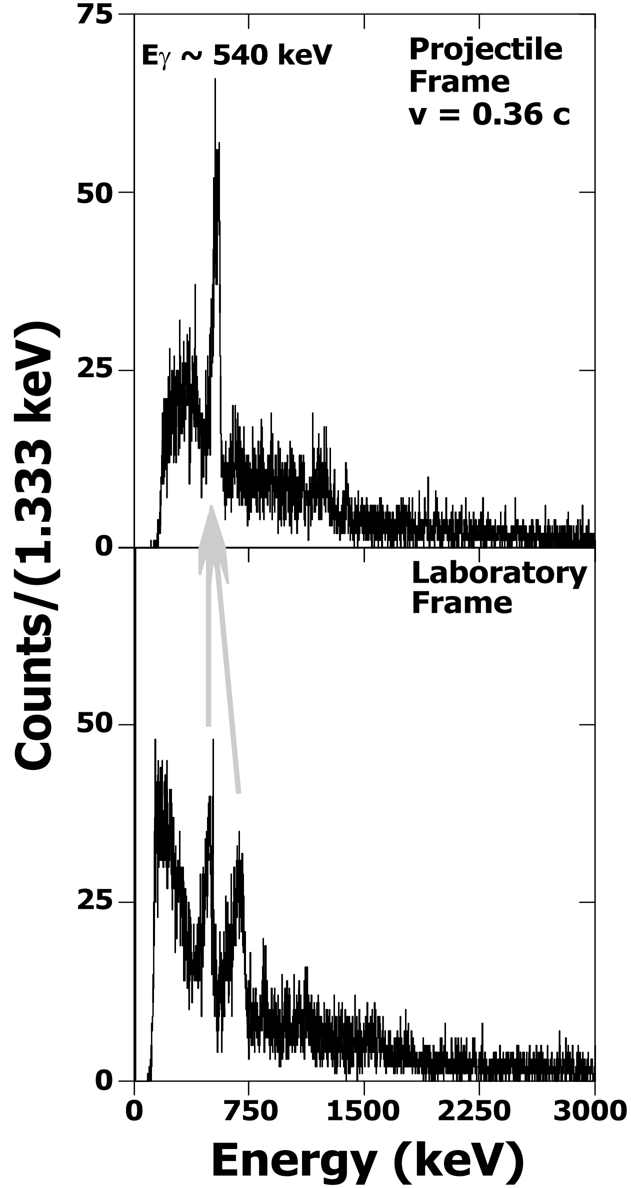
HgI_2 (5 times as efficient as NaI)

(Friday morning: Auxiliary detectors and new concepts in gamma detection)

Under initial investigation

1n knockout with SeGA ^{46}Ar(Be,^{45}Arγ)



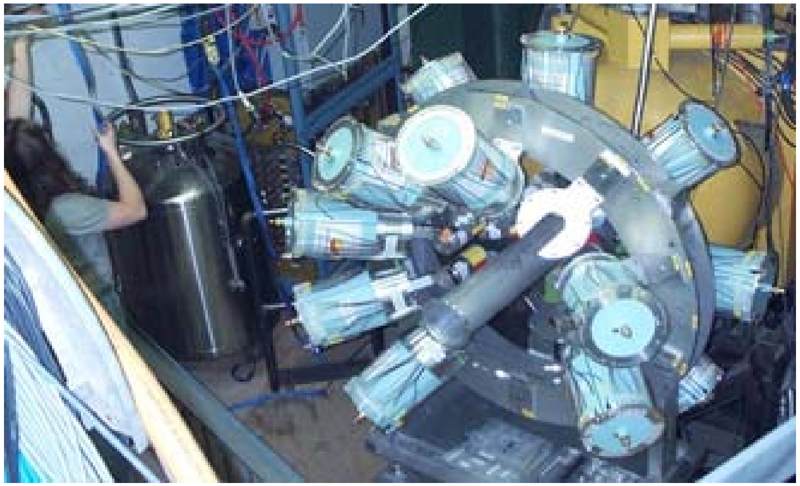


140 MeV/nucleon ^{40}Ar from CCF →
90 MeV/nucleon ^{46}Ar

NSCL

Segmented Germanium Array (SeGA)

Largest operational array of highly-segmented germanium detectors for fast beam experiments



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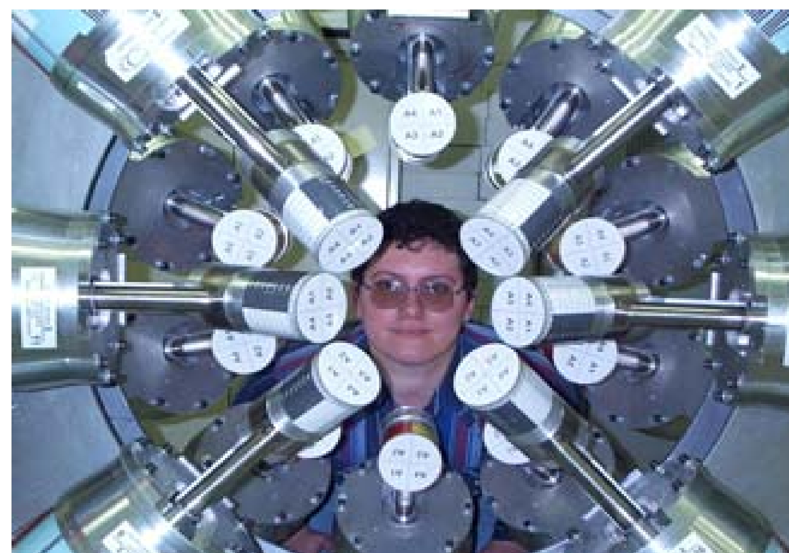
NSF

W. Mueller *et al*. Nucl. Instr. Meth. **A 466** (2001) 492.
Z. Hu *et al*. Nucl. Instr. Meth. **A 482** (2002) 715.
K.L. Miller *et al*., Nucl. Instr. Meth. **A 490** (2002) 140.



Two-proton knockout on neutron-rich nuclei around N=16 and N=20

Joachim Enders, P. Gregers Hansen

- N=16 $^{9}Be(^{28}Mg, ^{26}Ne+\gamma)X$
- N=20 $^{9}Be(^{34}Si, ^{32}Mg+\gamma)X$
- Access spectroscopy information of very neutron-rich nuclei
- Cross sections smaller than one-neutron knockout but outweigh secondary beam production cross sections
  - For example, compare ^{27}Ne (1μb) to ^{28}Mg (1.5mb) from ^{40}Ar

- Mostly one-step process
  - Competing two-step process involves proton evaporation
  - Due to binding energies and Coulomb barrier, the neutron evaporation channel opens first