Large gamma-ray detector arrays and electromagnetic separators

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γ-ray spectroscopy with separators

1) Prompt Spectroscopy
   - Gamma-ray detectors at target position
   - Tag on recoils at focal plane of separator
2) Decay Spectroscopy
   - Implant recoil in focal plane detector
   - Identify decays of recoil (proton, alpha, electron)
   - Detector gamma-rays in coincidence with decay

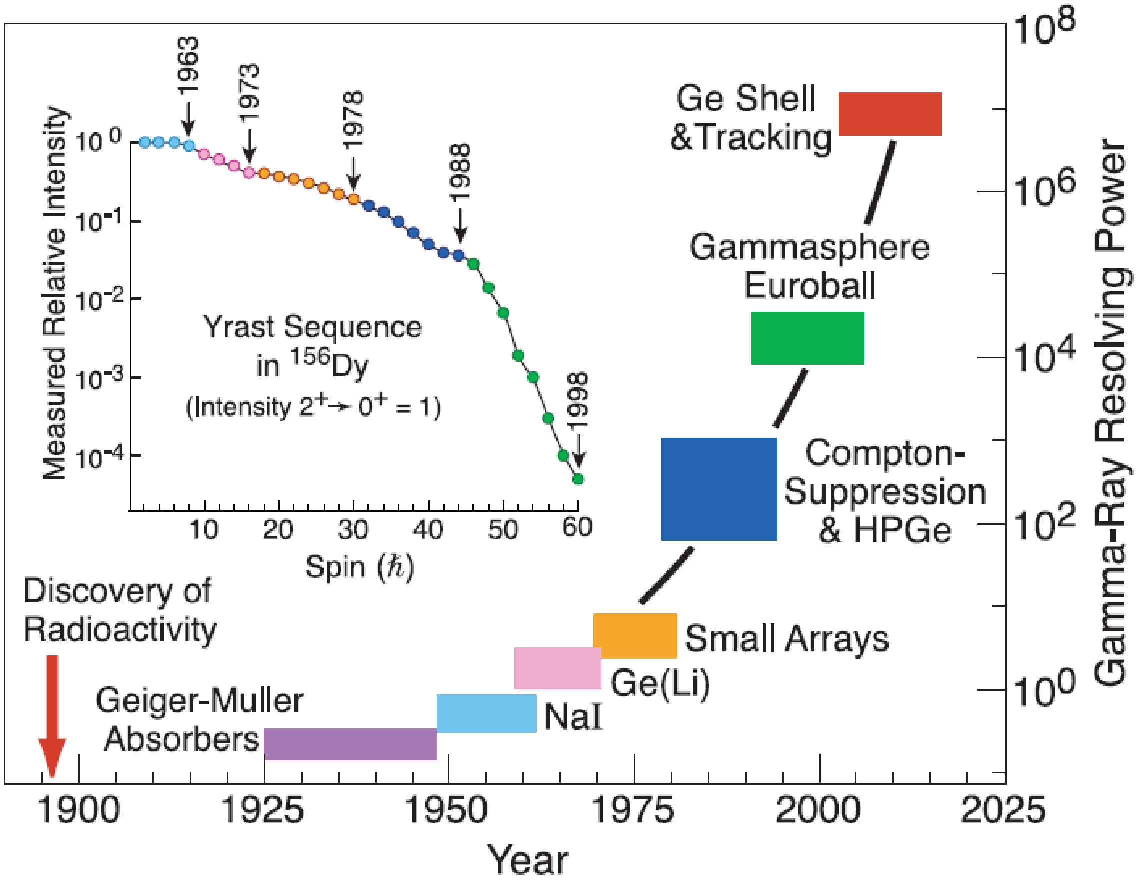
γ-ray detectors provide

Level energy
γ-ray multipolarity
Electromagnetic moments
Lifetime

Separators provide

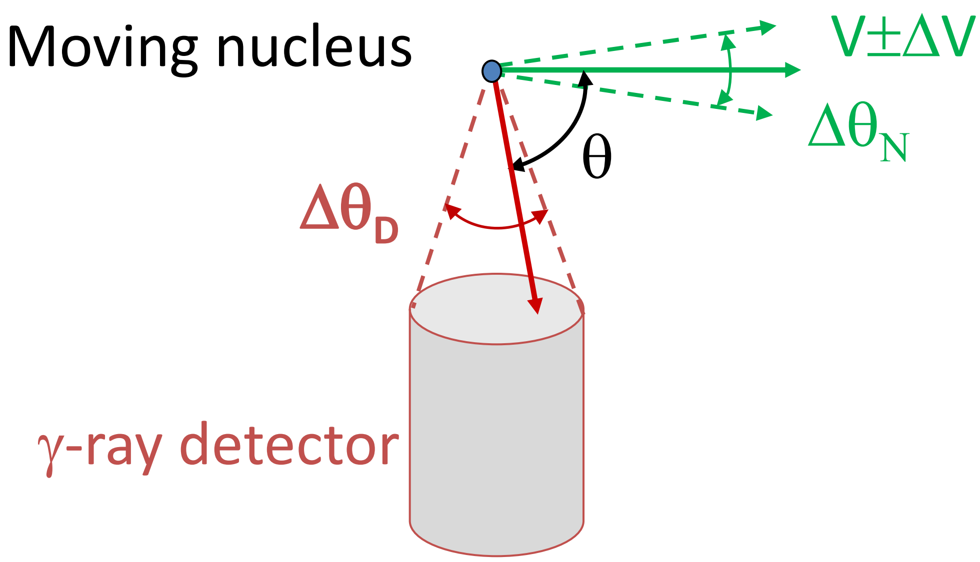
Mass measurements/separation
Z identification
Velocity vector

γ-ray array development



- **The resolving power is a measure of the ability to observe faint emissions from rare and exotic nuclear states.**

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:

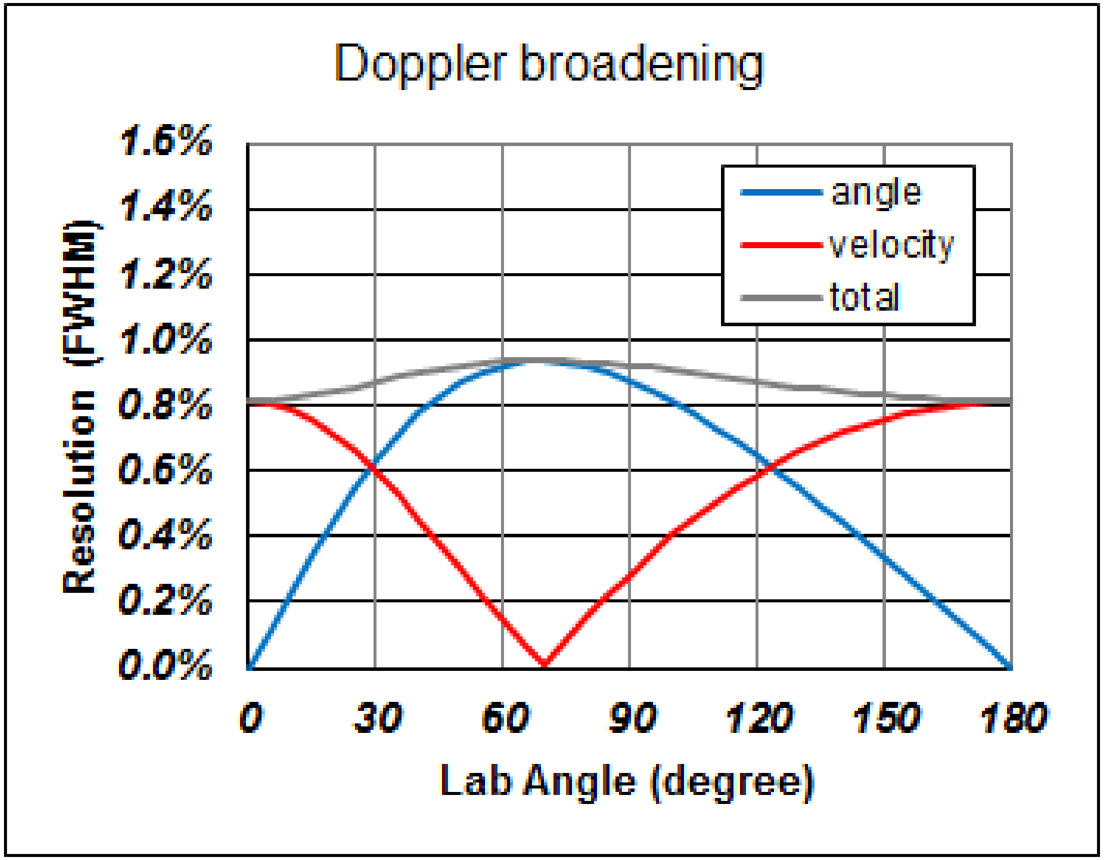
- Spread in speed ΔV
- Distribution in the direction of velocity $\Delta\theta_N$
- Detector opening angle $\Delta\theta_D$

➔EM separator to determine nuclear velocity V.

➔ Position sensitive detector for γ-ray detection

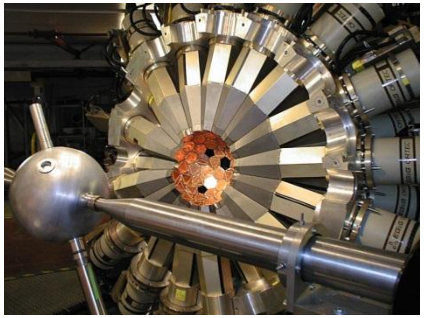
Doppler broadening example

65 MeV/u, β= 0.36
Δθ=1.4°
Δβ/β = 0.02



Gamma-ray detector arrays

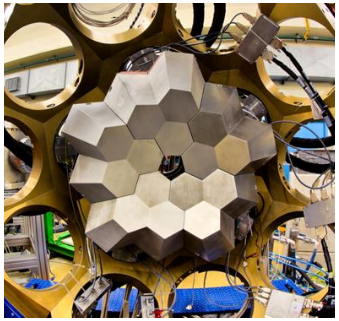
Detector	efficiency	Peak/total	Resolution Slow beams	Resolution fast beams
Compton shielded Ge	5 – 10%	0.50	2.5-5.0 keV	10%
Segmented Ge	3- 5%	0.20	2.5 keV	1-2%
Scintillation(NaI, CsI) **($LaBr_3$)**	50%	0.50	100 keV 30 keV	10% 3%
Tracking Ge (now) **(4π)**	5 –7% 50%	0.50	2.5 keV	1%



Gammasphere

GRAPE

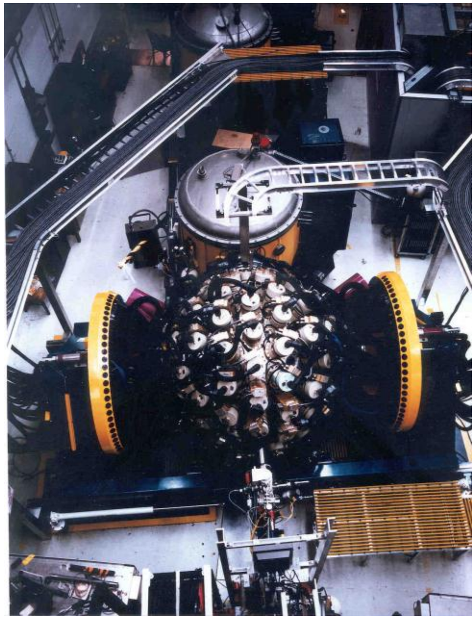
DALI

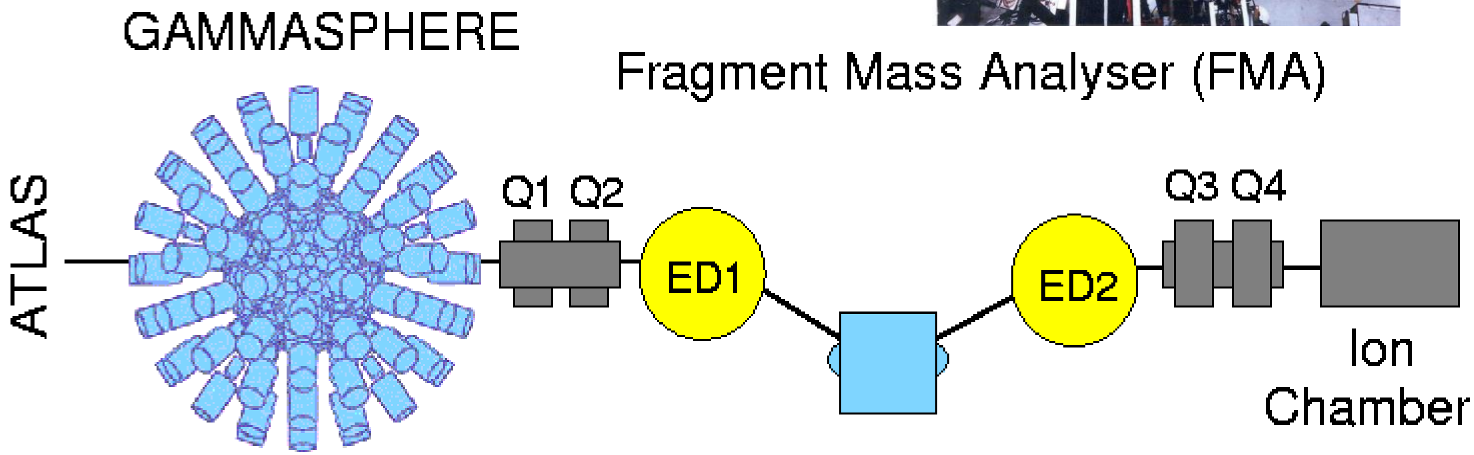


AGATA Demonstrator

Gammasphere at FMA

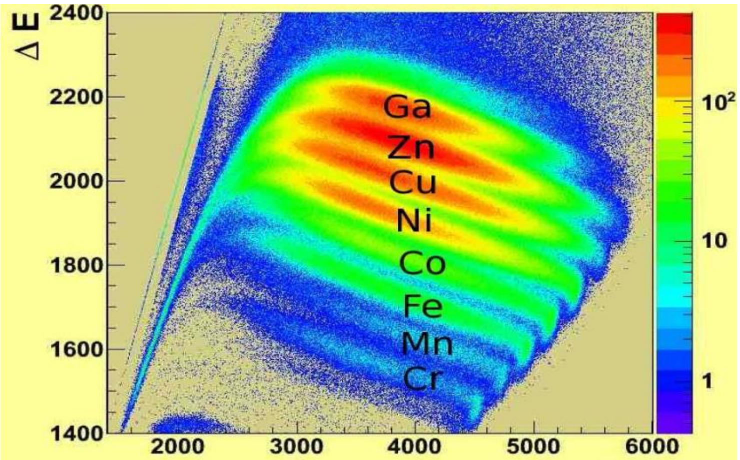
Gammasphere		
Compton shielded	**modules**	110
Peak efficiency	9% (1.33 MeV)	
Peak/Total	55% (1.33 MeV)	
Resolving power	10,000	
Optimal coincidence fold		4



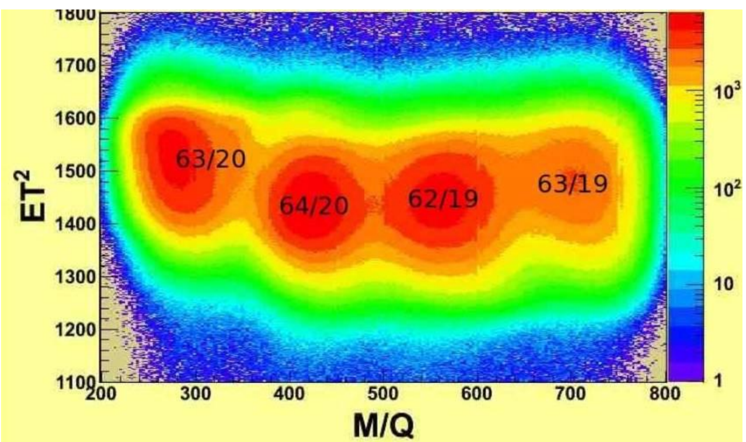


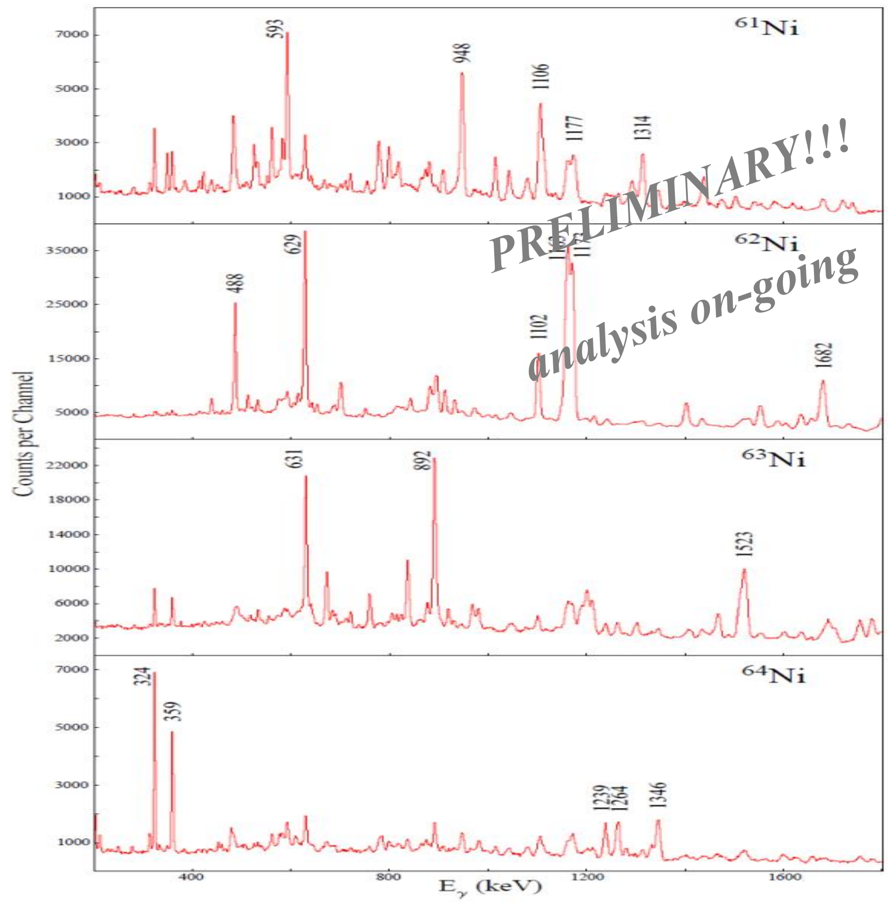
Evolution of the structure of Ni isotopes

$^{48}Ca + ^{26}Mg$ ~ 200% above barrier & Gammasphere + FMA



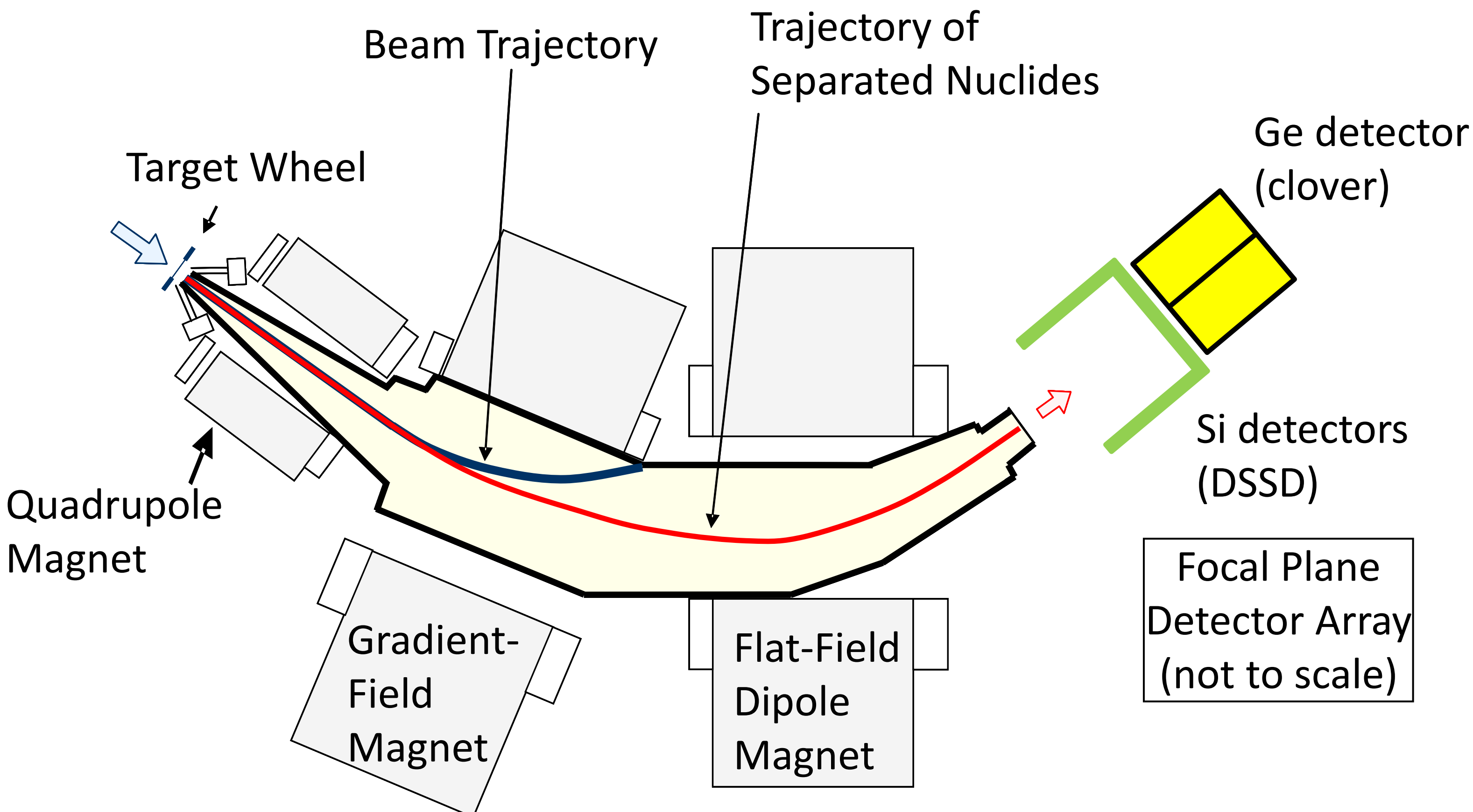
ΔE –E & M/Q identification





S. Zhu, C. Hoffman, and M. Albers

Berkeley Gas-filled Separator



BGS

Large acceptance: 45 msr

High transmission: (Ca+Pb: 60%)

Large bend angle: 70˚

Low background rates: (20Hz/pμA)

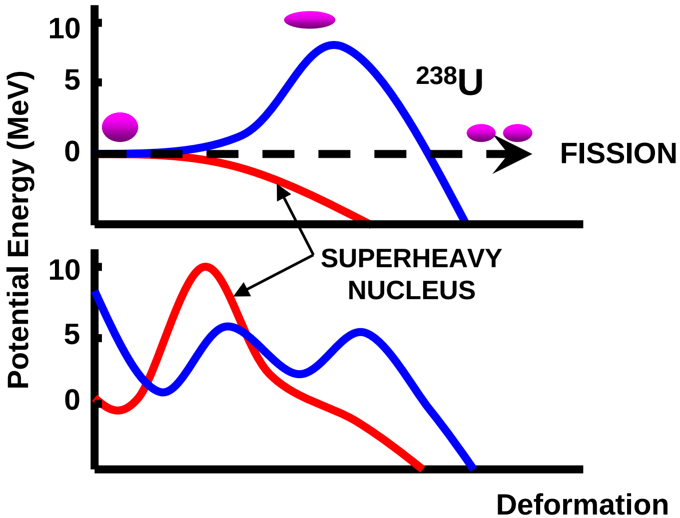
Clover Ge detector

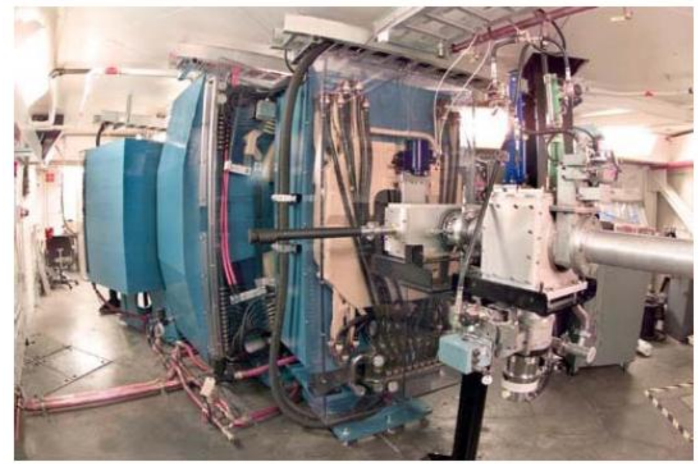
4 crystals

Total efficiency: 6% (@1.3 MeV)

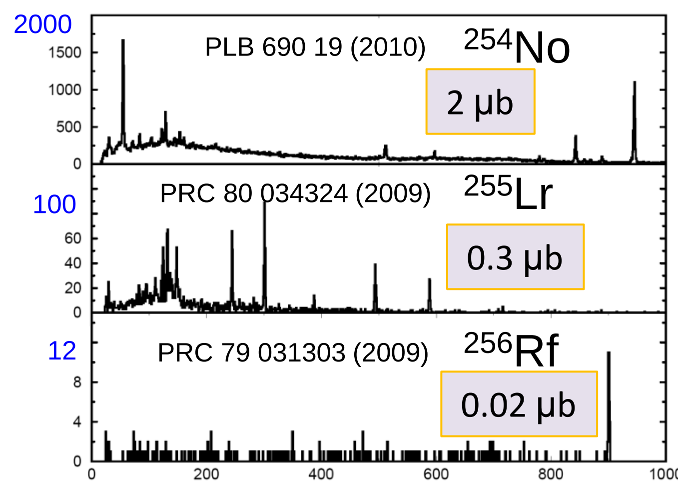
Isomer Spectroscopy Z>100 at BGS focal plane

Measure properties and production mechanisms of the elements above Z~102 to understand the nature and behavior of these nuclei, and to assist theoretical predictions for the stability, structure and production of super-heavy elements ***(NS8, 2015).***





- Studying the decay of isomers at focal plane of BGS.
- Addressing the question of the location and extent of shell-stabilized spherical super-heavy nuclei.
- Determining properties for Z>100 nuclei such as
  - single quasi-particle structure
  - pairing strength
  - deformation
  - excitation modes
- Testing the same models that predict properties of super-heavy nuclei near Z=114, N=184.

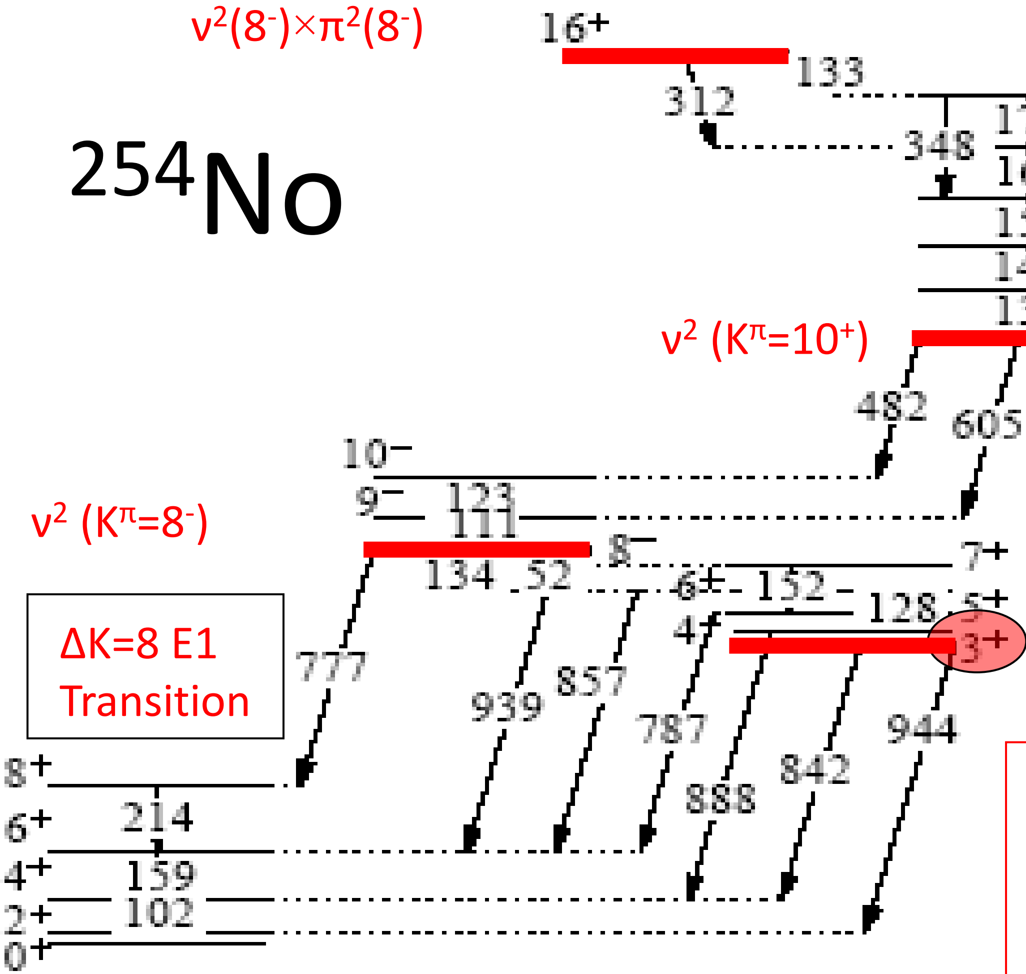


Results on ^{254}No

Rotational sequences:

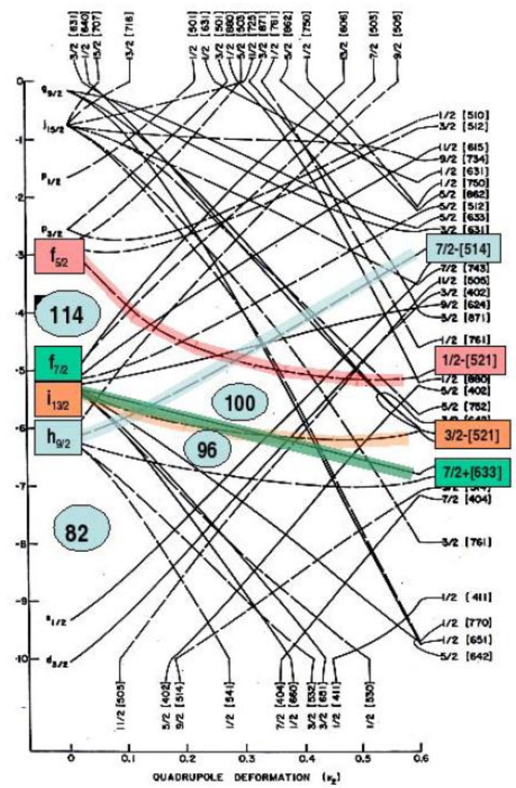
$$E_{rot} = \frac{\hbar^2}{2Á}\left[I(I+1)\right] + E_K$$

^{254}No



ΔK=8 E1 Transition

Involves proton in the **$f_{5/2}$** orbit



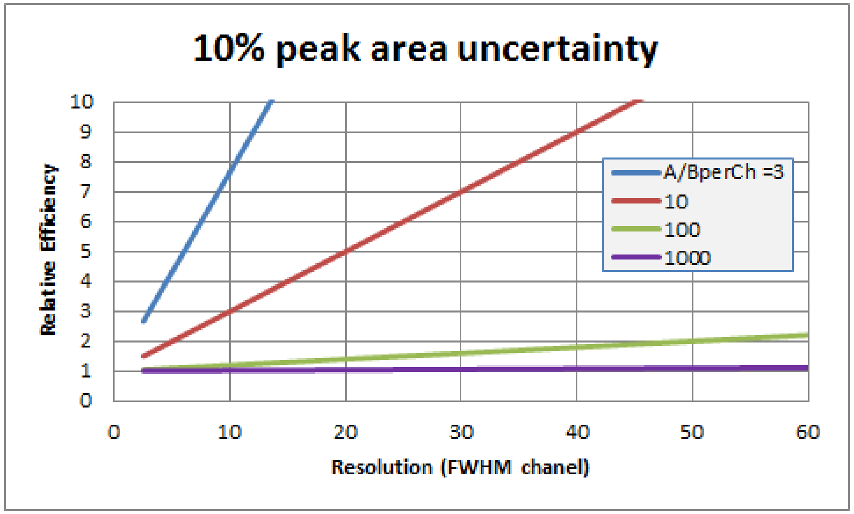
R.M.Clark *et al.*, PLB 690 19 (2010)

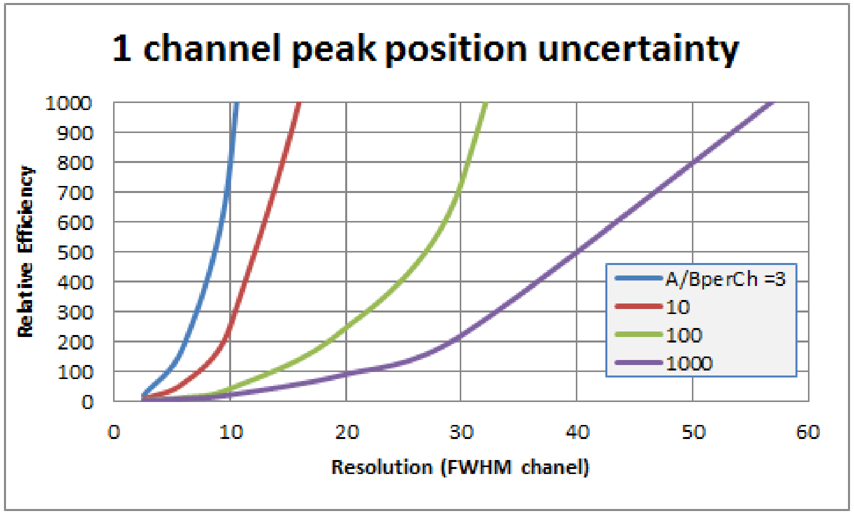
γ-ray scintillation detectors

Material	Density (g/ml)	Light output (photon/keV)	Main decay time (nsec)	Peak wavelength (nm)	Resolution @662 keV
NaI(Tl)	3.67	38	250	415	6%
CsI(Tl)	4.51	56	1,000	550	6%
BaF_2	4.88	10 2	630 0.6	310 220	8%
$LaBr_3$(Ce)	5.08	63	16	380	3%
Cs_2LiYCl_6(Ce) (CLYC)	3.31	20	1.4 50 450 1,000	270 380	4%

- Examples of 4π arrays
  - NaI- Crystal ball, Spin Spectrometer, DALI2
  - CsI – CEASAR
  - BaF_2 – DANSE
  - $LaBr_3$ - SHOGUN

Efficiency vs. resolution





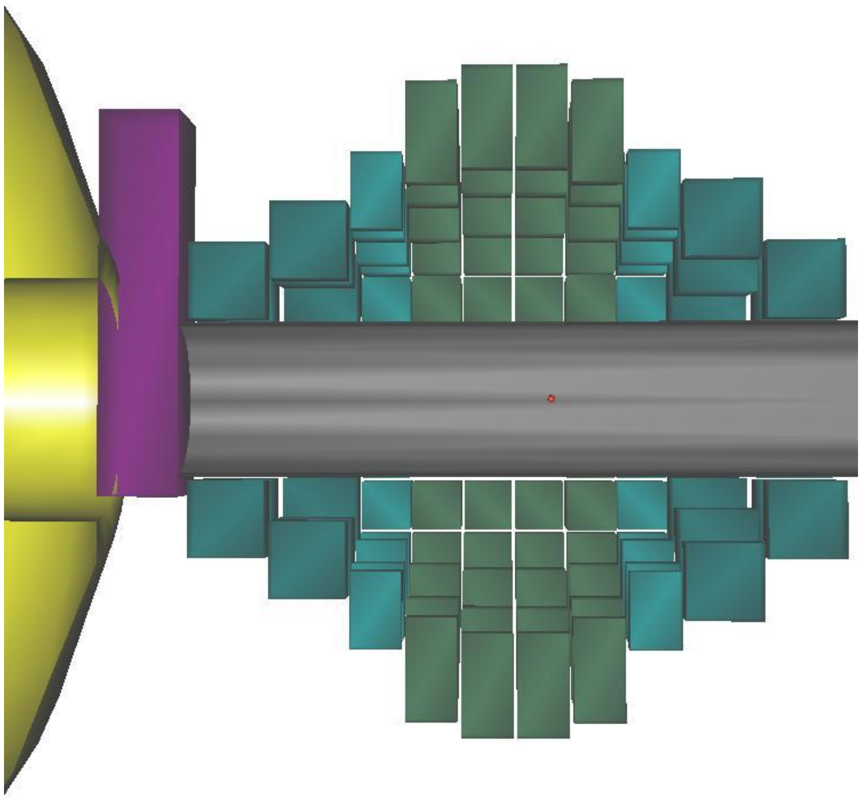
$$\frac{\Delta A}{A} = \sqrt{1/A + 2\,W/(A/BperCh)}$$

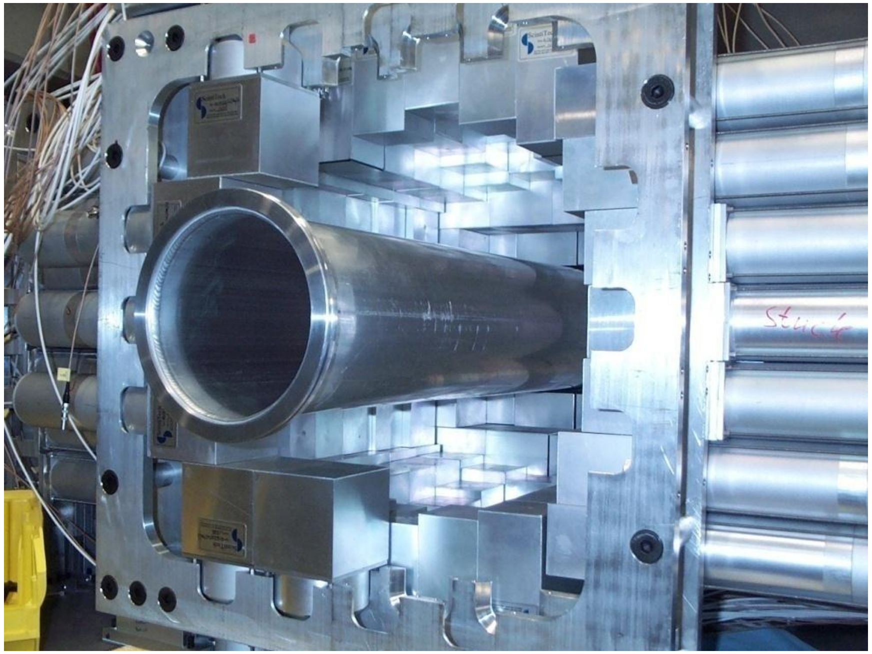
$$\Delta ch = \sqrt{\frac{(W/2.355)^2 + W(W+1)(2W+1)/(A/BperCh)}{A}}$$

- For given uncertainties, more counts (higher efficiency) are needed with worse resolution and/or peak-to-back ground ratio.

The CAESium iodide ARray

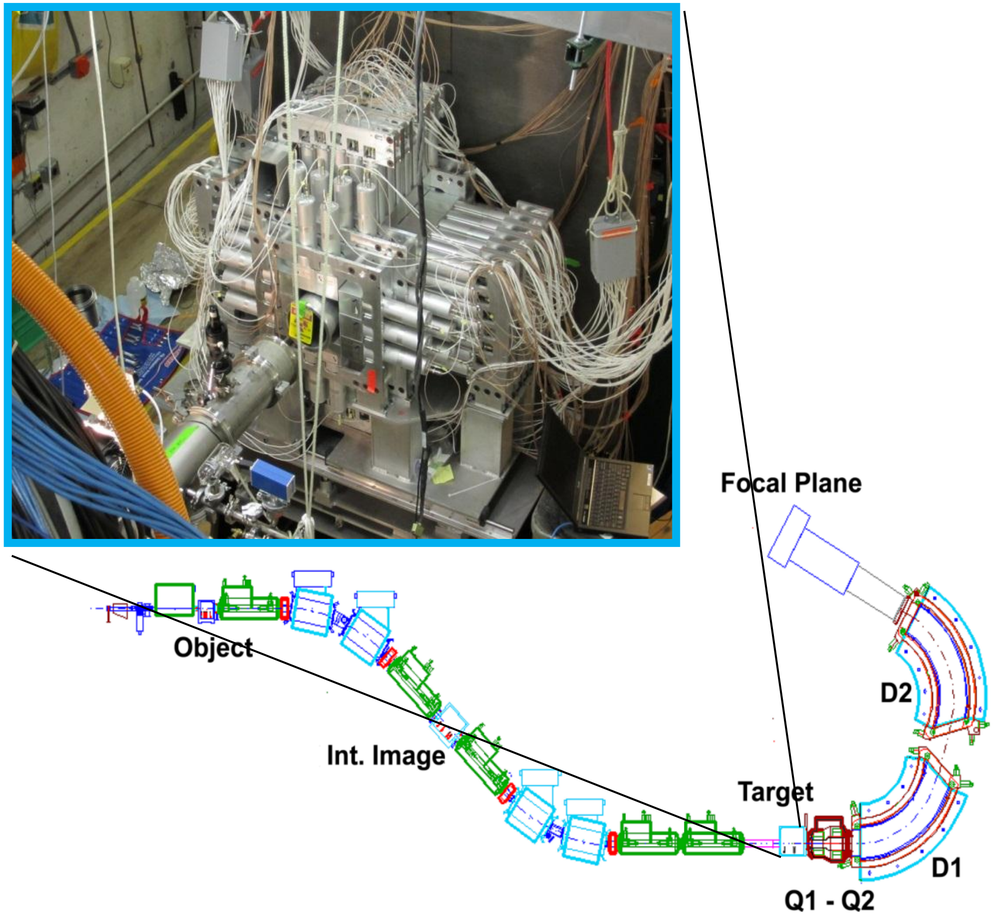
- CsI(Na)
- 48 3”x 3”x 3” crystals
- 144 2”x 2”x 4” crystals
- Solid angle coverage 95%
- In-beam FWHM: 9.2% (@1 MeV)
- Full-energy-peak efficiency 35% at 1MeV

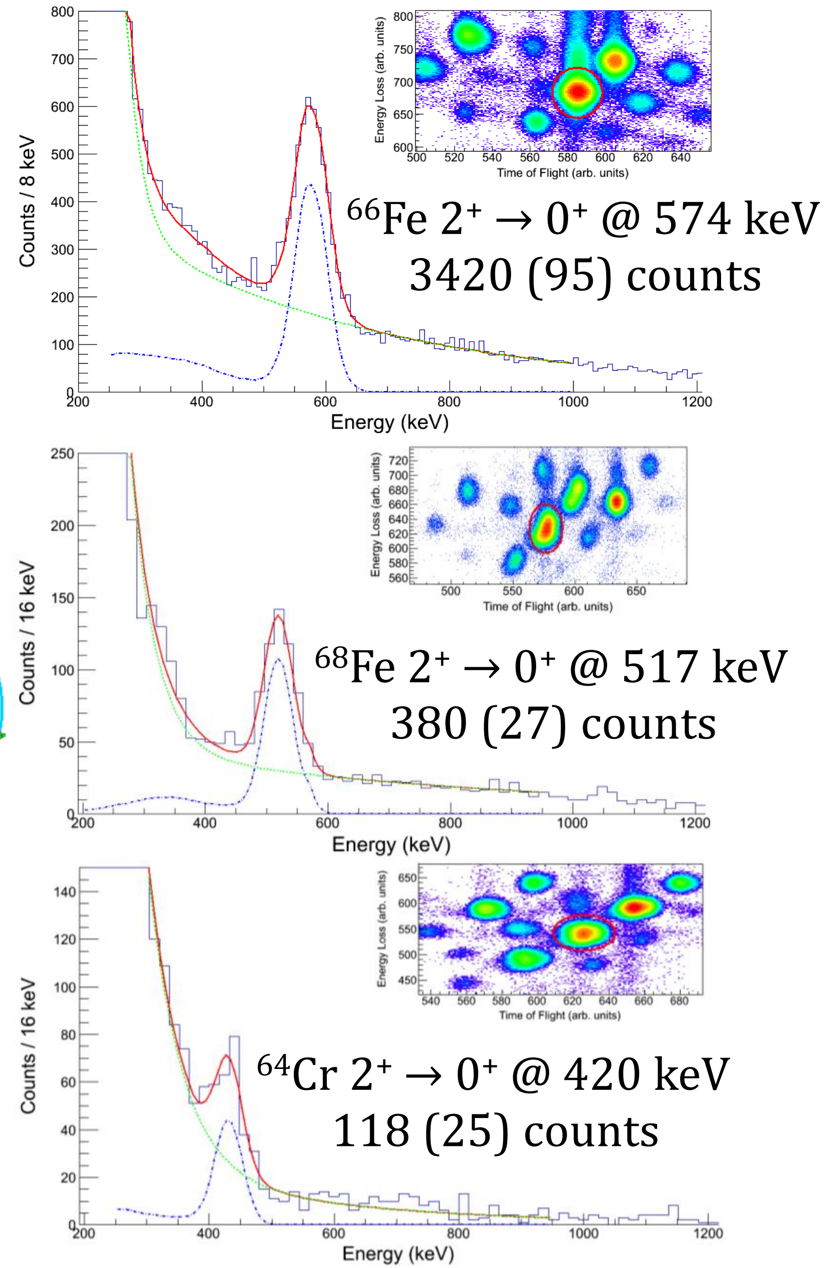




D. Weisshaar *et al.*

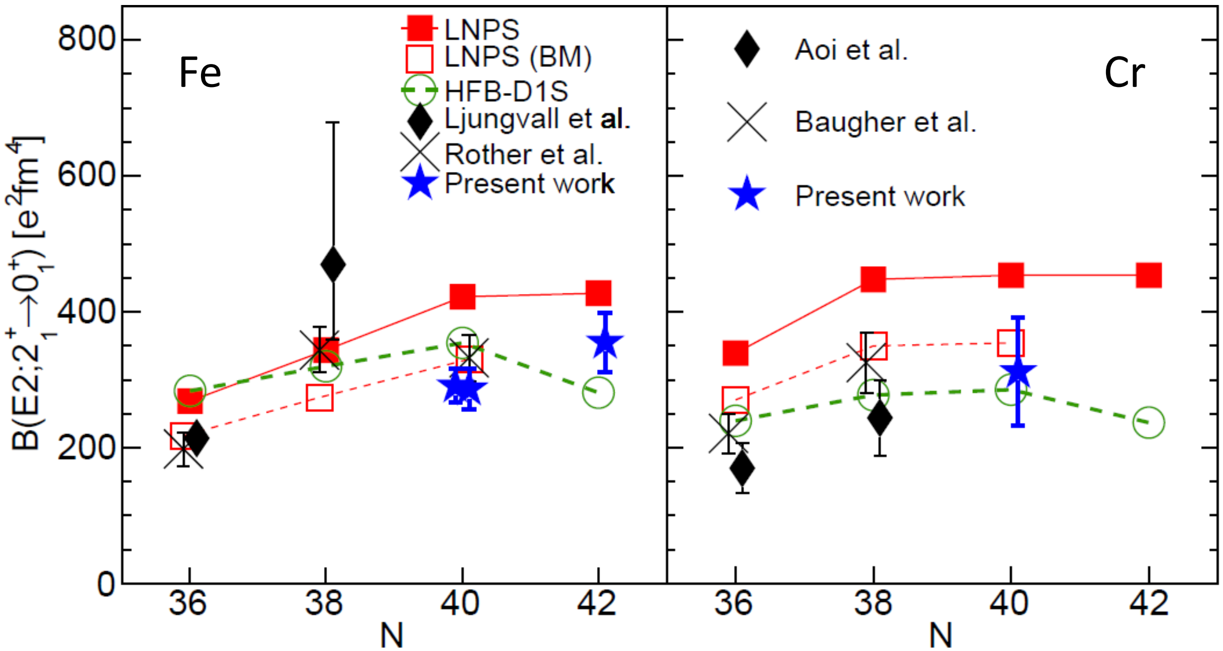
Coulex of Neutron-Rich Fe and Cr





Coulomb excitation of ^{66,68}Fe and ^{64}Cr, with incoming particle rates of 300, 20 and 2 pps respectively , was performed using a thick Bi target, detecting γ-rays in CAESAR, and particles in the S800.

Coulex of Neutron-Rich Fe and Cr



Results for the B(E2) in ^{66}Fe agree well with a previous RDM lifetime measurement, while the measured B(E2) values in ^{68}Fe and ^{64}Cr are in good agreement with the prediction of large-scale shell-model calculations, after adjustment of the effective charges.

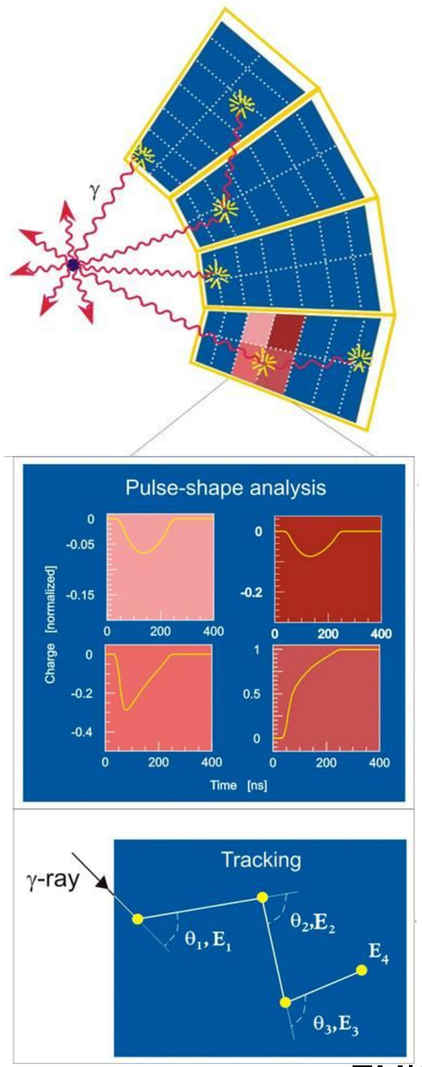
H. Crawford *et al.*

Principle and advantages of γ-ray tracking

3D position sensitive Ge detector shell

Resolve position and energy of interaction points

Determine scattering sequence



- **Efficiency (50% Ω)**
  Proper summing of scattered gamma rays, no solid angle lost to suppressors
- **Peak-to-background (60%)**
  Reject Compton events
- **Position resolution (1-2 mm)**
  Position of 1st interaction
- **Polarization**
  Angular distribution of the 1st scattering
- **Counting rate (50 kHz)**
  Many segments

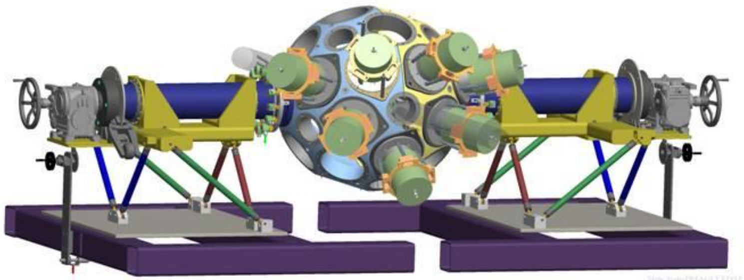
γ– ray tracking is essential

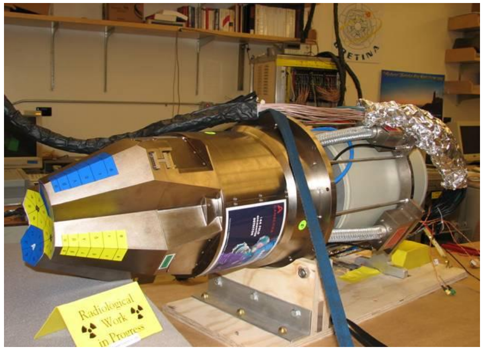
Especially for radioactive beam experiments

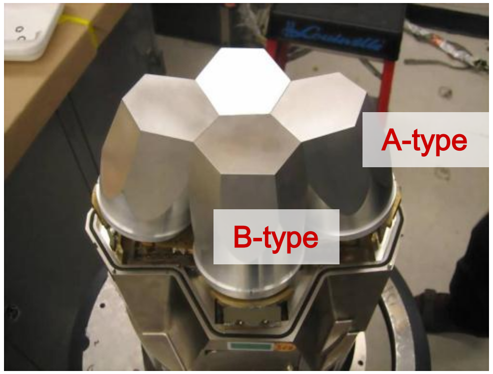
Tracking capabilities	Experimental conditions
• High position resolution	Large recoil velocity – Fragmentation – Inverse reaction
• High efficiency	Low beam intensity
• High P/T • High counting rate • Background rejection	High background rate Beam decay Beam impurity

GRETINA

- Array covers ¼ of 4π solid angle (ε =7.5%)
- 28 36-fold segmented Ge crystals
- Mechanical support structure
- Data acquisition system:1120 digitizers
- Data processing system: 500 nodes

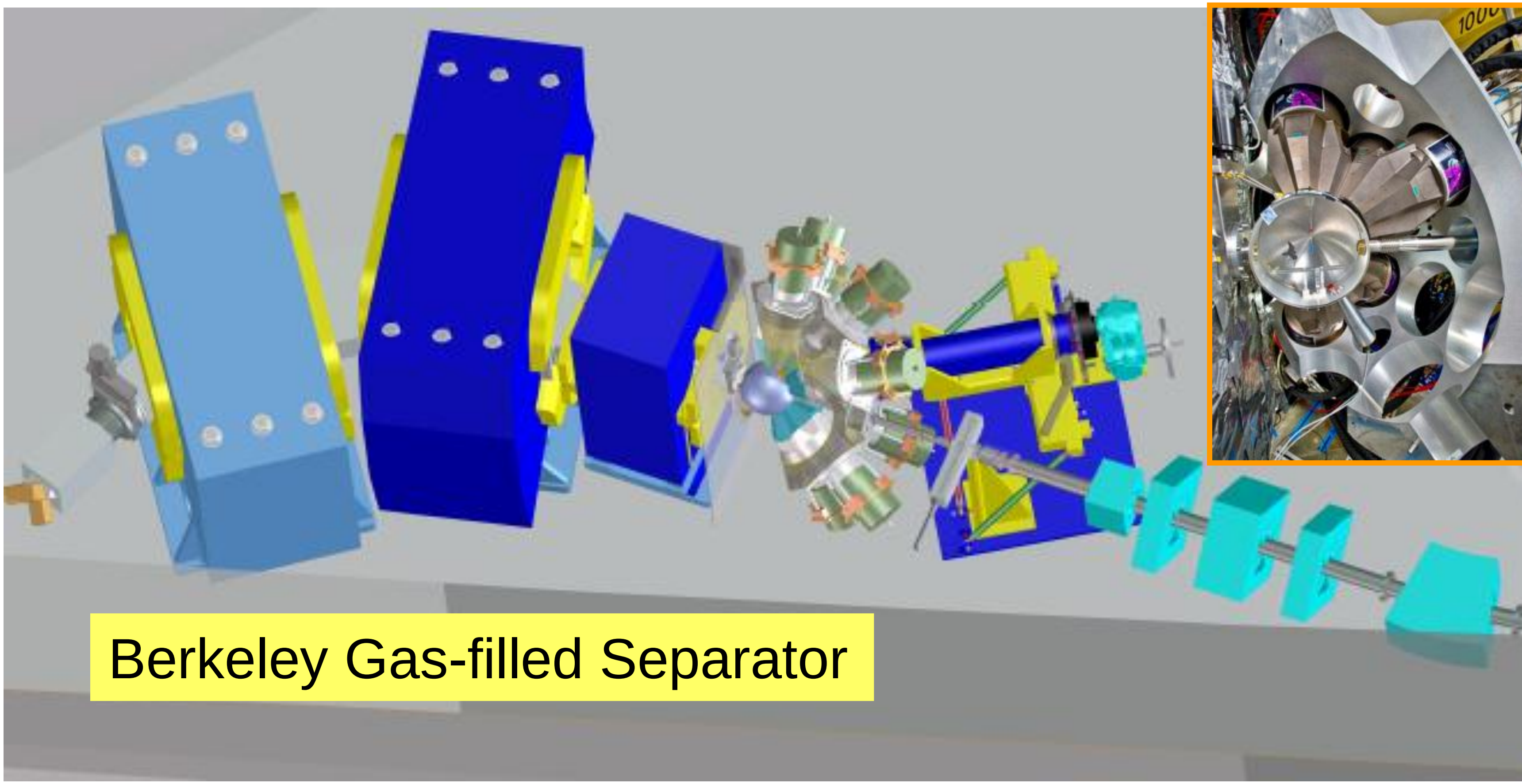






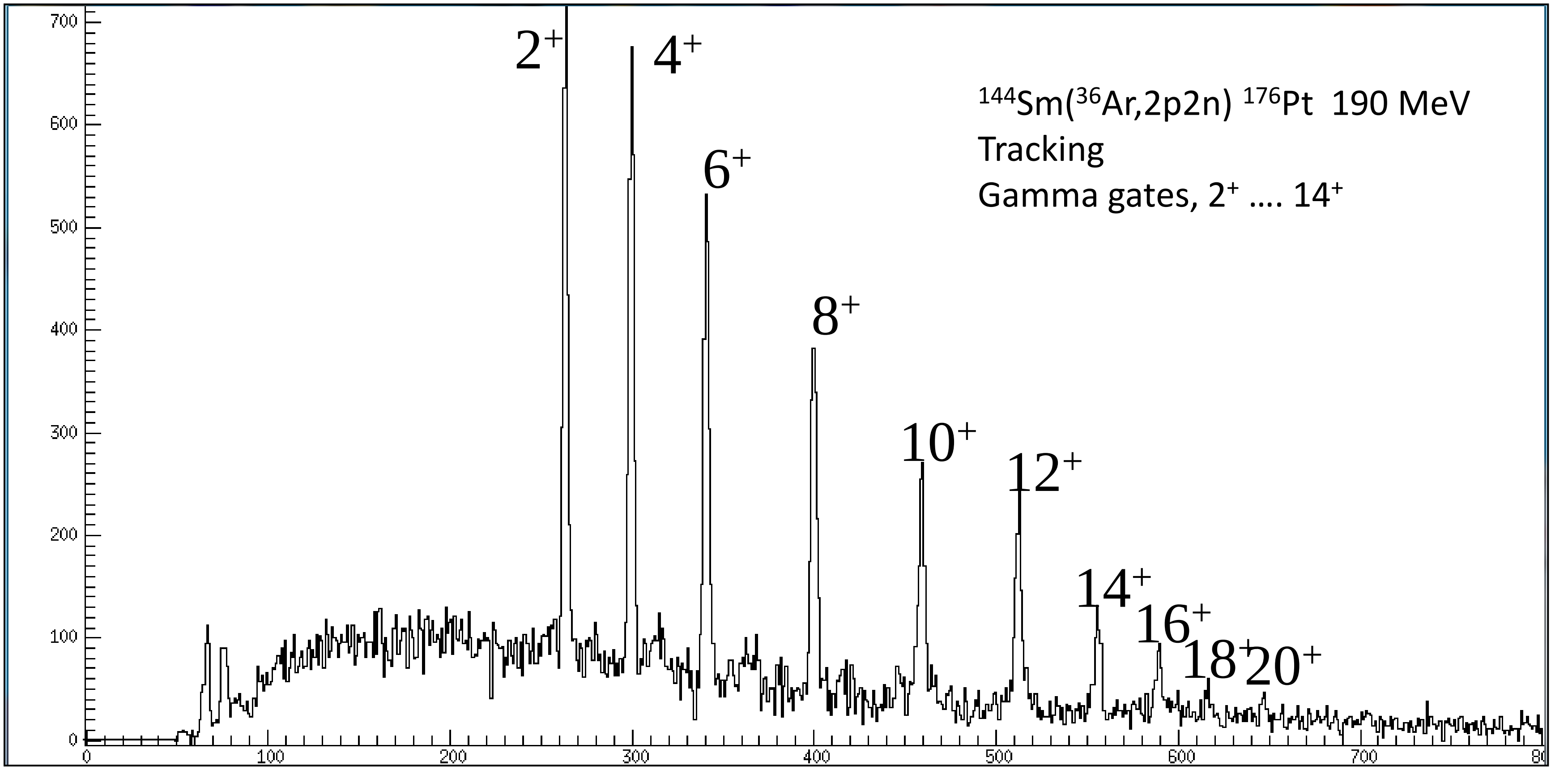
GRETINA at BGS LBNL

- GRETINA set up at BGS target position
- Experiment September 7, 2011 – March 23, 2012



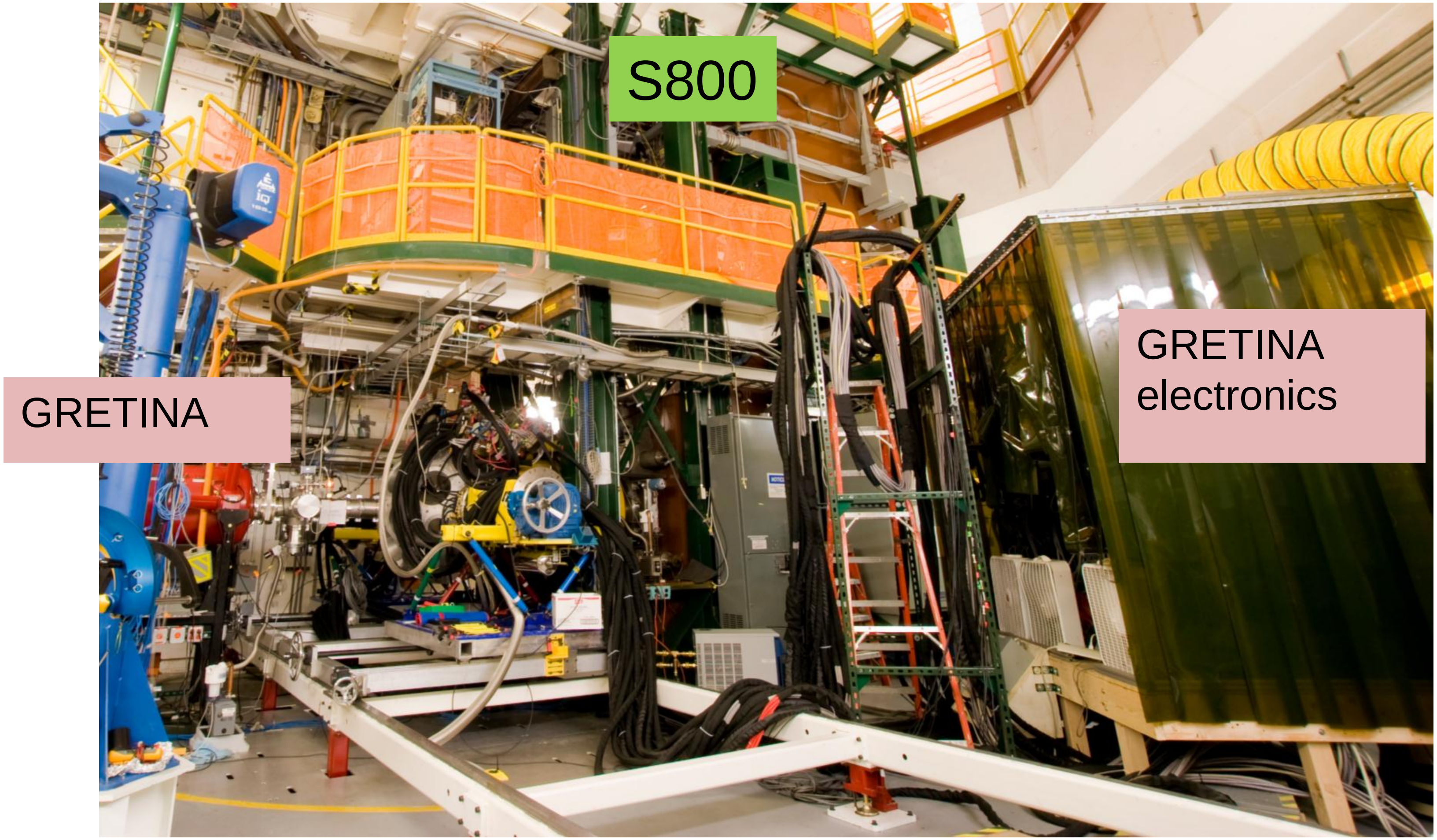
Slow beam test experiment

- GRETINA – BGS coincidence
- Data acquired using separate systems
- Use time stamps to correlate data



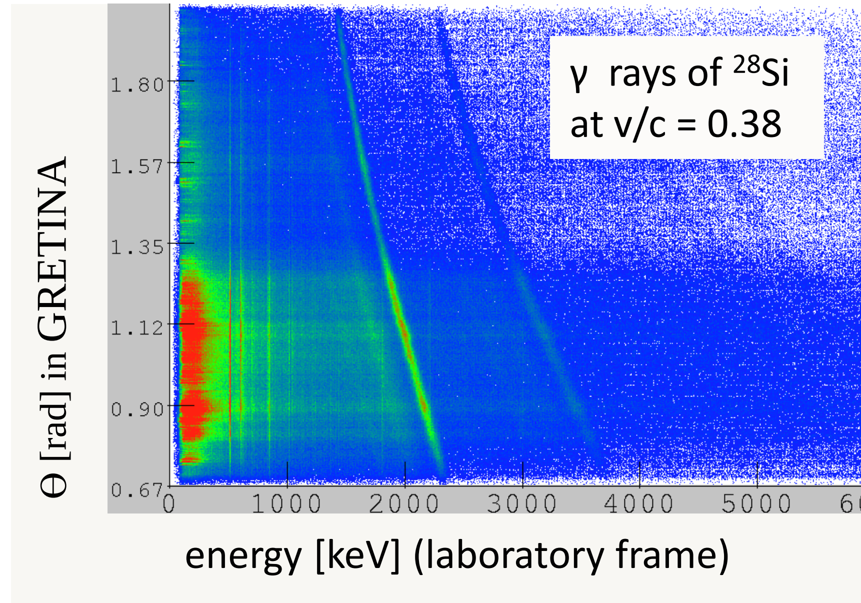
GRETINA at NSCL MSU

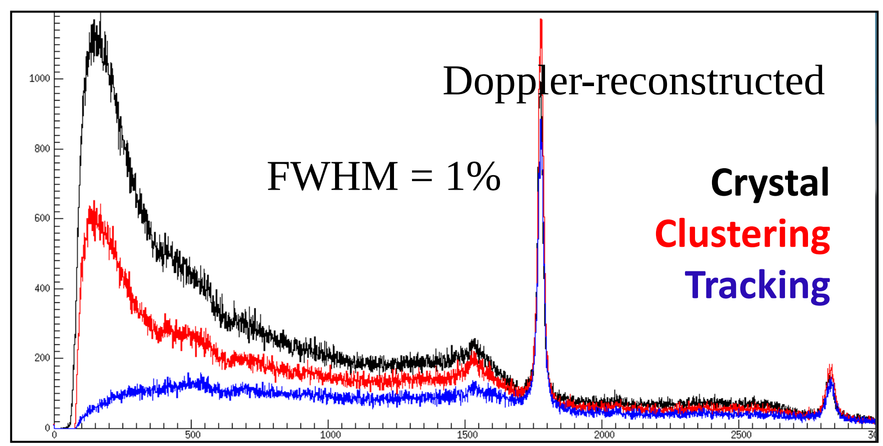
- GRETINA at target position of S800 spectrograph
- Experiments started May 2012

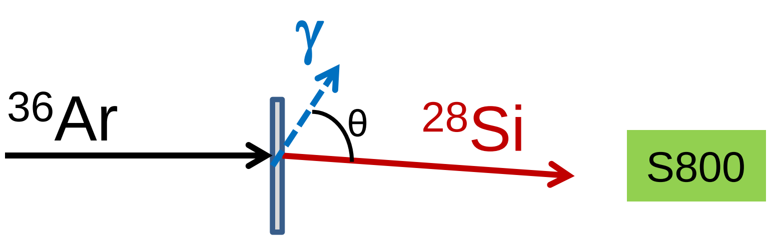


Fast beam test experiment

^{28}Si from ^{36}Ar fragmentation







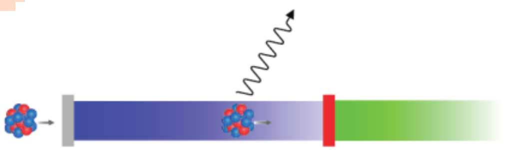
Experiments at NSCL

Nuclear Shell Evolution

- *N=Z* Mirror Spectroscopy ✓
- Structure in ^{221,223}Rn
- $^{50\text{-}52}$Ca neutron knock-out ✓
- Neutron-rich Ti
- Odd neutron-rich Ni
- ^{34}Si Bubble nucleus? ✓
- Neutron-rich Si ✓
- GRETINA commissioning ✓
- Neutron-rich *N*=40 nuclei ✓
- Normal and intruder configurations in the Island of Inversion

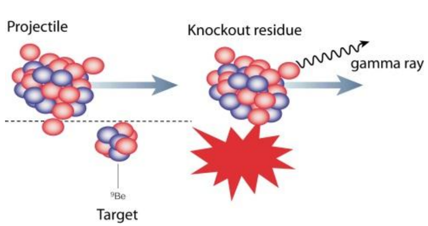
Nuclear Astrophysics

- Excitation energies in ^{58}Zn ✓
- Measurement of the ^{56}Ni(d,n)^{57}Cu transfer reaction



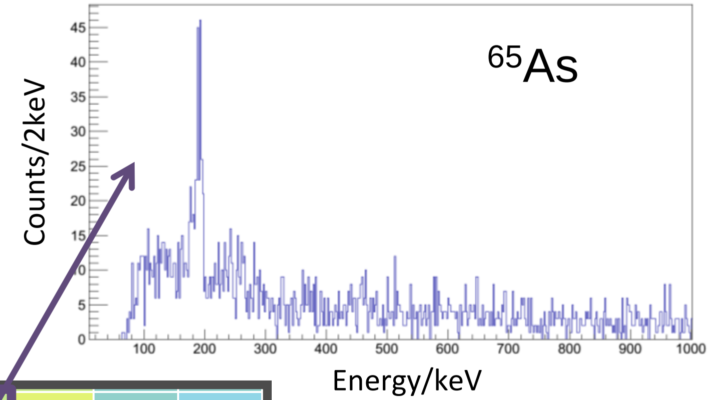
Collective Nuclear Structure

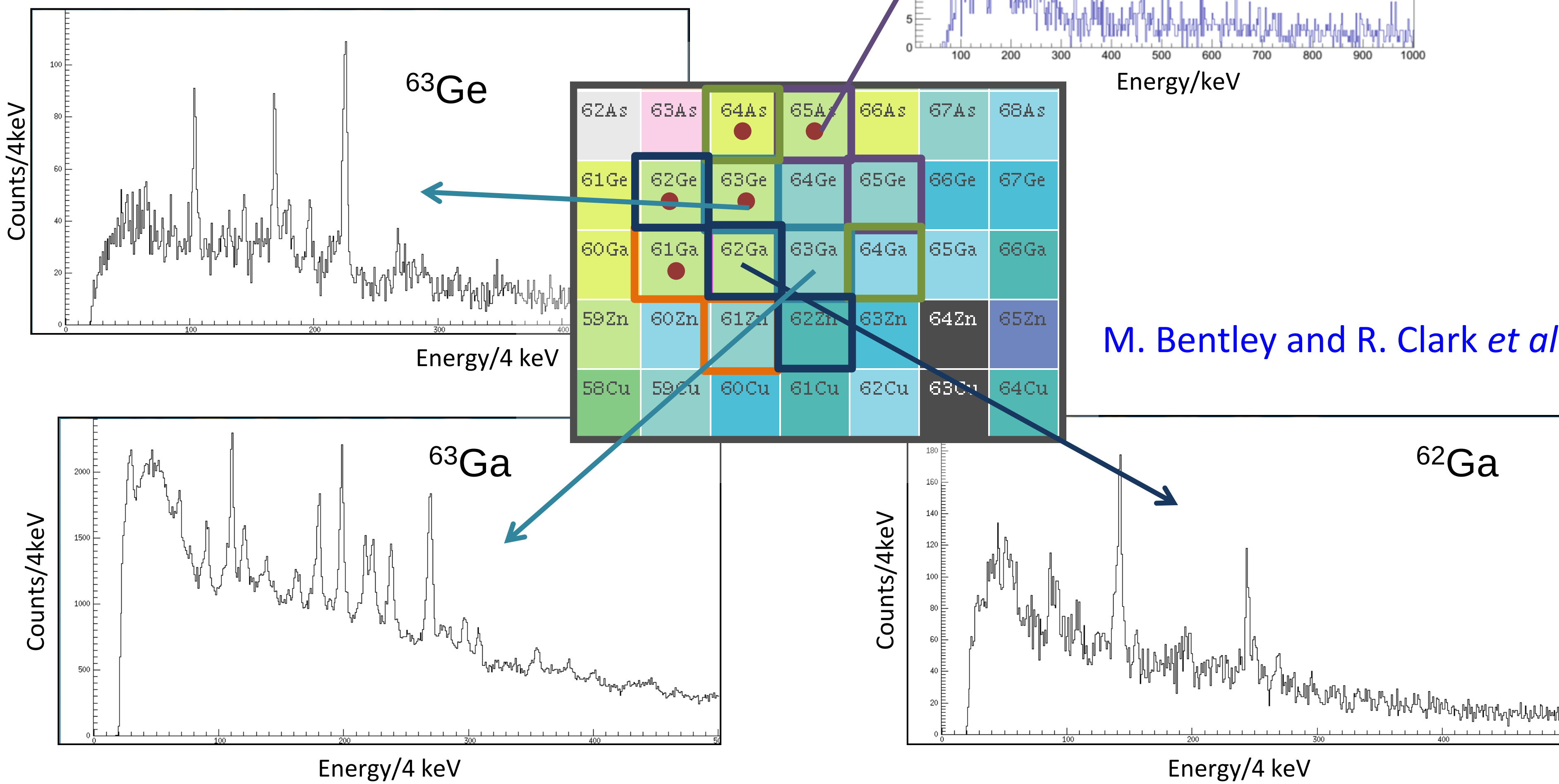
- Transition matrix elements in ^{70,72}Ni ✓
- Quadrupole collectivity in light Sn
- γ-γ spectroscopy in neutron-rich Mg
- Neutron-rich C lifetime measurement
- Collectivity at *N=Z* via RDM lifetime measurements ✓
- B(E2:2→0) in ^{12}Be
- $^{71\text{-}74}$Ni excited-state lifetimes
- Inelastic excitations beyond ^{48}Ca
- Triple configuration coexistence in ^{44}S
- GT strength distributions in ^{45}Sc and ^{46}Ti ✓
- Search for isovector giant monopole resonance



Mirror nuclei in the upper fp shell

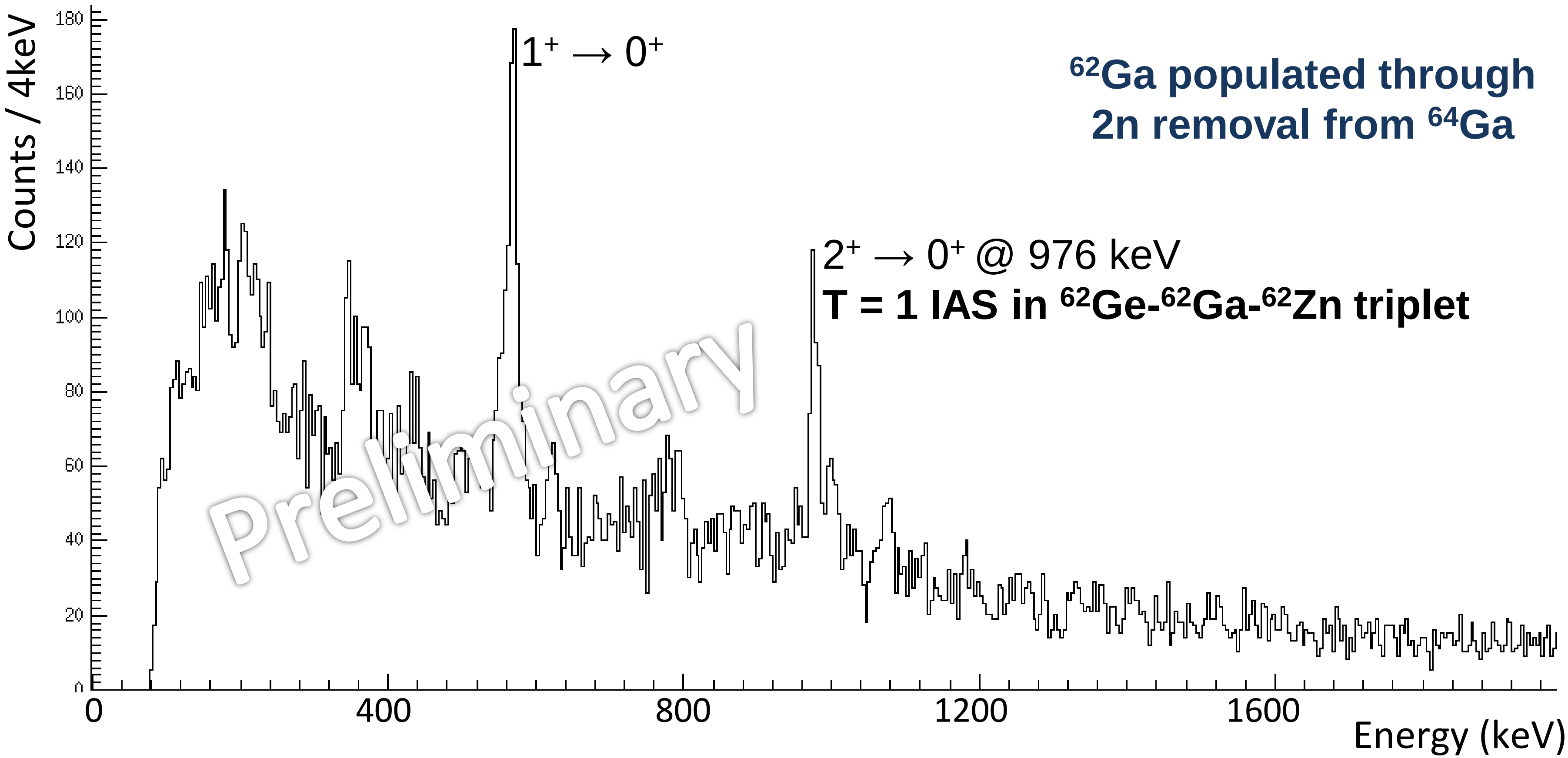
Looking into a small fraction of the data, a large amount of new information in isospin pairs and triplets above A=60 will be added to our current body of knowledge.





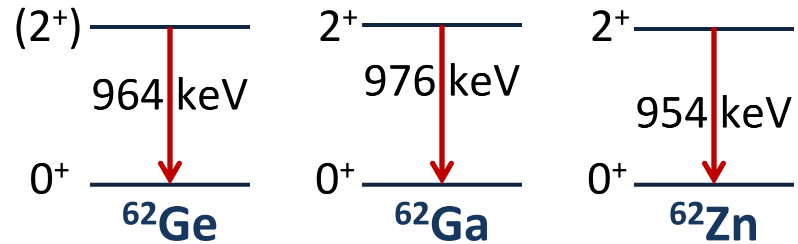
M. Bentley and R. Clark *et al.*

Case in point: A=62 T=1 Triplet



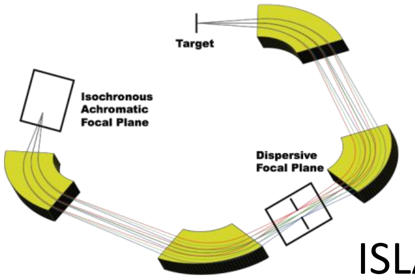
^{62}Ga populated through 2n removal from ^{64}Ga

T=1 2^+ state in ^{62}Ga only tentatively placed at 1017 keV -- observation of strong transition at 976 keV is **firm identification of the T=1 2^+ state**.



Summary

- The combination of large γ-ray array and separator is a power tool which provides many science opportunities.
- For exotic nuclei studies, it is essential to use large γ-array together with separators.
- Opportunities to optimize future combined system together.
  - Separator parameters –
    - space at target and focal plane,
    - (A,Z) identification,
    - velocity determination,
    - image size
  - γ-ray array parameters –
    - efficiency,
    - energy resolution,
    - position resolution,
    - peak-to-background ratio



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