# Gamma Detection Efficiency of a State-of-the-Art Ge Detector

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# Talk Outline

- Photon Interaction with Matter
- Gamma Ray Detection
  - Semiconductor Detectors
- My Project
- Results

# Photon Interaction with Matter

- Photons are neutral particles which cannot be detected on their own
- Detection arises from an interaction with matter, such as an electron.
- Three main photon interactions:
  - Photoelectric Effect
  - Compton Scattering
  - Pair Production

# Photoelectric Effect

- The dominant effect in low energy range (up to several hundred keV)
- Electromagnetic radiation is absorbed by a bound electron, causing it to become excited and break free of the atom
- The energy of the ejected electron is thus

$$E = h\nu - B.E.$$

- In a detector, materials with higher Z are favored for this effect
  - Cross-section dependence goes as ~ $Z^5$

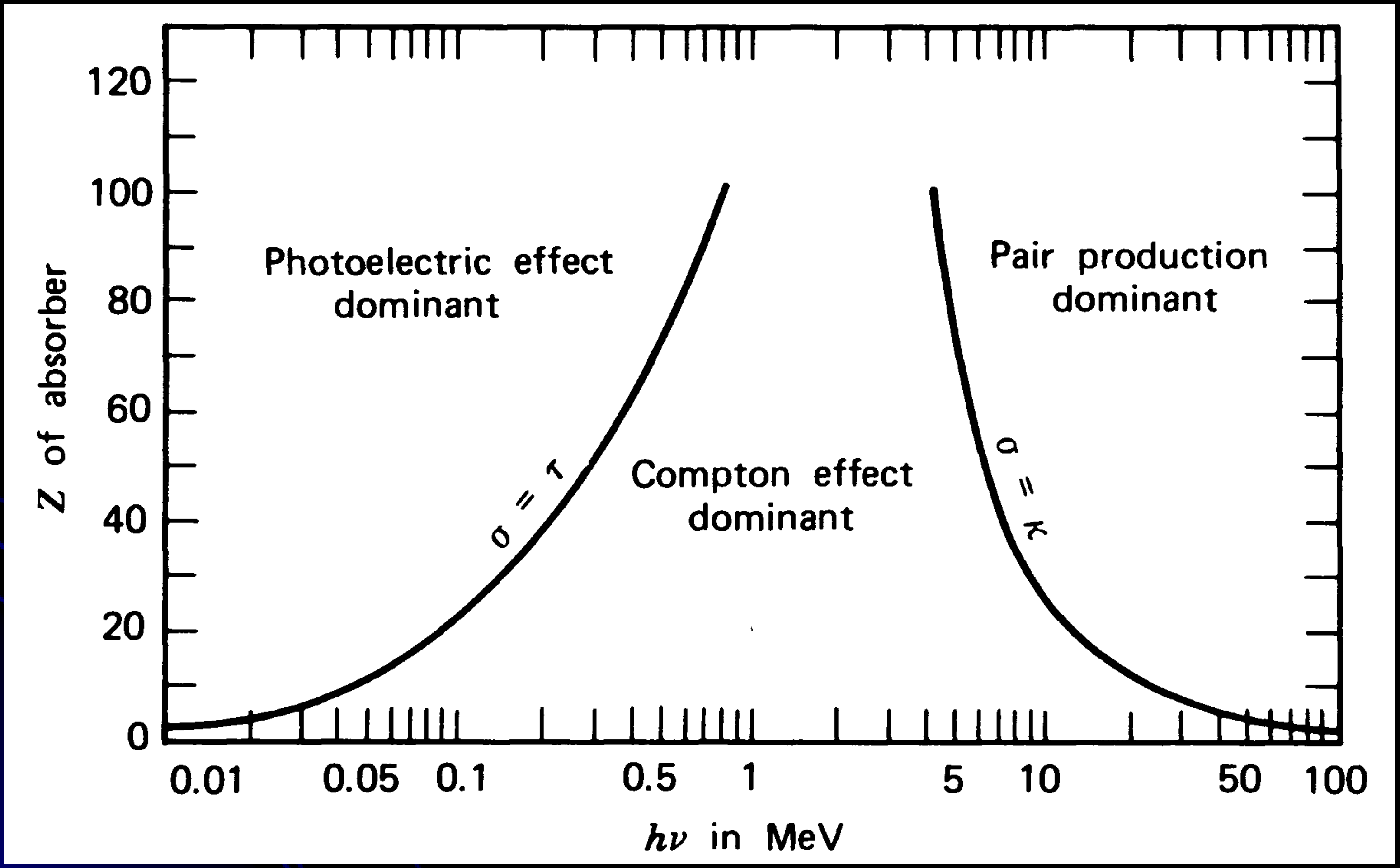
# Compton Scattering

- Dominant effect in the energy range of about 1 to 5 MeV
- Gamma ray collides inelastically with an electron and scatters, losing a significant amount of energy in the process.
- Dependence on the material goes linearly as ~Z

# Pair Production

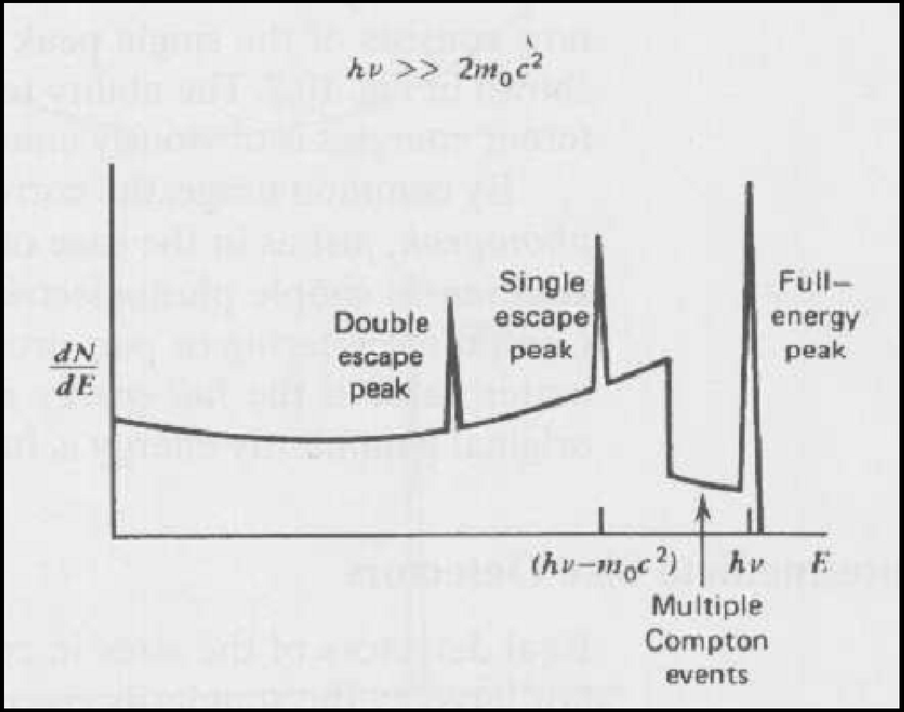
- Dominant in the high energy range above 5-10MeV
- Photon is transformed into an electron-positron pair.
  - Minimum energy required is ~1.02 MeV (at least the total rest mass energy of the two particles)
- Cross Section varies approximately as ($Z^2$)

# Interaction Summary



# Photon Interaction with a Detector

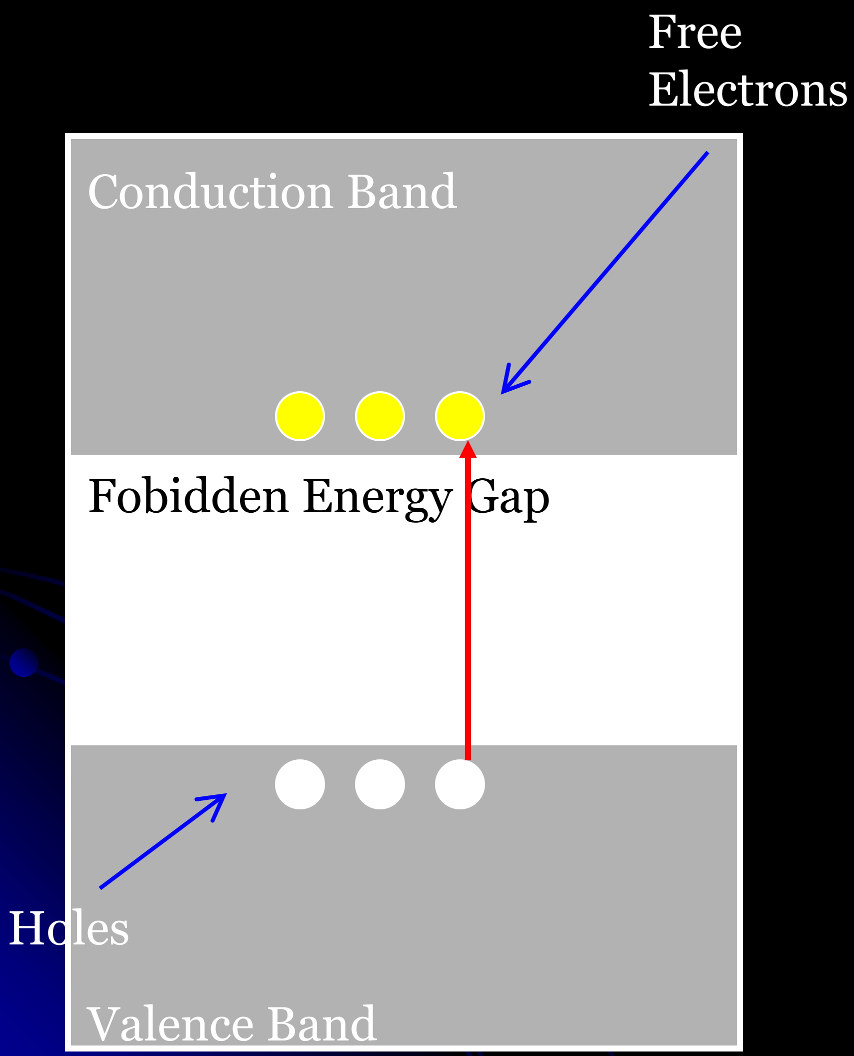
- Double escape peak from the two annihilation photons which do not further interact in the detector
- Single escape peak from the escape of one annihilation photon
  - other is totally absorbed
  - appears ~0.511 MeV below the photopeak
- Sharp full-energy peak from photoelectric interaction
- Compton continuum where multiple events occur



# Gamma Ray Detectors

- Semiconductor Detectors – Germanium
  - Excellent energy resolution (~FWHM of a couple keV)
  - Smaller cross sectional area translates into reduced efficiency
- NaI
  - Poor energy resolution in comparison to Ge
  - Excellent light yield allows for greater efficiency

# Germanium Detectors



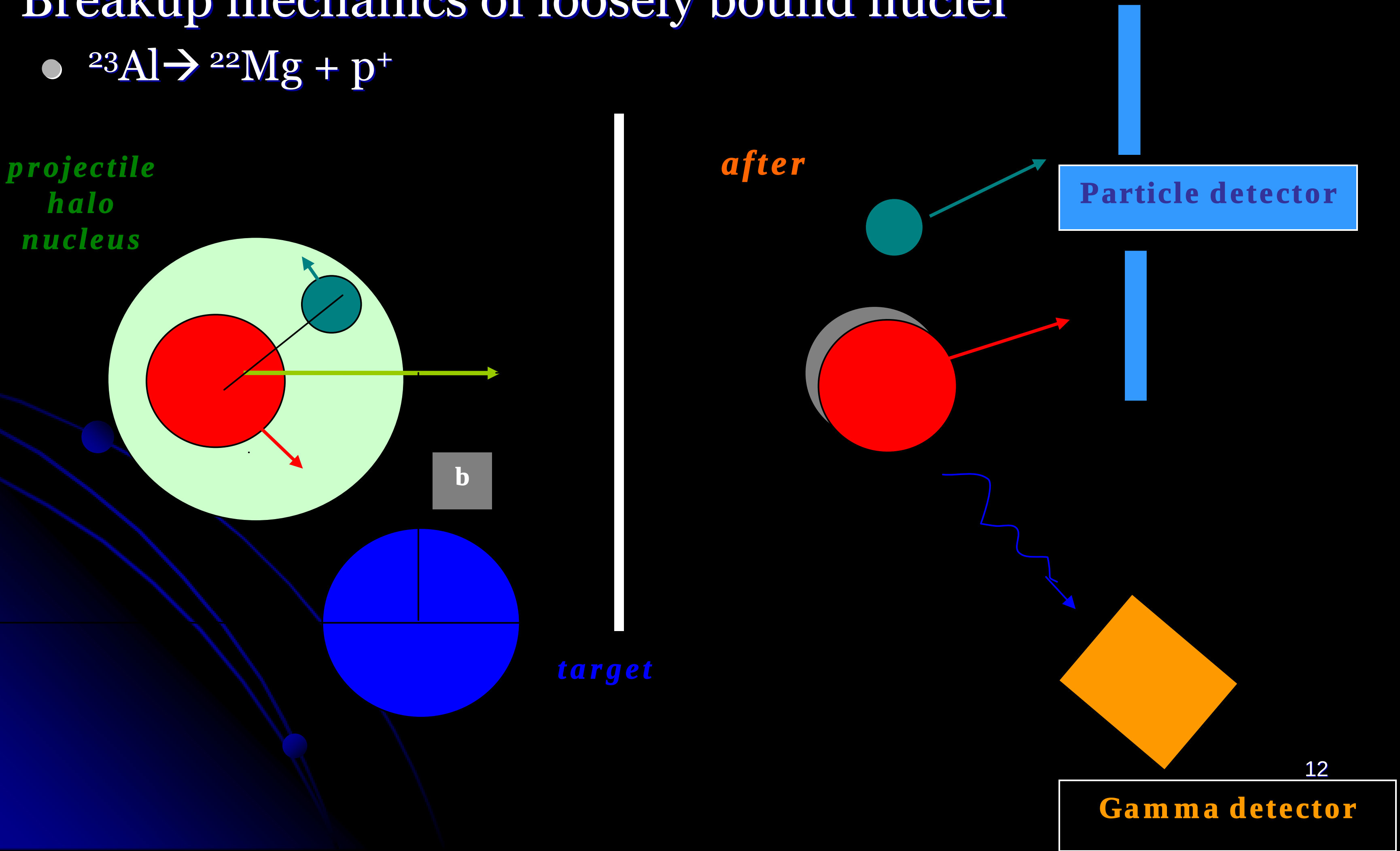

- Electromagnetic radiation allows electron in valence band to jump the energy gap into the conduction band
- Resolution allows for the separation of many closely spaced gamma-ray energies which remain unresolved in NaI
  - Few tenths of a percent (compared to 5-10% for NaI)
- But smaller size and lower Z give an order of magnitude less efficiency than NaI

# My Project

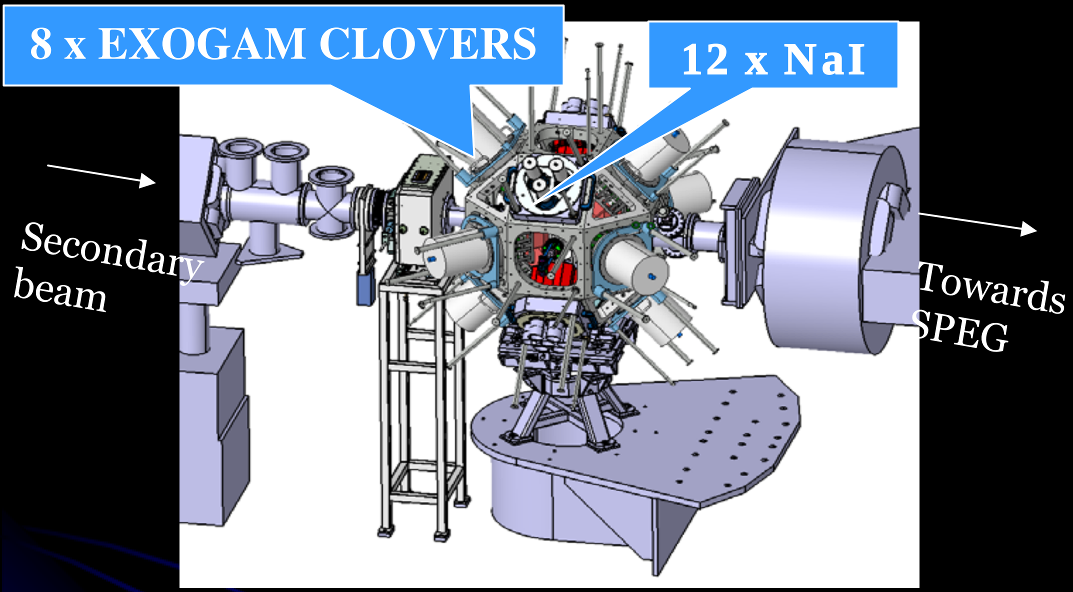
- Derive an analytical expression for the efficiency of Ge detectors
  - Four sources used to calibrate:
    - $^{60}$Co, $^{137}$Cs, $^{152}$Eu, $^{56}$Co
    - $^{56}$Co is the only source that supplies high energy gammas ( >3 MeV).
- Determine an estimate of the activity of $^{56}$Co
- This experiment, performed at GANIL laboratory in France, was motivated by fundamental questions in nuclear physics and astrophysics

# Experimental Details

- Breakup mechanics of loosely bound nuclei
  - $^{23}Al \rightarrow {}^{22}Mg + p^+$

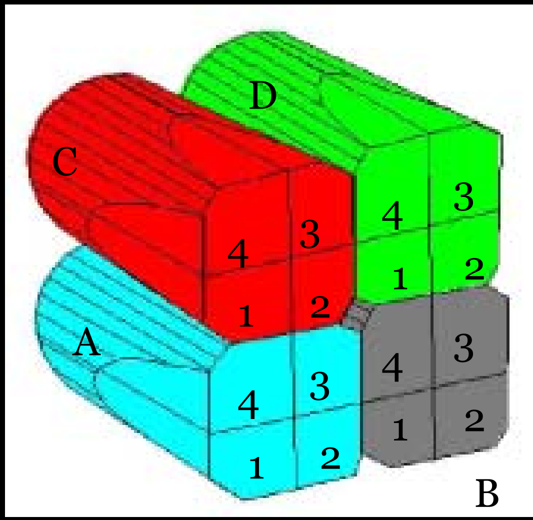


# Setup



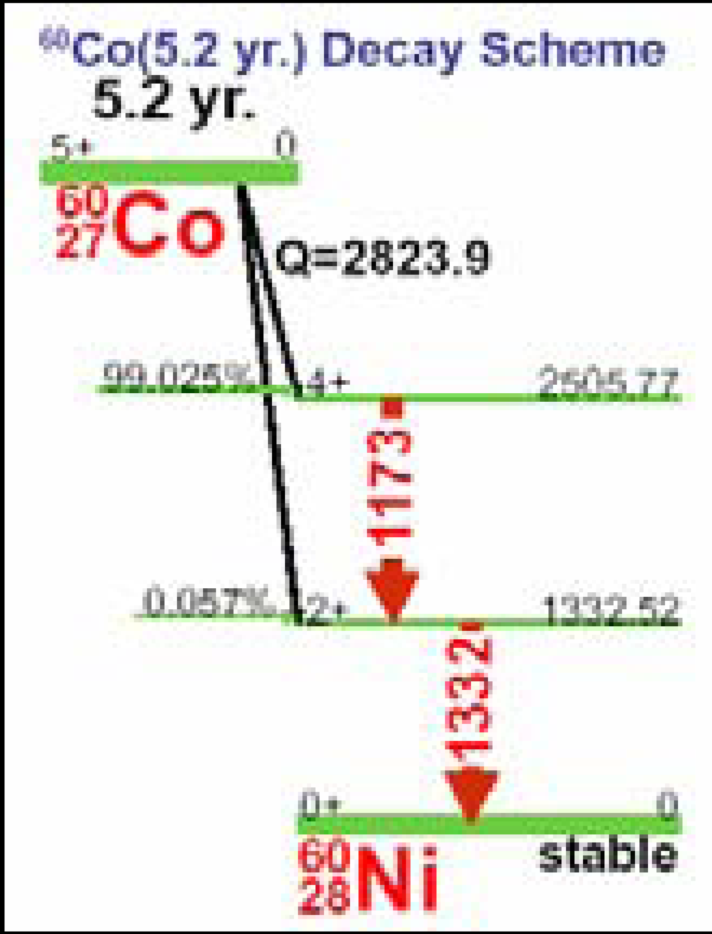

An illustration of the experimental setup at GANIL. The beam enters from the left where it interacts with the target surrounded by 8 Ge and 12 NaI detectors.

- Each of the 8 Ge clovers used in the setup is segmented into 4 crystals (A, B, C, D) and segmented again into parts (1, 2, 3, 4).
- Segmentation provides for careful consideration of Doppler corrections such as energy shifting and energy broadening.



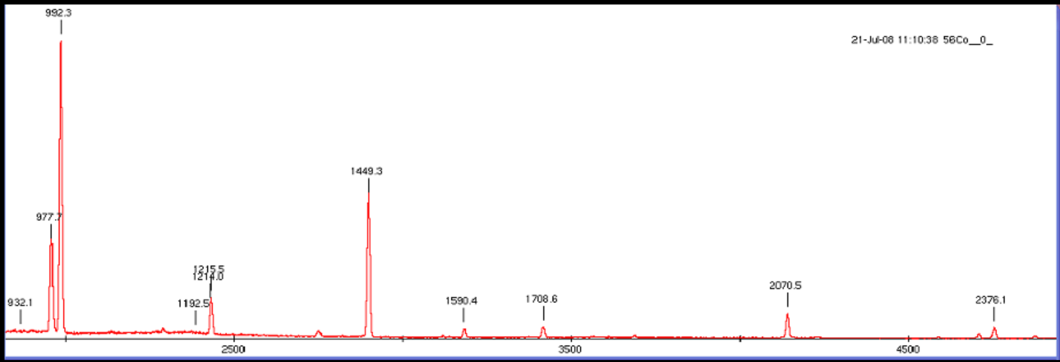
# Standard Gamma Calibration Sources

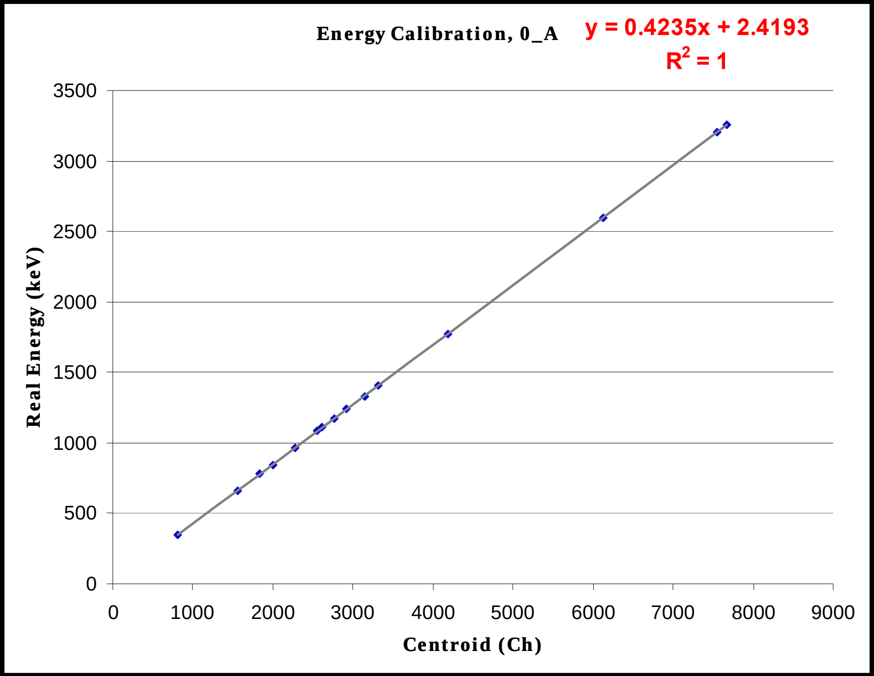
- Sources with well known emission spectra:
  - 60Co (1137keV, 1332keV)
  - 137Cs (662 keV)
  - 152Eu (up to 1.5 MeV)
  - 56Co (up to 3MeV)



# Energy Calibration

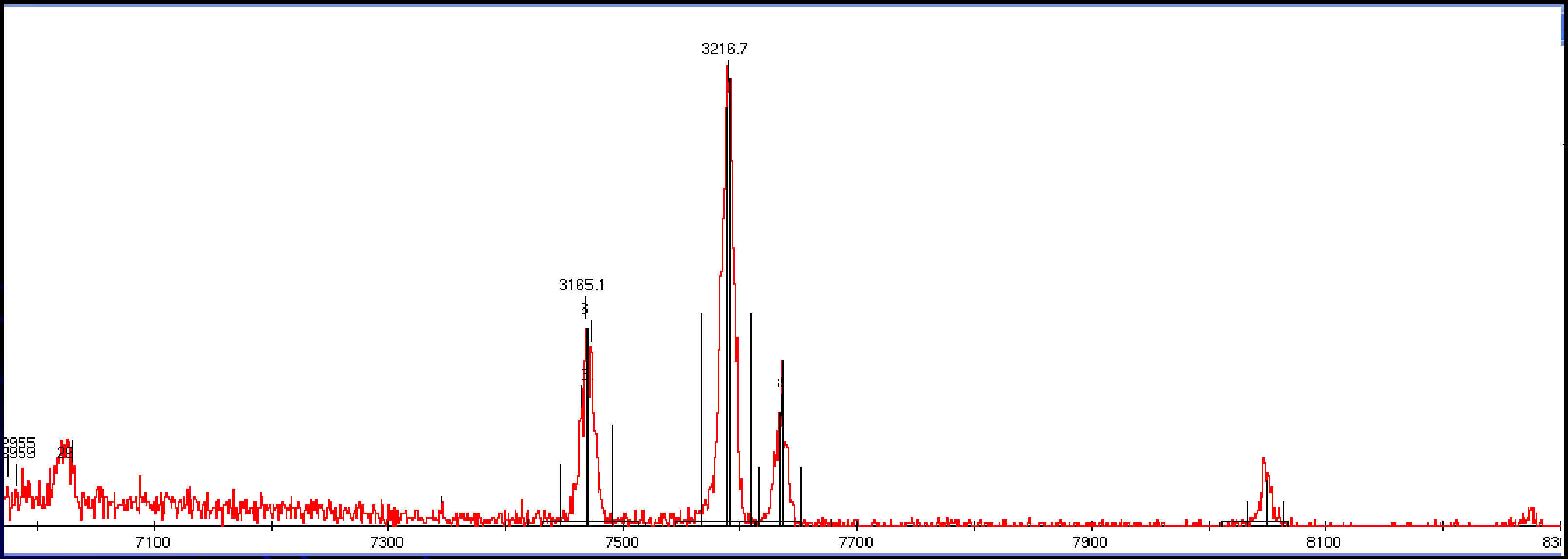
- In order to convert the electric signal of the detector (channel #) to energy (keV), an energy calibration must be performed
- Use RADWARE to measure the centroids and areas of each peak
- Plot centroids vs. known energies to find linear relation and analytical expression



# The Task

- Using RADWARE Software, analyze gamma spectra




- After performing the energy calibration, re-fit the peaks to calculate the corrected energies and the areas underneath each curve.

# Efficiency

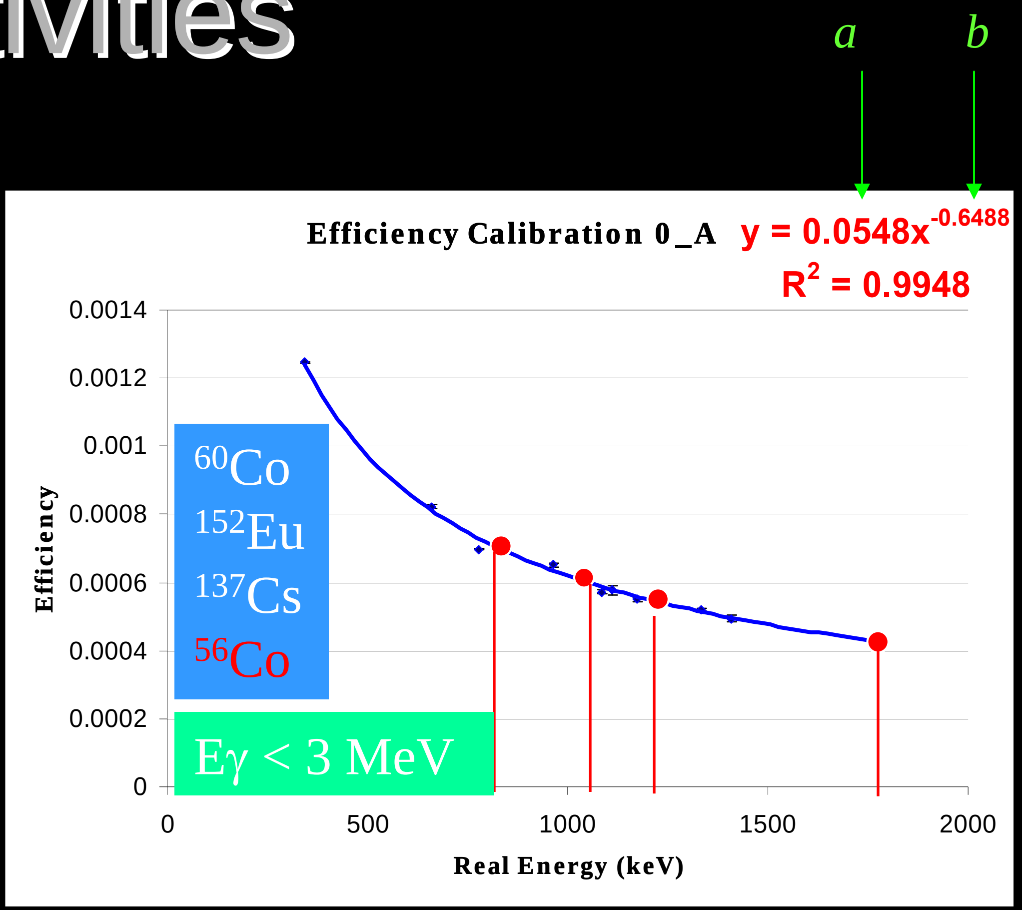
- Must know activity of each source at the time of the experiment
- Efficiency of the detector is dependent on the energy of each gamma ray
- Equations for Activity and Efficiency:

$$A(t) = A_0 e^{-\lambda t}$$

$$\varepsilon_{ph}(E_\gamma) = \frac{N(E_\gamma)}{A_o * \Delta t' * b_\gamma}$$

# Activities

- 60Co (1.1-1.2 MeV, 13988 Bq)
- 137Cs (0.6 MeV, 34825 Bq)
- 152Eu (121 keV-1.5 MeV, 23209 Bq)
- **56Co** (0.8 – 3.6 MeV, **unknown activity**).




**Above:** An efficiency calibration for one of the EXOGAM clovers. *Without 56Co we cannot extrapolate the analytical expression for the efficiency beyond 2 MeV.*

# Finding Coefficients

- Approximate analytical efficiency expression $y = ax^b$ as $ln(y)= ln(a)+bln(x)$ by using a Taylor expansion

$$\ln(y \pm \sigma_y) = \ln(y(1 \pm \frac{\sigma_y}{y})) = \ln(y) + \ln(1 \pm \frac{\sigma_y}{y}) \rightarrow \ln(1 \pm \frac{\sigma_y}{y}) = \frac{\sigma_y}{y} = \sigma_i$$

- Find $a$ and $b$ coefficients manually

$$a = \frac{1}{\Delta}\left(\sum \frac{x_i^2}{\sigma_i^2} \sum \frac{y_i}{\sigma_i^2} - \sum \frac{x_i}{\sigma_i^2} \sum \frac{x_i y_i}{\sigma_i^2}\right)$$

$$b = \frac{1}{\Delta}\left(\sum \frac{1}{\sigma_i^2} \sum \frac{x_i y_i}{\sigma_i^2} - \sum \frac{x_i}{\sigma_i^2} \sum \frac{y_i}{\sigma_i^2}\right)$$

$$\Delta = \sum \frac{1}{\sigma_i^2} \sum \frac{x_i^2}{\sigma_i^2} - \left(\sum \frac{x_i}{\sigma_i^2}\right)^2$$

$$\begin{pmatrix} \sigma_a^2 & \sigma_{ab}^2 \\ \sigma_{ab}^2 & \sigma_b^2 \end{pmatrix} = \frac{1}{\Delta}\begin{pmatrix} \sum \frac{x_i^2}{\sigma_i^2} & -\sum \frac{x_i}{\sigma_i^2} \\ -\sum \frac{x_i}{\sigma_i^2} & \sum \frac{1}{\sigma_i^2} \end{pmatrix}$$

# Procedure

- Determine analytical expressions of the efficiency for each of the 32 crystals
- Apply those analytical expressions to the low $\gamma$-ray energies of 56Co:
  - energies: 846.76 keV, 1238.27 keV, and 1771.32keV
- Manipulate efficiency equation and solve for activity
- Calculate the activity of $^{56}Co$ using the low energies

**1.**

$$Activity = \frac{N(E_\gamma)}{\varepsilon * \Delta t' * b_\gamma}$$

**2.**

20405 ± 107

20604 ± 157

20994 ± 311

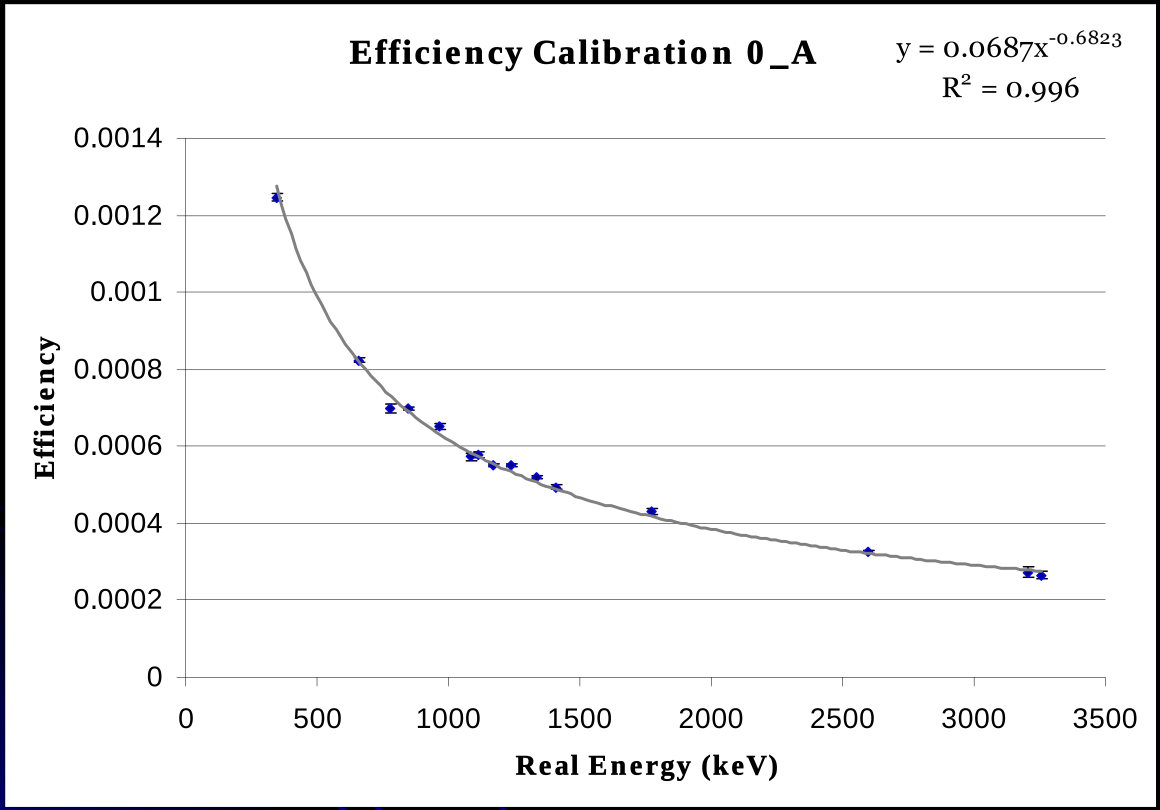
...

**3.**

**<Ā> =20238 ± 16 Bq**

$$\bar{A} = \frac{\frac{A_1}{\sigma^2_{A_1}} + \frac{A_2}{\sigma^2_{A_2}} + \ldots \frac{A_n}{\sigma^2_{A_n}}}{\frac{1}{\sigma^2_{A_1}} + \frac{1}{\sigma^2_{A_2}} + \ldots \frac{1}{\sigma^2_{A_n}}}$$

# Results




- The total efficiency calibration for the whole energy range of interest (up to 3 MeV) of an EXOGAM clover.
- The same work was done for each of the 32 crystals of the EXOGAM setup.

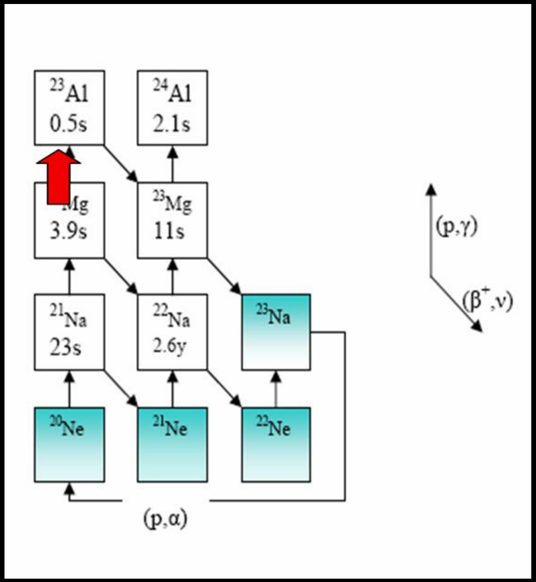
# Acknowledgements

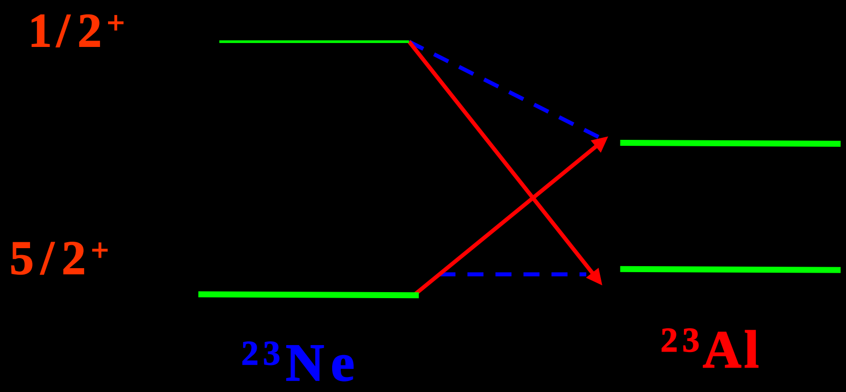
- Special thanks to Dr. Carl A. Gagliardi and Dr. Adriana Banu for their guidance and support during the project.
- Also thank you to Dr. Livius Trache, Ellen Simmons, and Alexandra Spiridon for their advice and aid during the summer.

# Backup Slides

# Motivation for Experiment

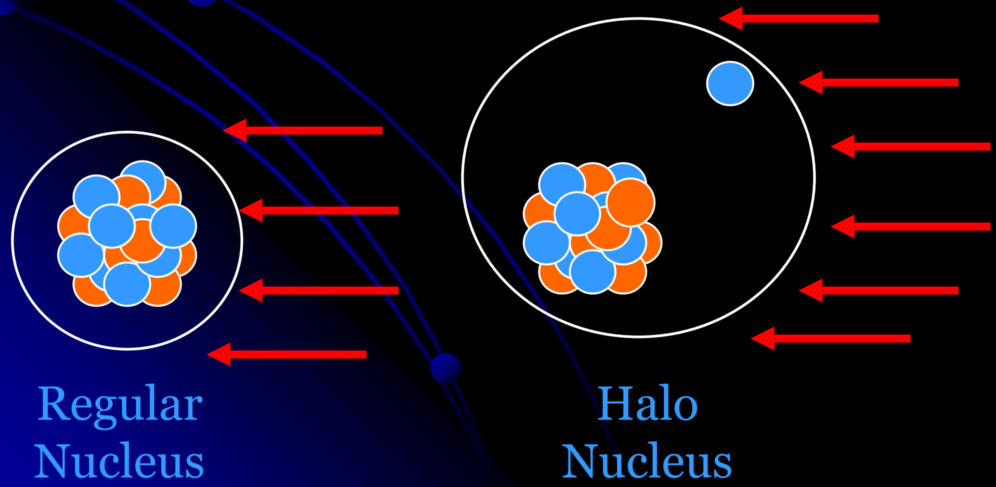
- Astrophysics
  - No evidence so far for the expected 1.25MeV gamma ray following the decay of $^{22}$Na
  - What is the reaction rate for $^{22}$Mg(p,γ)$^{23}$Al?
- Nuclear Physics
  - The nuclear structure of $^{23}$Al is not precisely known
  - Is mirror symmetry with $^{23}$Ne broken?

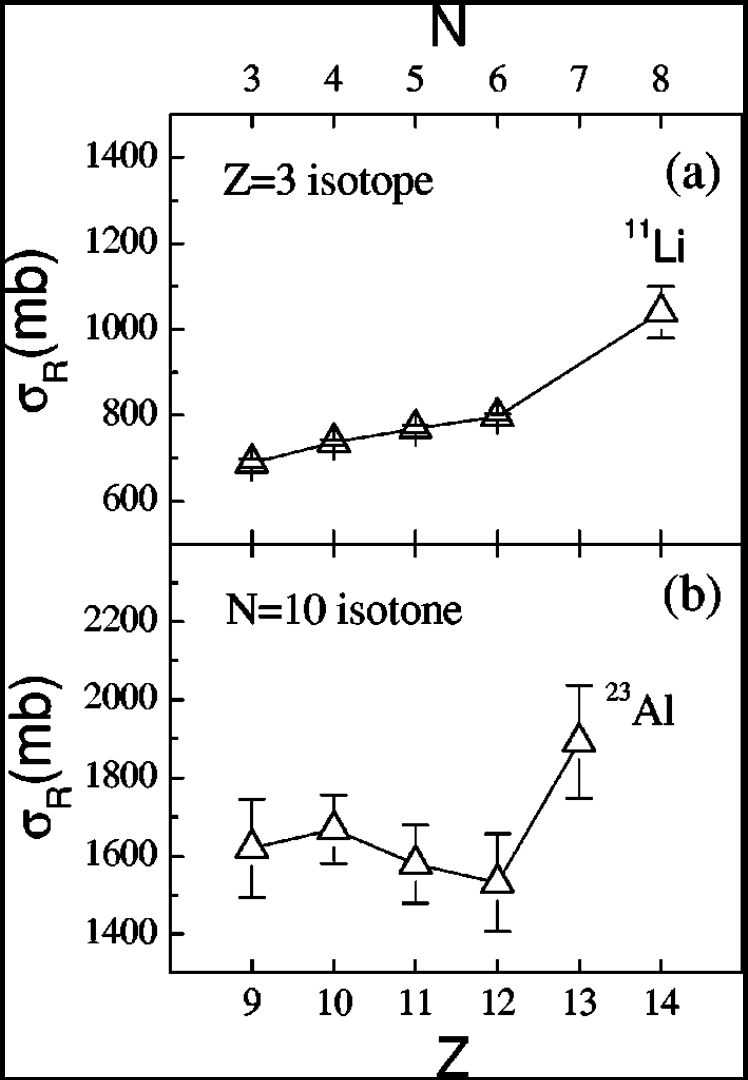


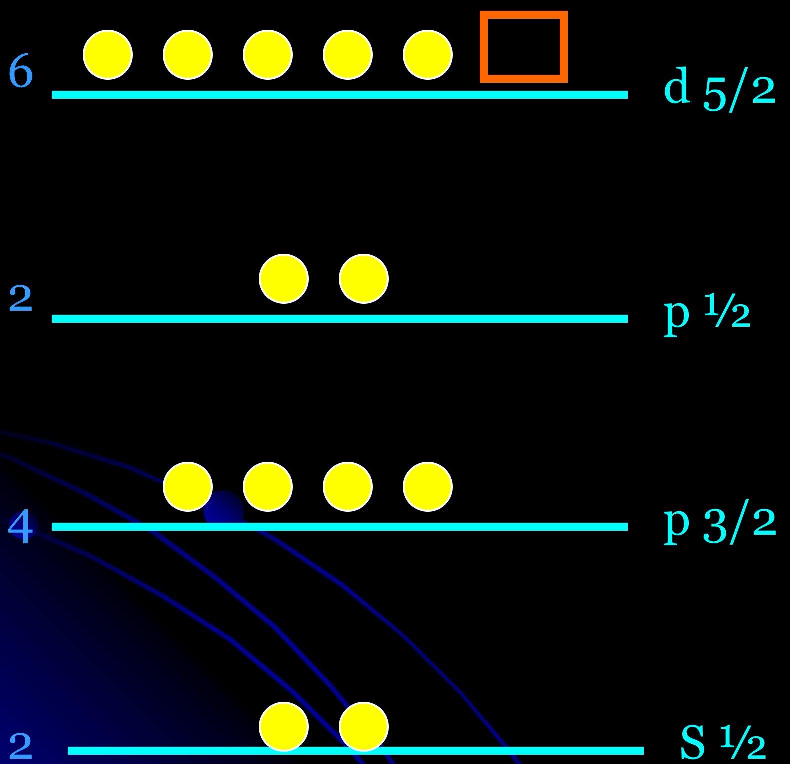
# Motivation, continued

- Understanding the Nuclear Force
  - how is the outer-most proton on the liquid drop line bound to the rest of the nucleus?
- Chinese physicists observed a very large cross sectional area for $^{23}Al$, similar to large $\sigma_R$ of the known halo nucleus $^{11}Li$
  - Is $^{23}Al$ a halo nucleus?



# Nuclear Shell Structure

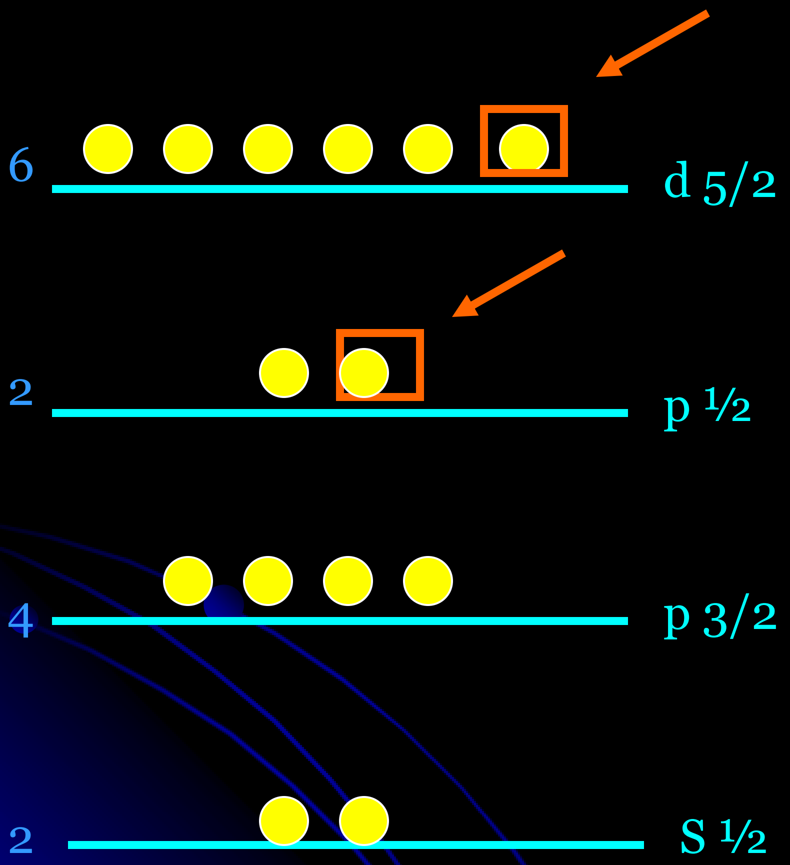



Shell Structure of $^{23}$Al Nucelus

Z=13

- The energy levels increase with increasing orbital quantum number, l.
  - The value of l determines the orbital → s, p, d, f… also like the atomic case
    - l = 0, s shell
    - l = 1, p shell
    - l = 2, d shell
    - …
- Spin # j = l ± s
  - (always positive)
- The number of nucleons allowed in a shell depends on the value j, which is a combination of l and the intrinsic spin, s.
  - ***# nucleons in a shell= 2j+1***

# Ground State Spin




Shell Structure of $^{23}$Al Nucelus

Z=13

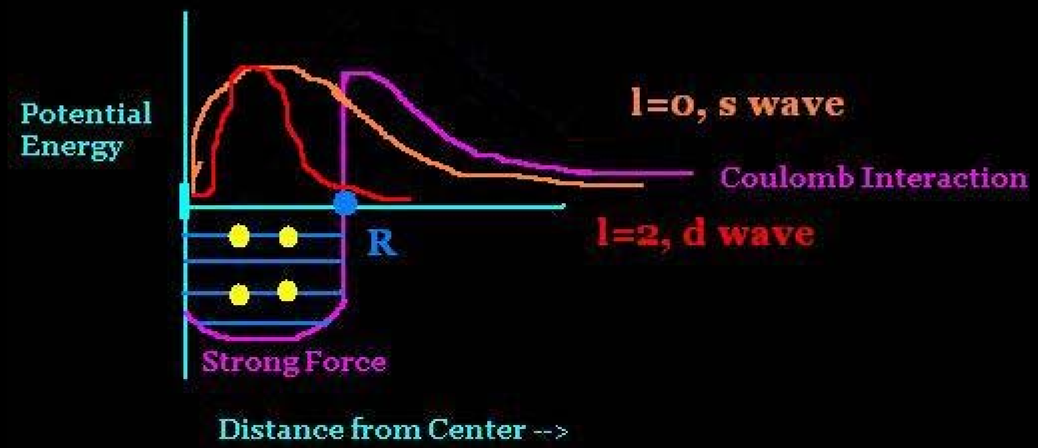
- Ground state spin is given the j value of the particular shell where last bound nucleon sits.
- Previous experiments showed g.s. spin of 5/2
  - Chinese showed it was possible for the spin to be ½,
    - Evidence for halo nucleus
- How do we figure out which one it really is?
  - In a slightly round about way…Gamma rays!

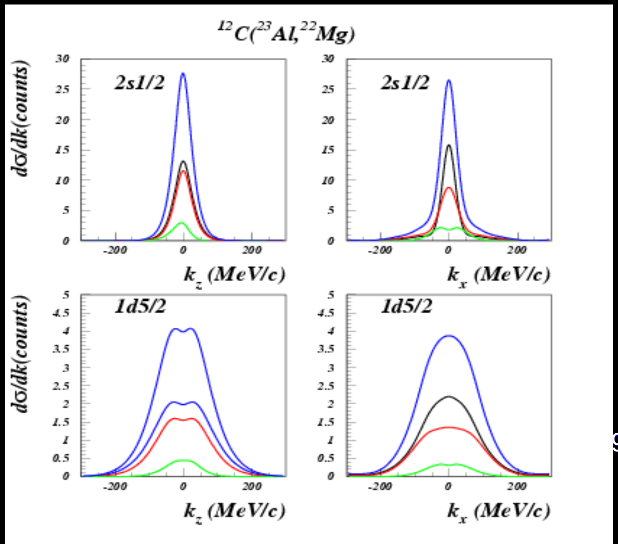
# Configuration Mixing

- Total spin can result from a combination of the wave functions
- $^{22}Mg$ is an even-even nucleus (same numbers of protons and neutrons
  - even-even nuclei have possible j= $0^+$, $2^+$, $4^+$..
  - Exact value j can be determined by the energies of detected gammas emitted from excited states in $^{22}Mg$ core
- Once j is known, then by the conservation of momentum, total spin must be conserved in the reaction
  - $^{23}Al \rightarrow {}^{22}Mg + p^+$
    $5/2 \rightarrow \#(\gamma) + ?$
  - (0, **5/2**) or (2, **½**)

# What the spin tells us

- Spin ½ indicates a s orbital
  - Large, spread out wave function
  - Narrow, very sharp momentum distribution
- Spin 5/2 indicates d orbital
  - Smaller, more contracted wave function
  - Wider, more flat momentum distribution
- Wider wave function provides evidence for a halo nucleus



# Compare Results

| | a (bev) | b (bev) | a (reg) | b (reg) |
|---|---|---|---|---|
| A | 0.0520 | -0.6343 | 0.0520 | -0.6348 |
| B | 0.0560 | -0.6438 | 0.0571 | -0.6478 |
| C | 0.0517 | -0.6307 | 0.0509 | -0.6292 |
| D | 0.0580 | -0.6571 | 0.0568 | -0.6546 |

| | σ_a (bev) | σ_b (bev) | σ_a (reg) | σ_b (reg) |
|---|---|---|---|---|
| A | 0.04741 | 0.00706 | 0.097218 | 0.01422 |
| B | 0.04712 | 0.00702 | 0.019463 | 0.01565 |
| C | 0.04695 | 0.00699 | 0.020979 | 0.01687 |
| D | 0.04796 | 0.007155 | 0.02305 | 0.01854 |

| | X^2 (Bev) | Unc | X^2 (Reg) | Unc |
|---|---|---|---|---|
| A | 14.9624 | 5.4736 | 16.1893 | 5.6902 |
| B | 19.9640 | 6.1388 | 24.6083 | 7.0154 |
| C | 17.411 | 5.0911 | 18.6705 | 19.5050 |
| D | 23.1725 | 6.8007 | 25.0205 | 7.0739 |