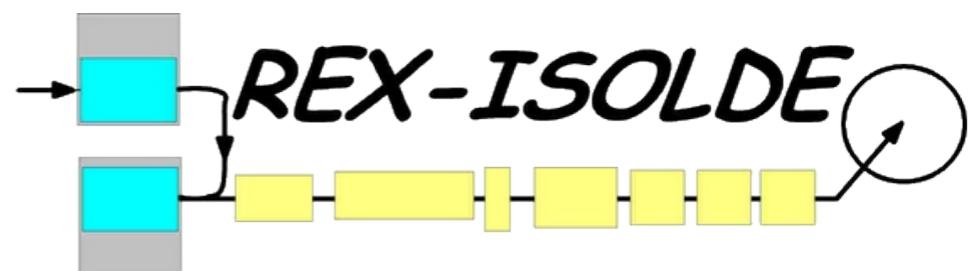


Octupole collectivity: Coulomb excitation of ^{224}Ra

Liam P. Gaffney

Peter A. Butler, Marcus Scheck

Oliver Lodge Laboratory, University of Liverpool

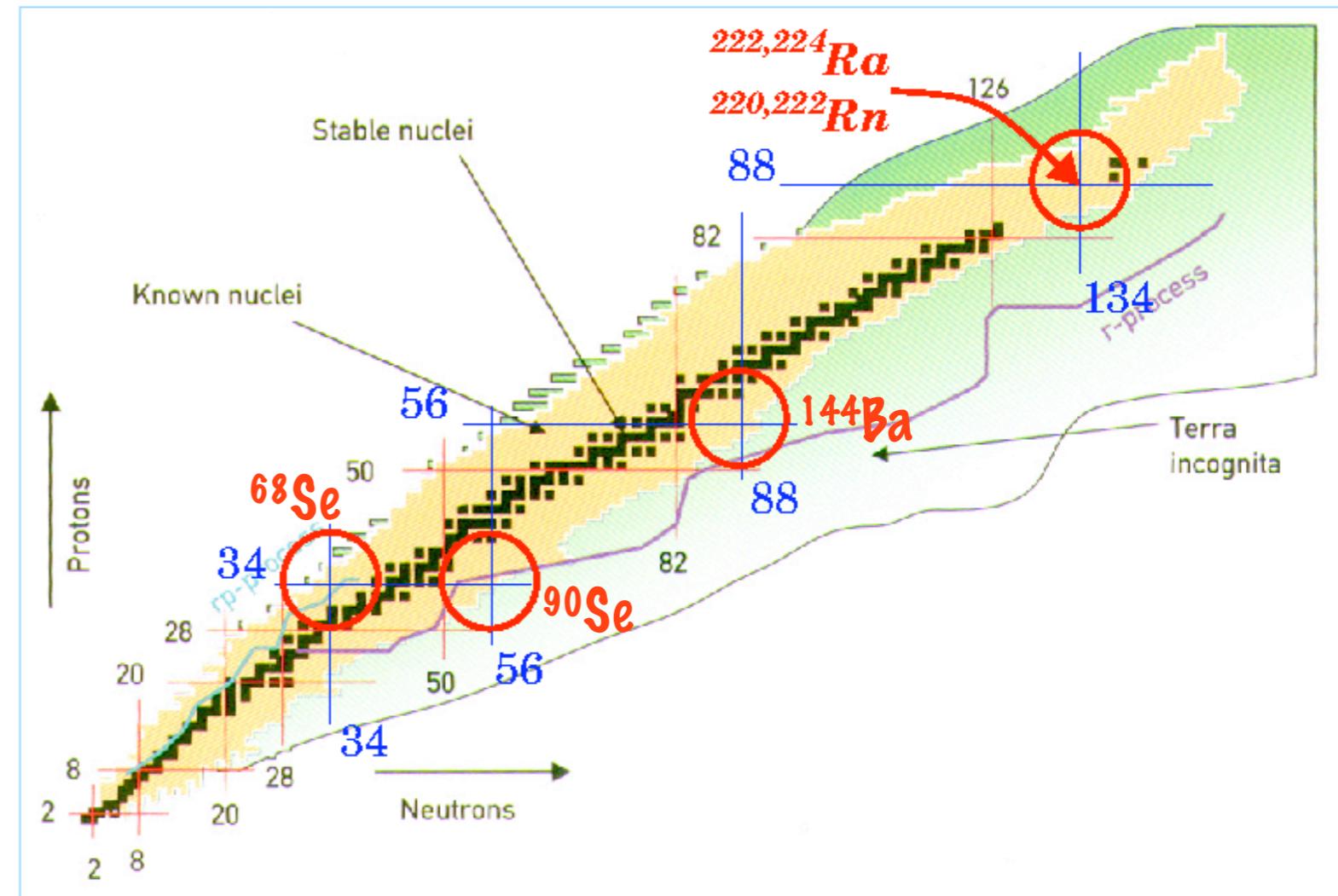
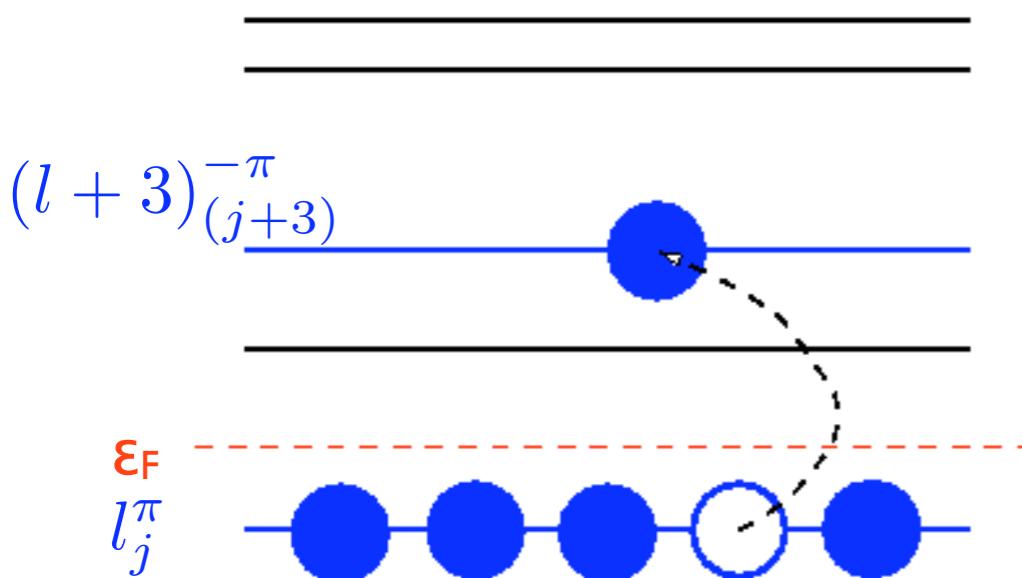


Octupole Collectivity

Octupole correlations enhanced at the magic numbers: **34, 56, 88, 134**

Microscopically...

Intruder orbitals of opposite parity and $\Delta J, \Delta L = 3$ close to the Fermi level



$^{220,222}\text{Rn}$ and $^{222,224}\text{Ra}$ lie near $Z=88, N=134$

$$\pi(f_{7/2} \rightarrow i_{13/2}) \quad \nu(g_{9/2} \rightarrow j_{15/2})$$

Octupole Collectivity

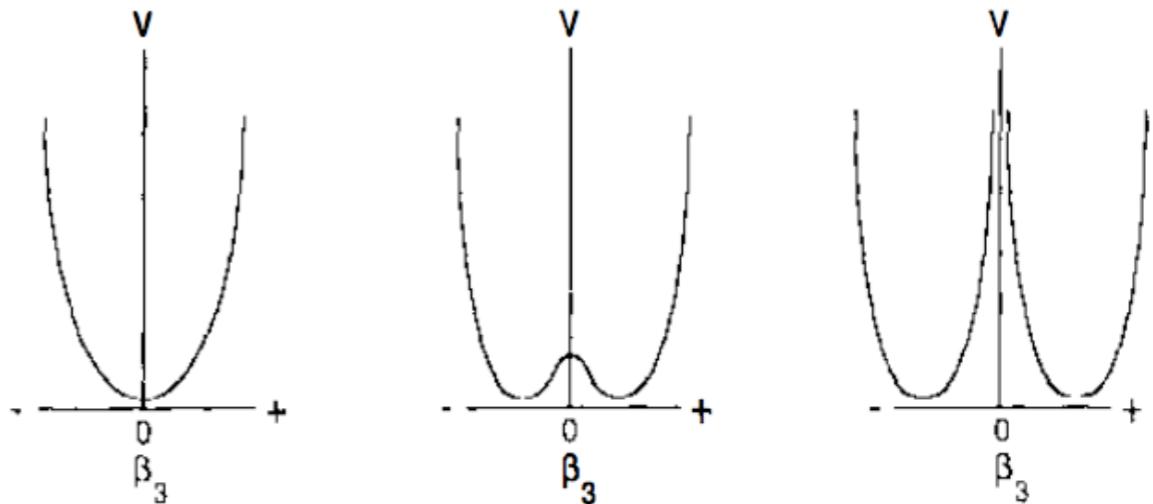
Macroscopically...



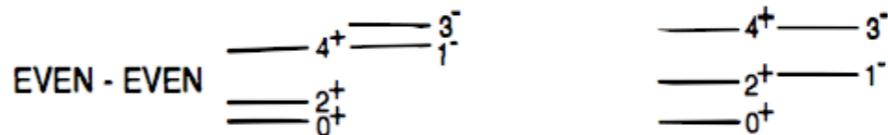
Nuclei take on a “pear” shape

Reflection asymmetric

- β_3 -vibration
- β_2 -deformation + β_3 -softness
- Static β_3 -deformation?



Signatures...



Odd-even staggering, negative parity

Image: I.Ahmed and P.A. Butler, Ann. Rev. Nucl. Part. Sci (1993) 43

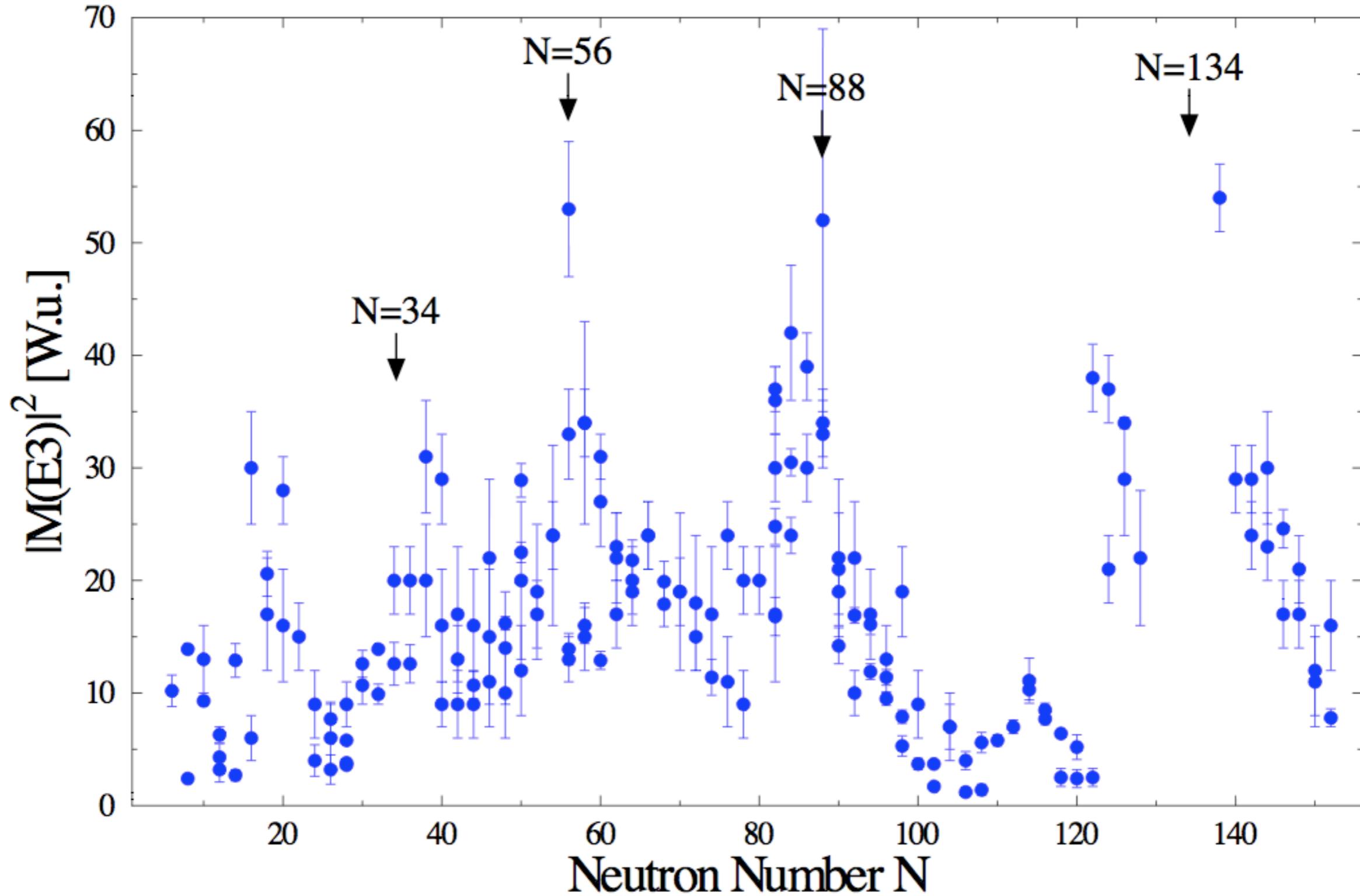
Parity doublets in odd-A nuclei

Enhanced EI transitions

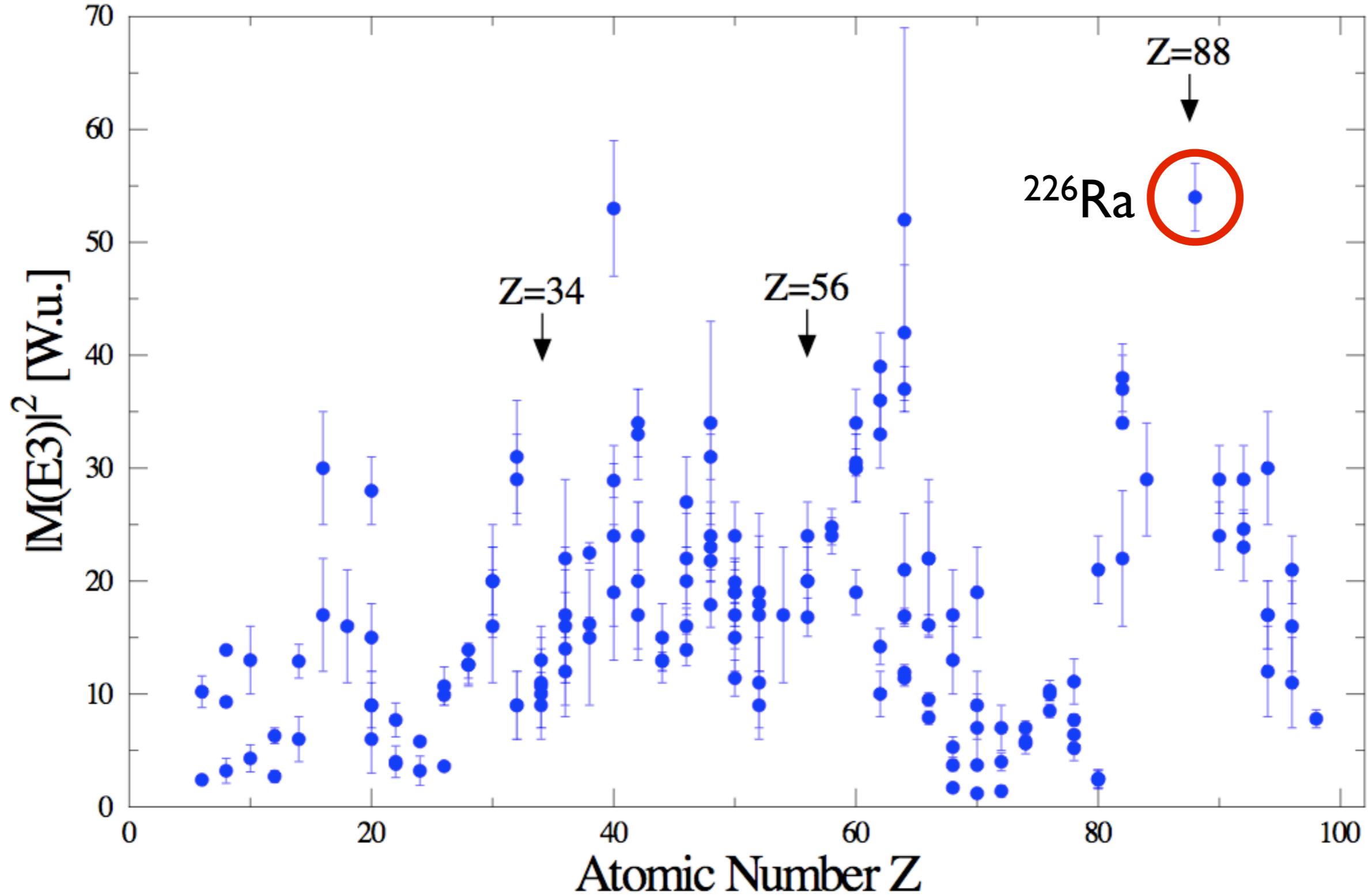
$$\text{Large E3 strength} \rightarrow B(E3; 0^+ \rightarrow 3^-) = \langle 0^+ | |E3| |3^- \rangle^2$$

2^L deformation -- β_L
L=2: Quadrupole, oblate/prolate shapes
L=3: Octupole, reflection asymmetry

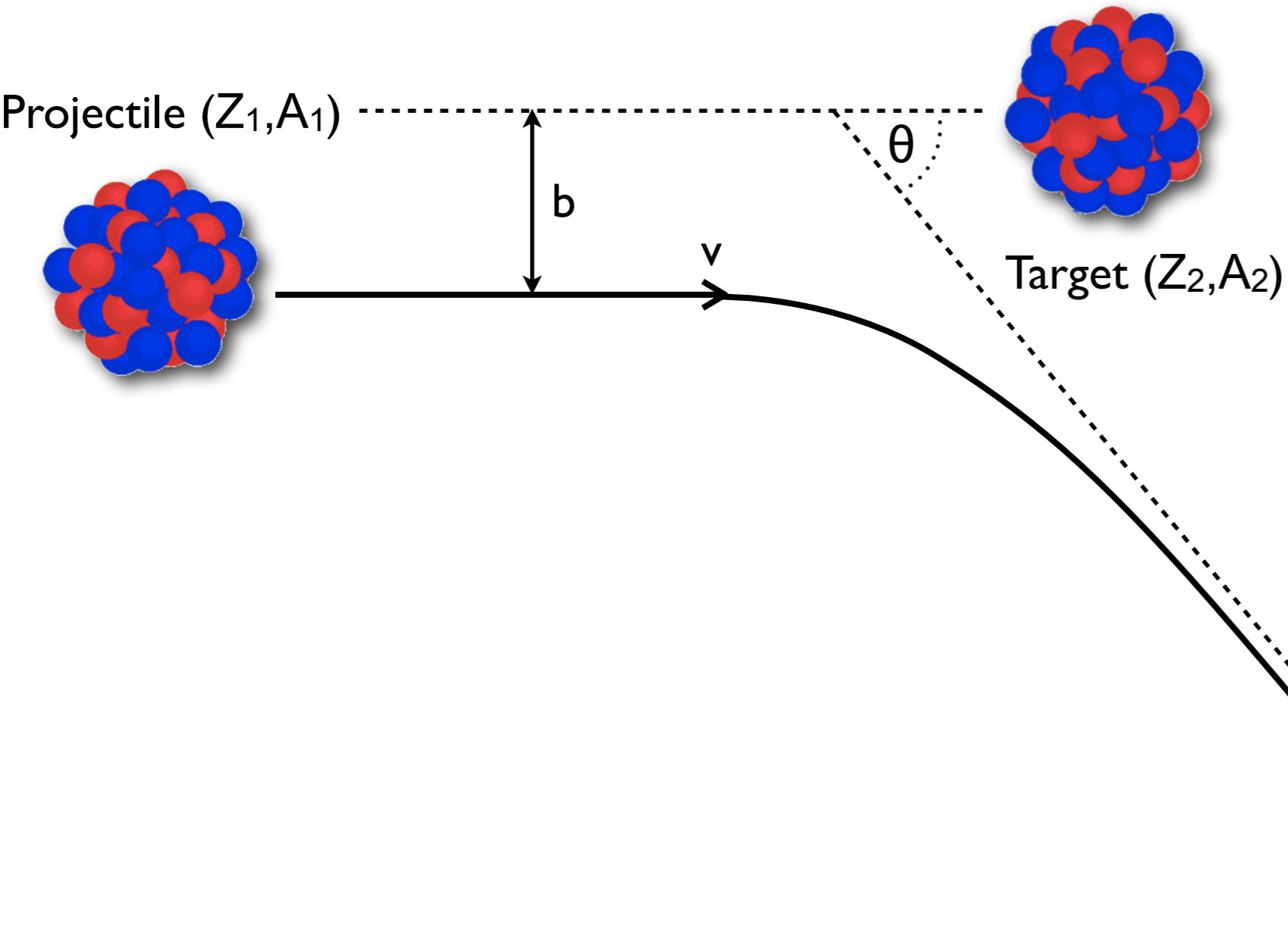
Octupole Collectivity



Octupole Collectivity



Coulomb Excitation



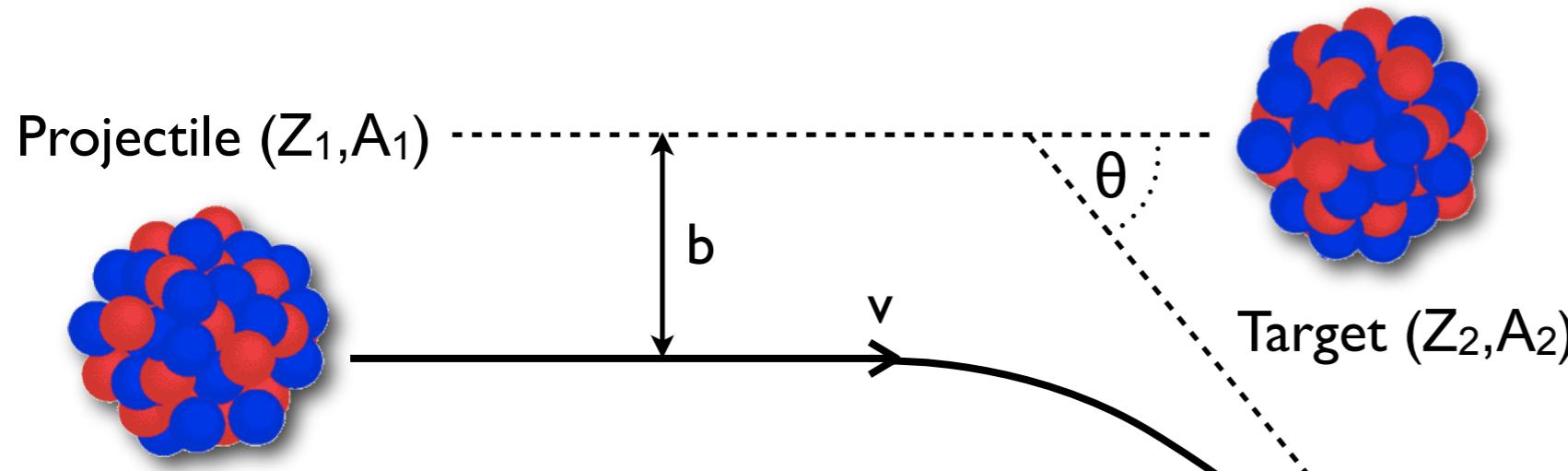
Sommerfeld parameter:

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

“Safe” Coulex:

$$\eta \gg 1$$

Coulomb Excitation

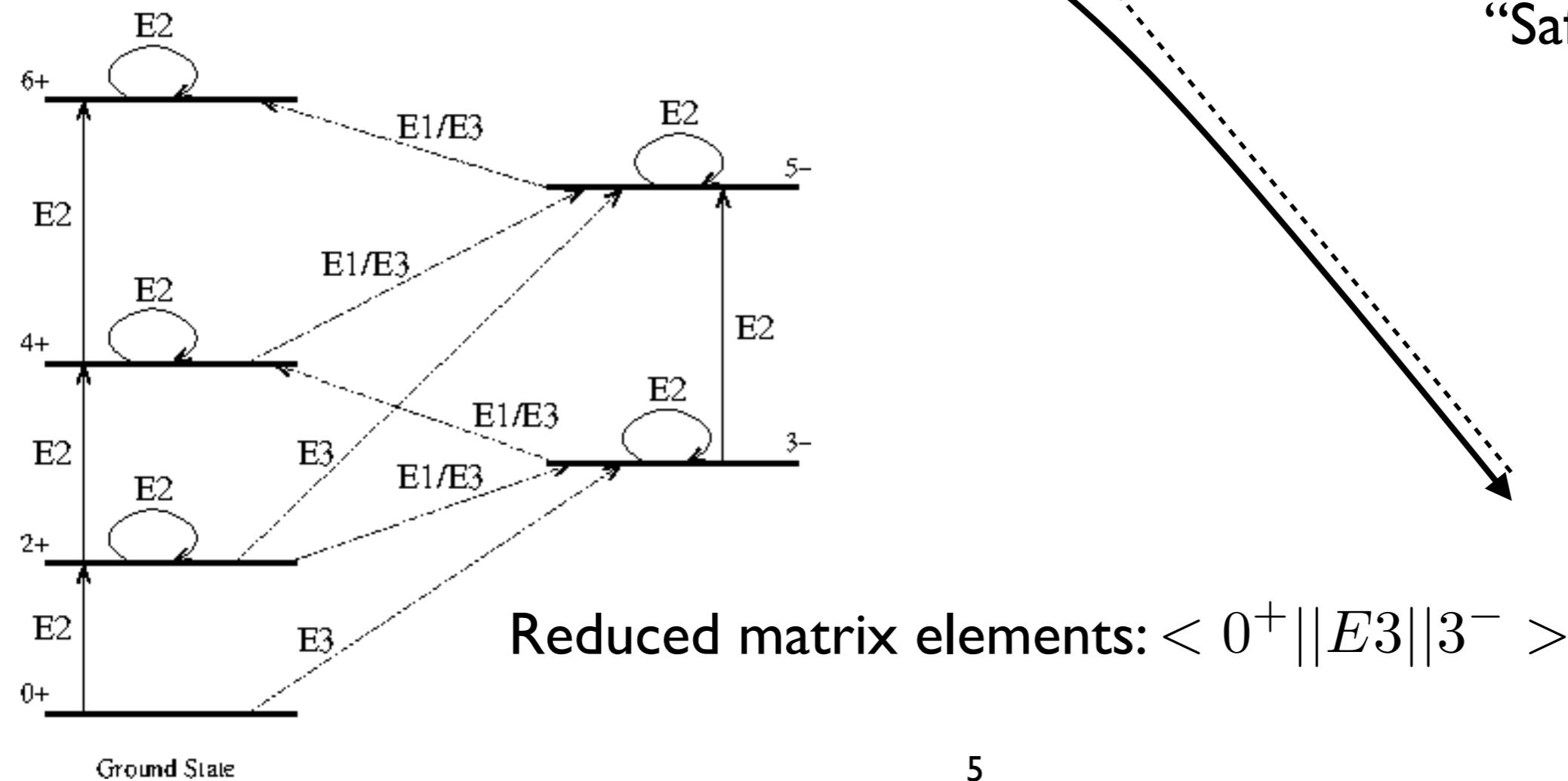


Sommerfeld parameter:

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“Safe” Coulex:

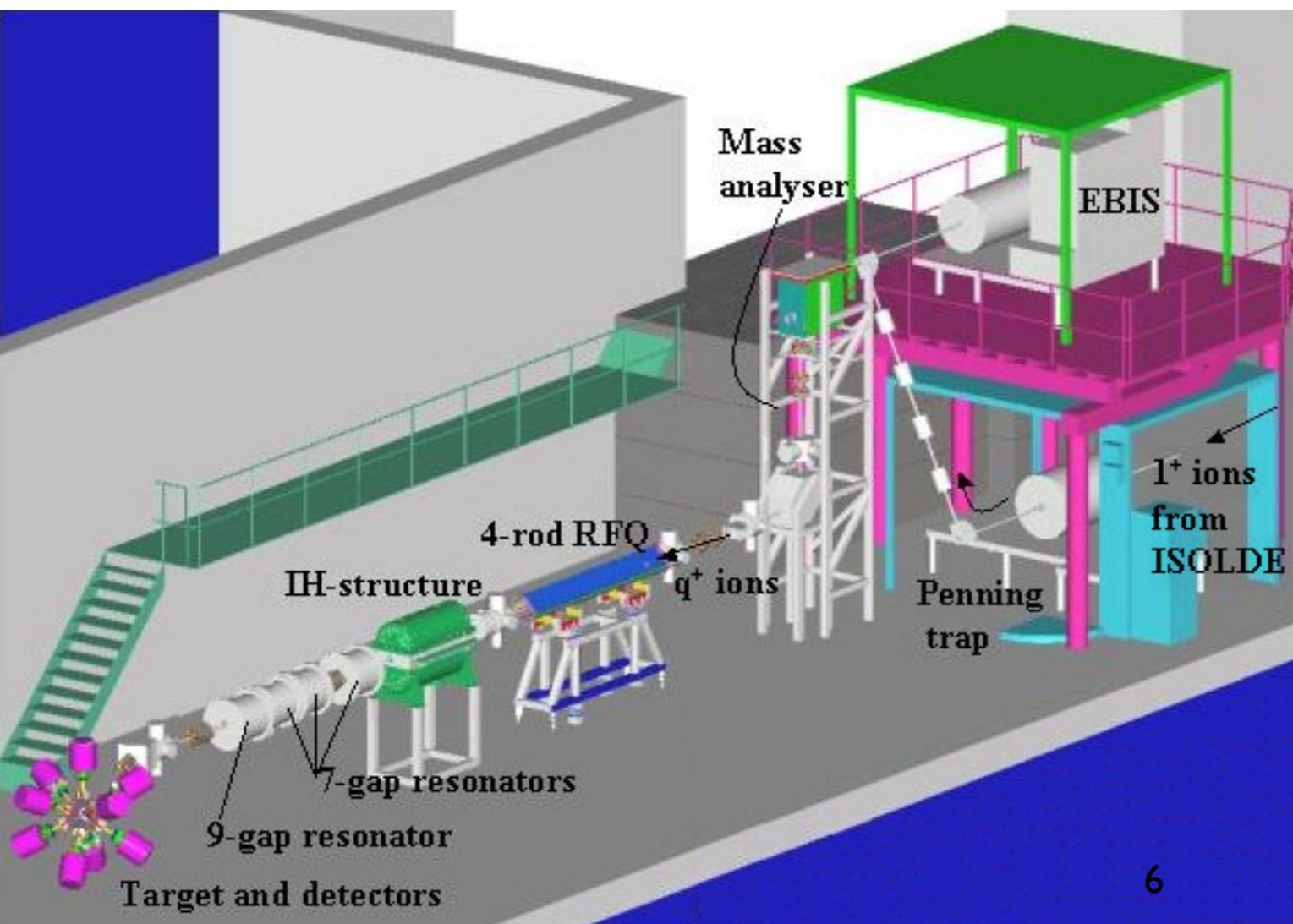
$$\eta \gg 1$$



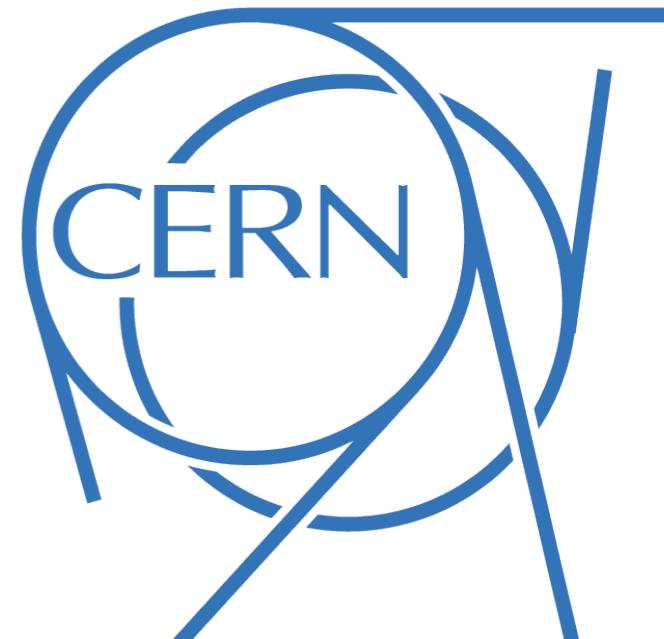
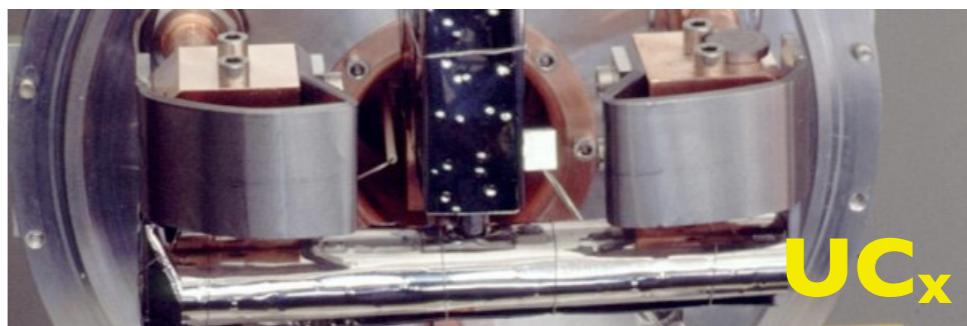
**Isotope
Separation
On-
Line
D ..?
E ..?**

**RIB
E-
Xperiment**

**Radioactive
Ion
Beam**



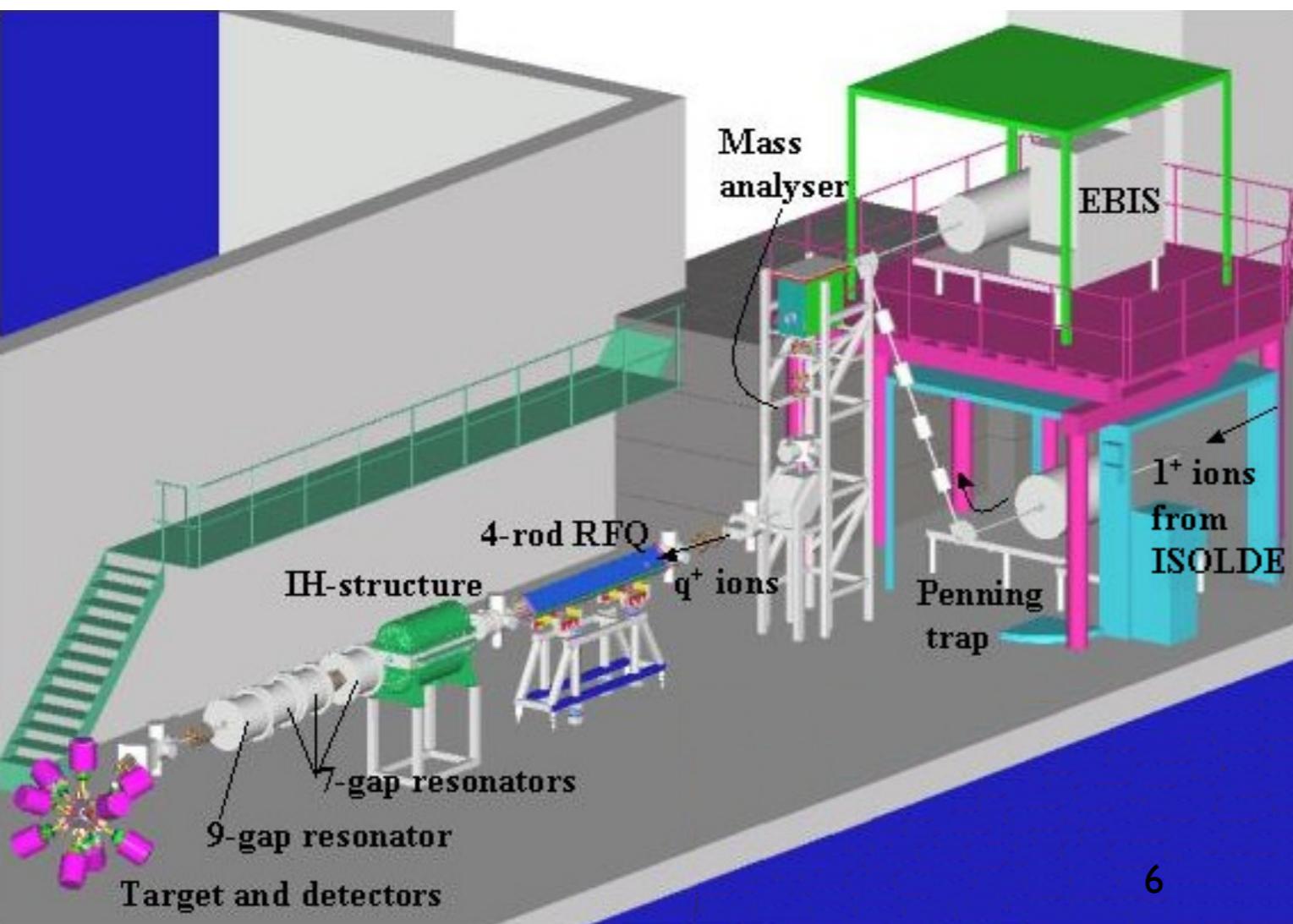
6



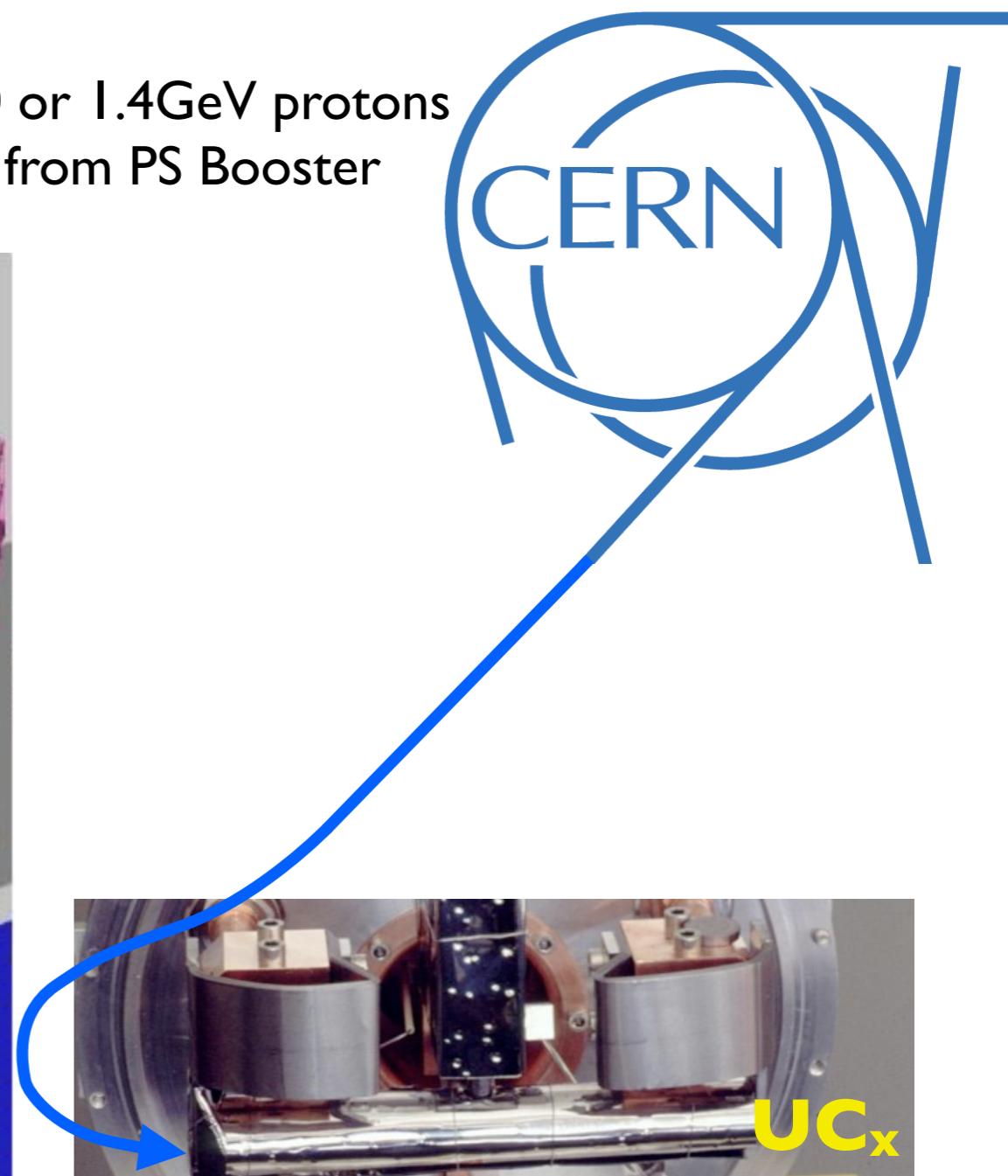
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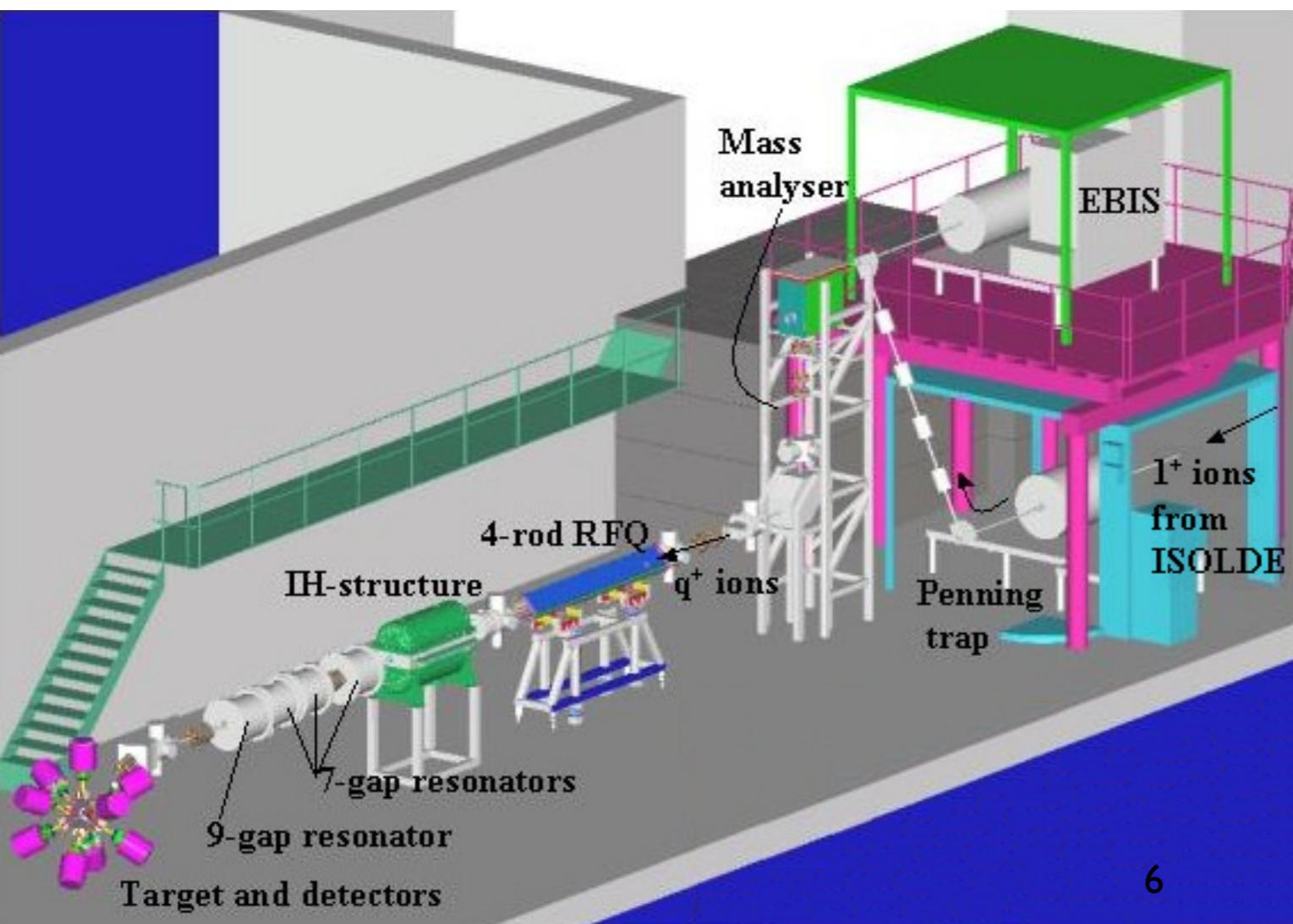
A 1.0 or 1.4GeV protons
from PS Booster



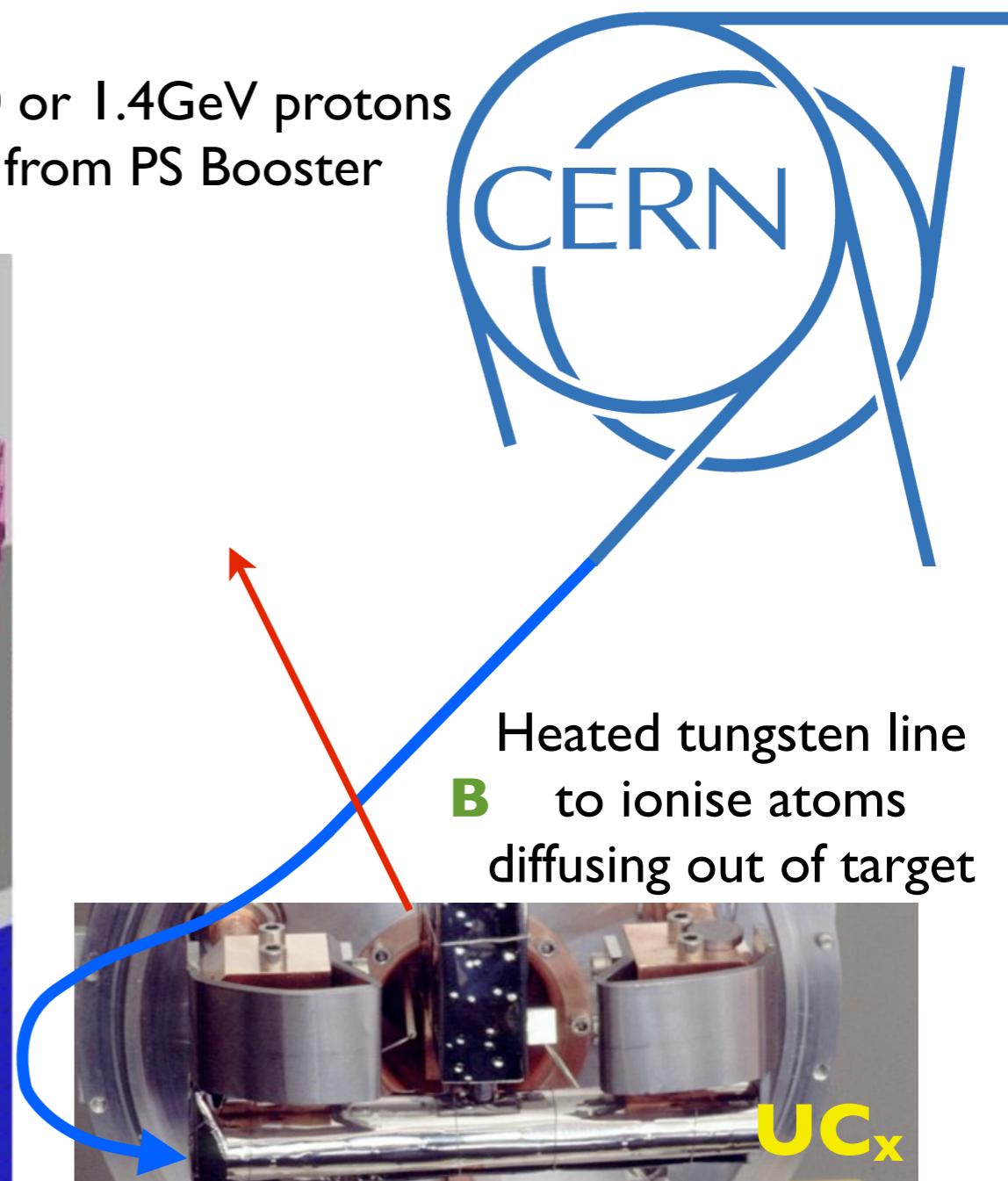
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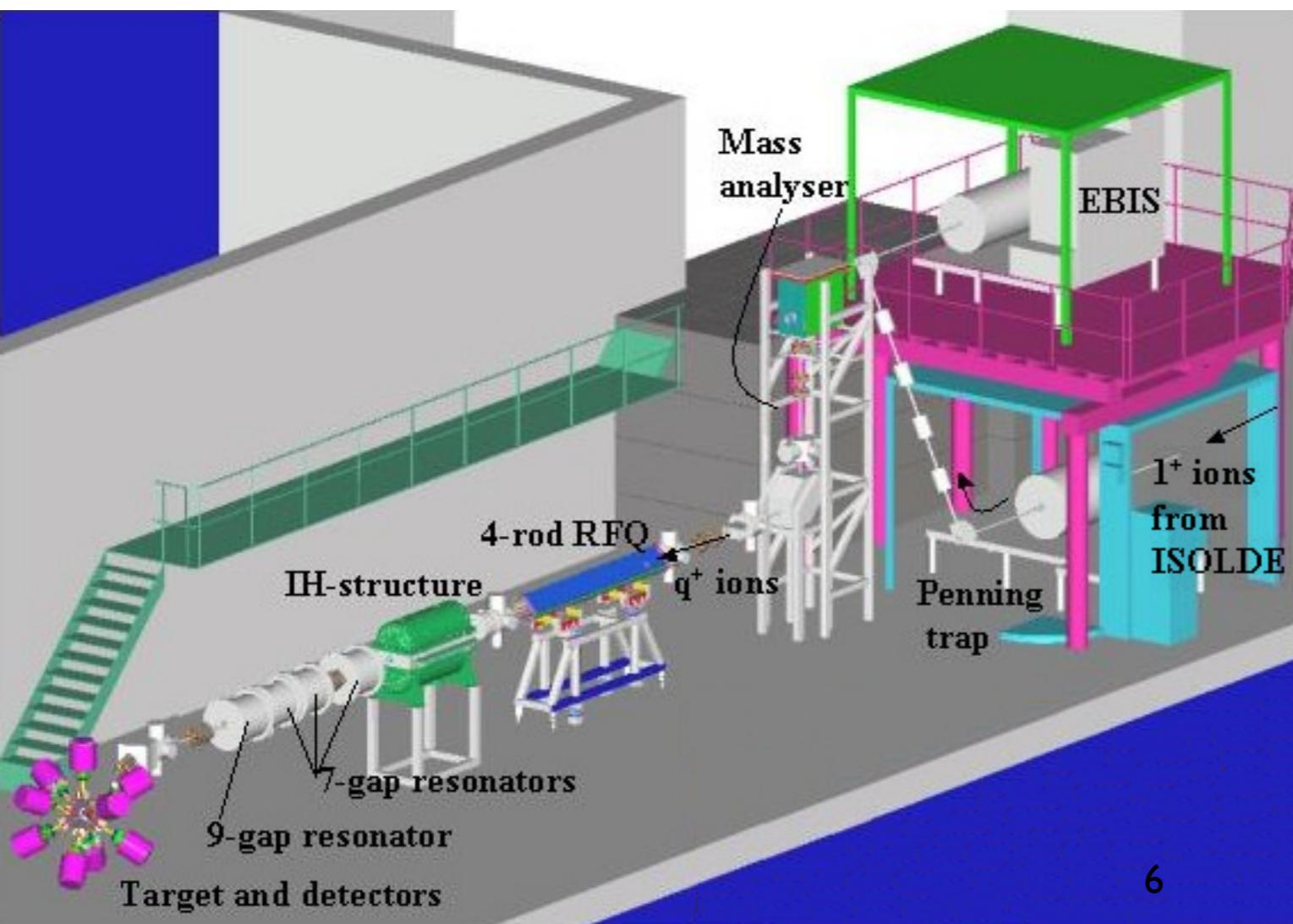
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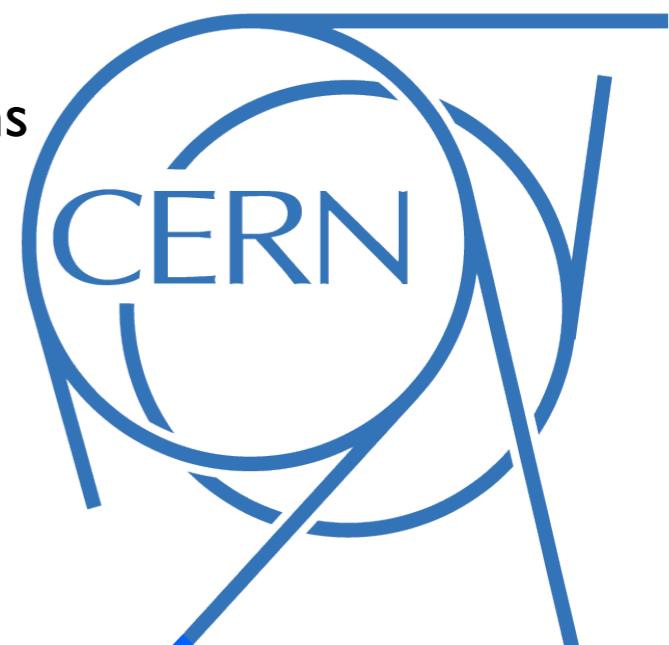


**Isotope
Separation
On-
Line
D ..?
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**RIB
E-
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**Radioactive
Ion
Beam**



A 1.0 or 1.4GeV protons
from PS Booster

C
Mass separation
in HRS

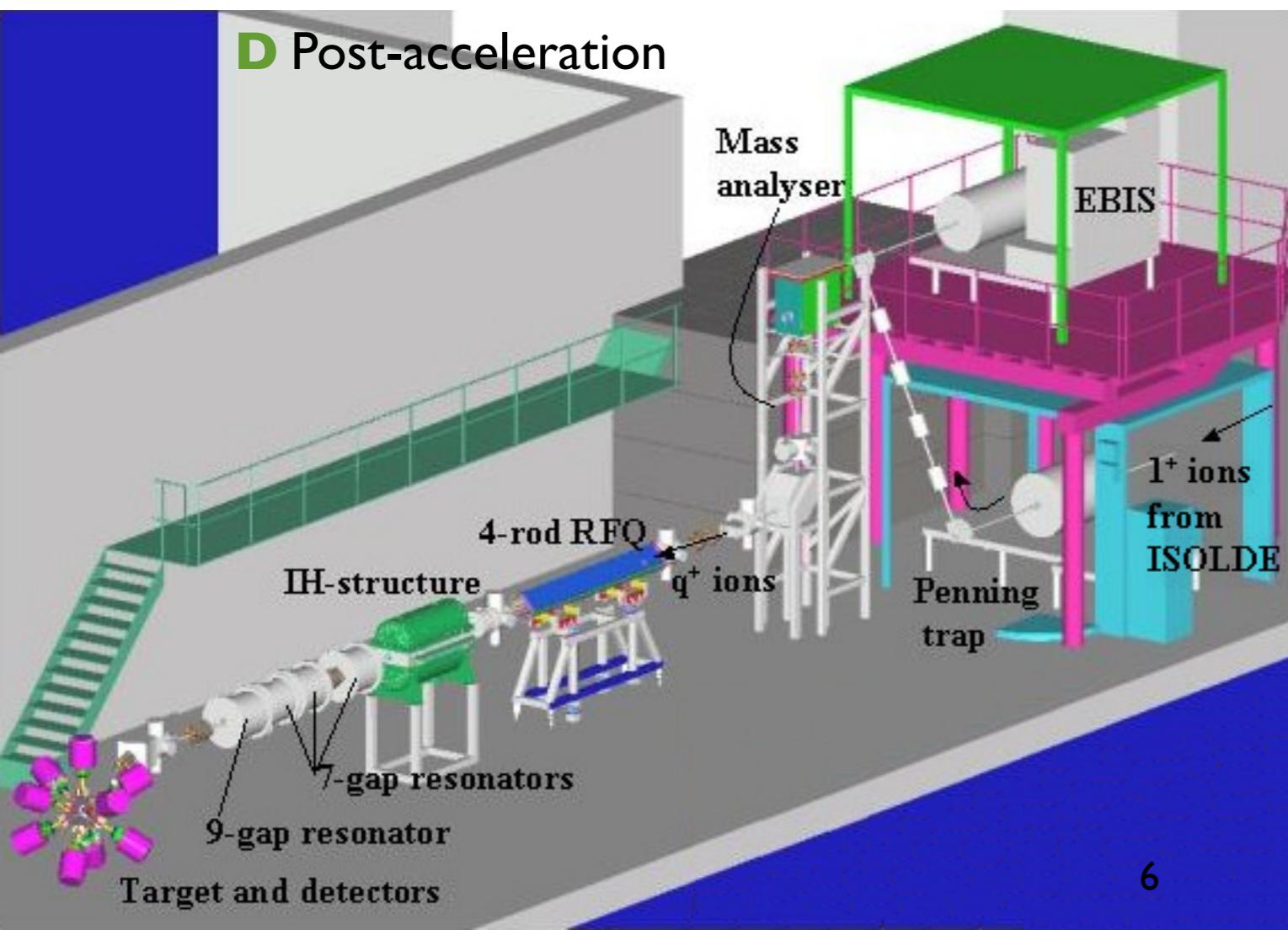


B Heated tungsten line
to ionise atoms
diffusing out of target



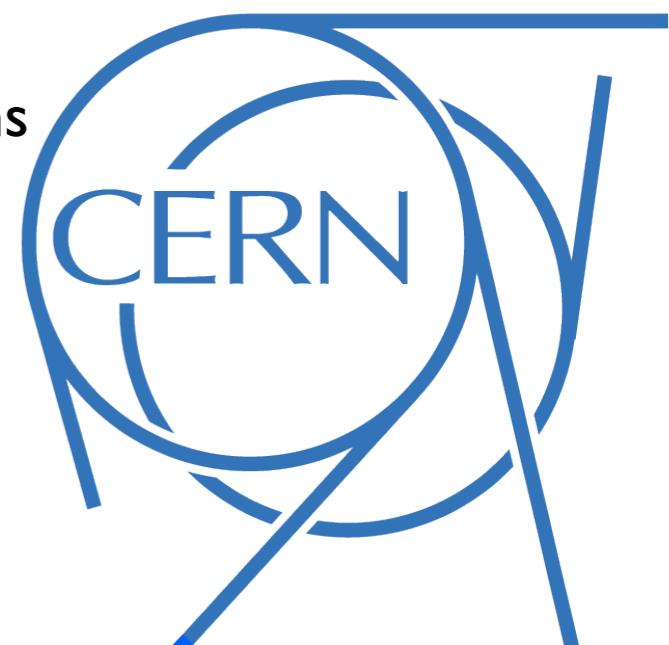
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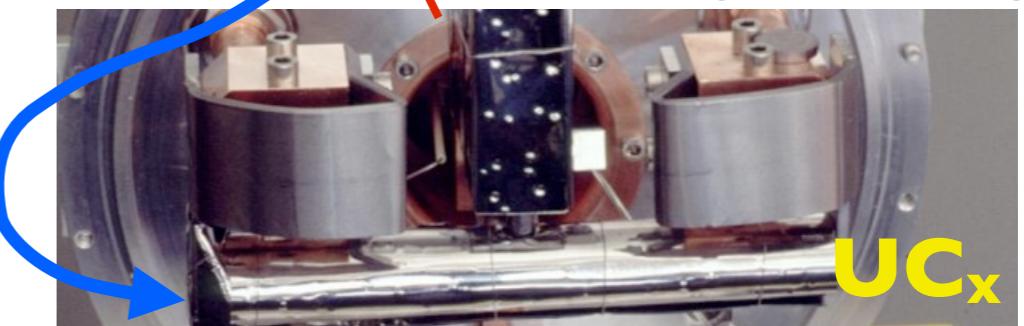


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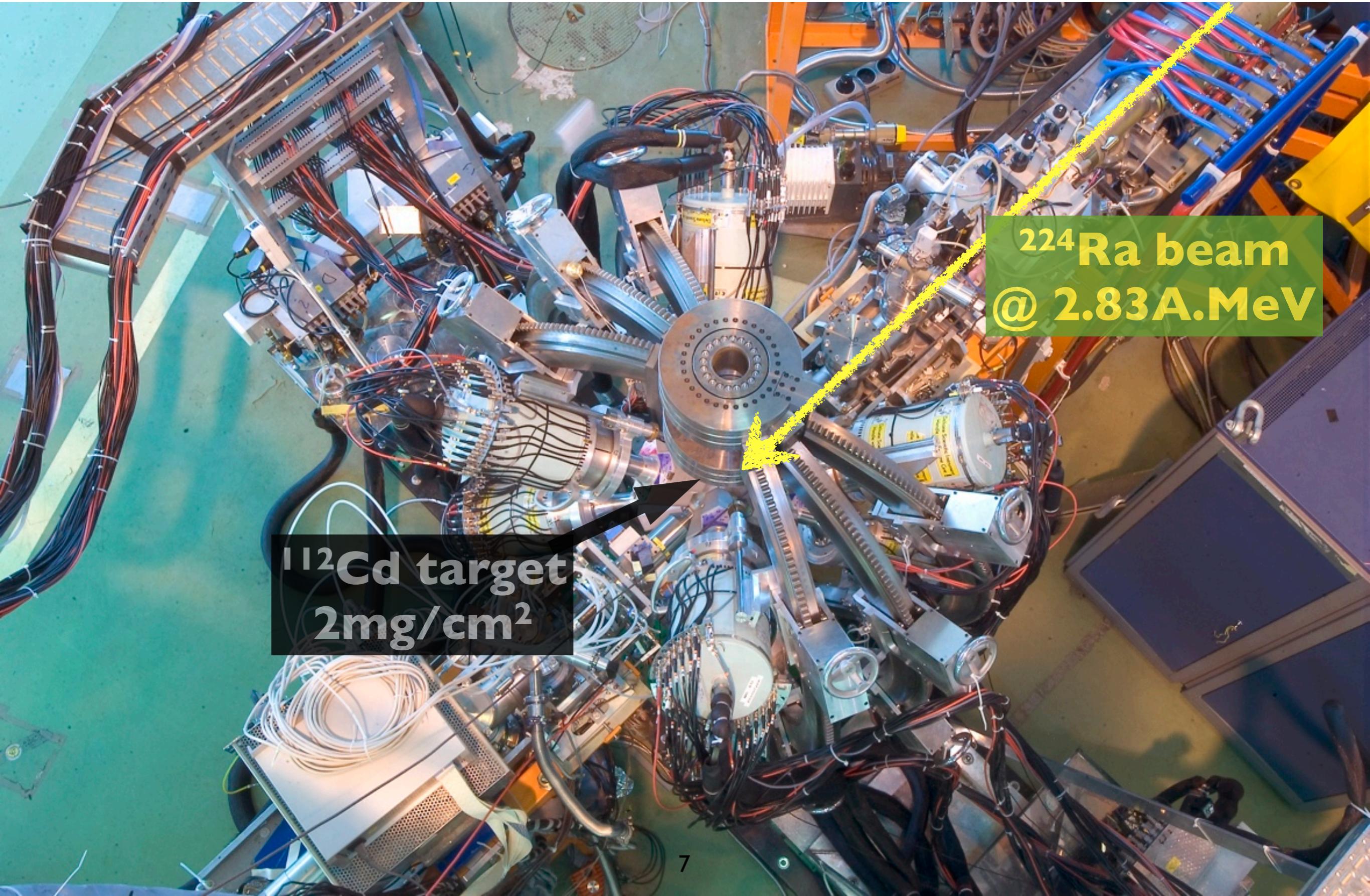
C Mass separation in HRS



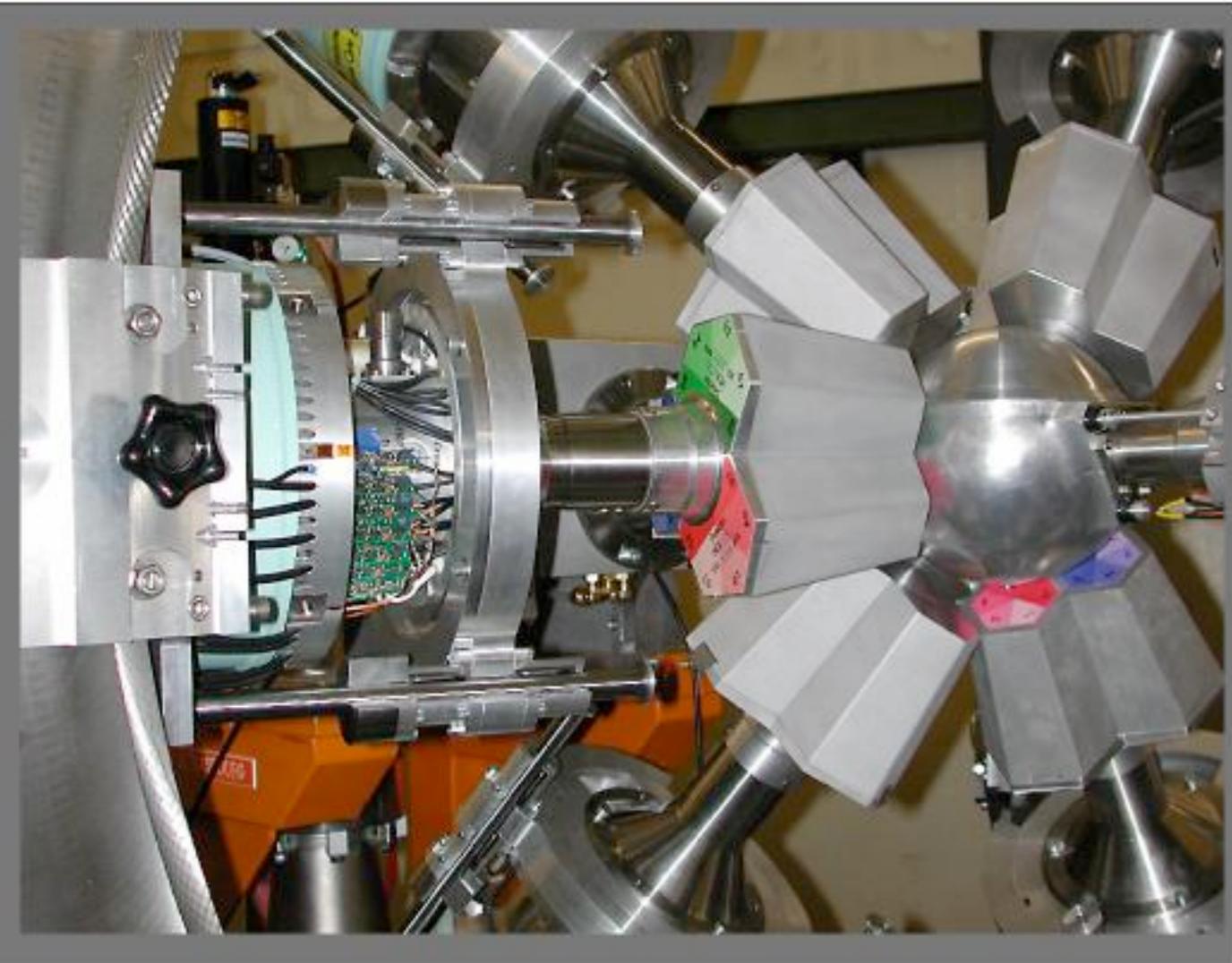
B Heated tungsten line to ionise atoms diffusing out of target



MINBALL

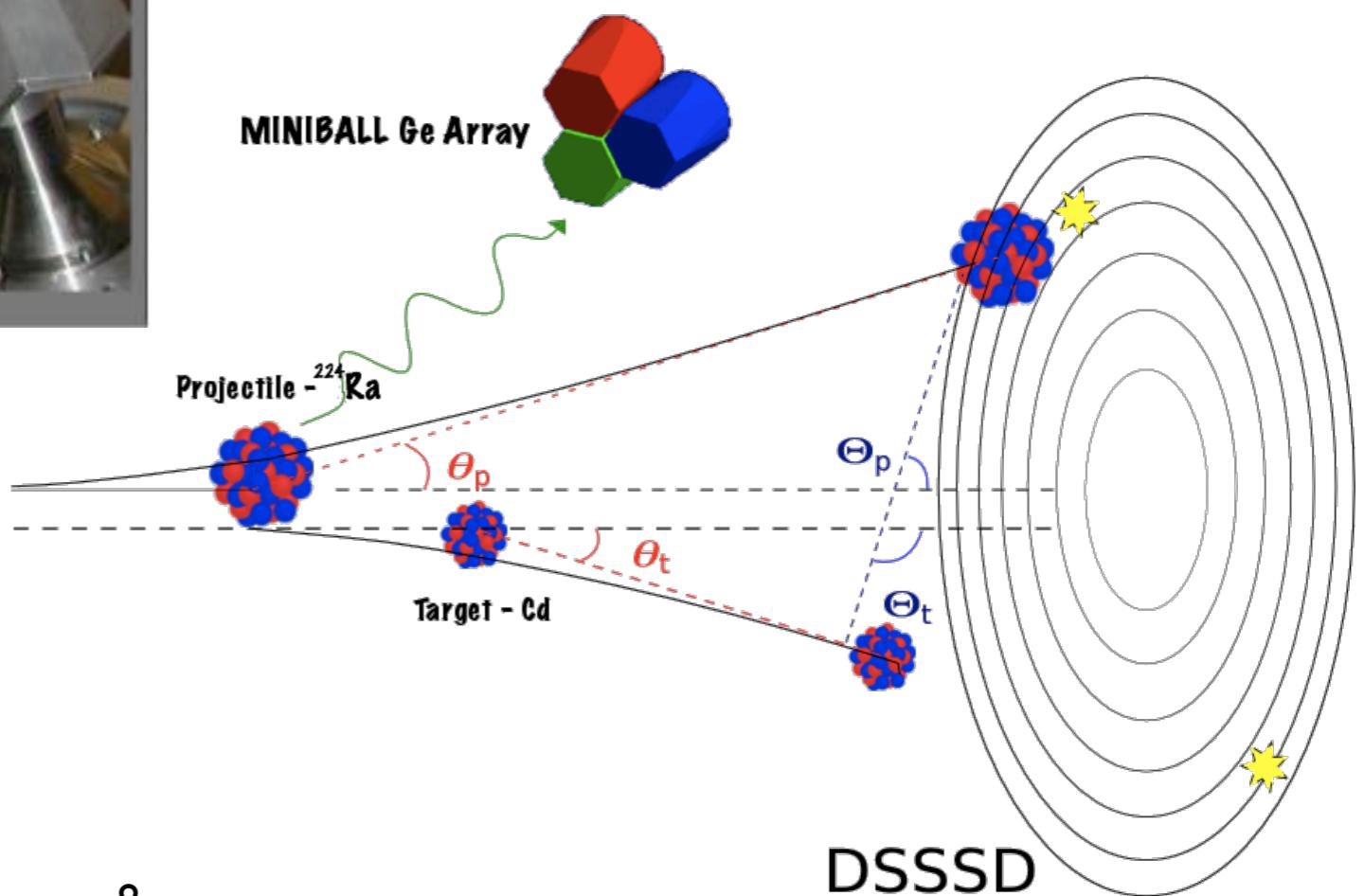
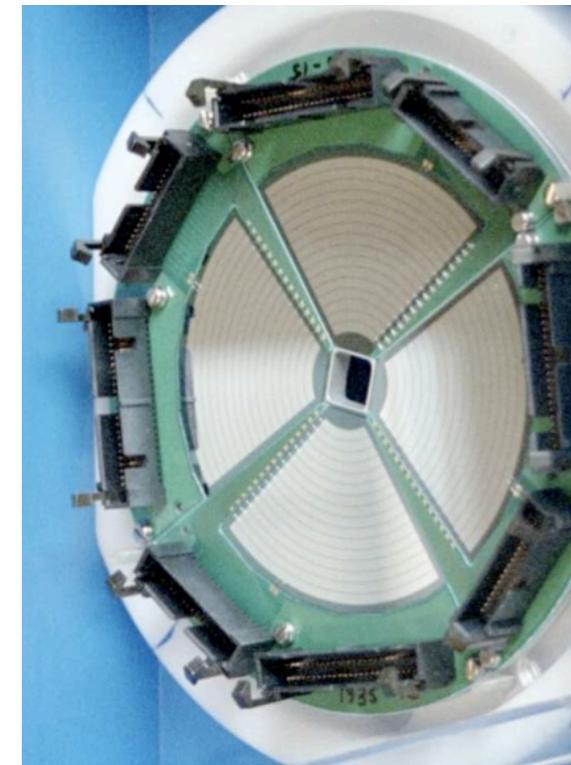


MINIBALL



- Array of HPGe of 8 triple clusters
- 6-fold segmentation for positioning
- $\epsilon > 7\%$ for 1.3MeV γ -rays

- Particle ID in a Double-Sided Si Strip Detector.
- Event by event Doppler correction.
- $17^\circ < \theta_{\text{lab}} < 54^\circ$



The experiment - ^{224}Ra

12+ 1413.7

1220.7 11-

10+ 1067.4

906.2 9-

8+ 754.8

640.9 7-

6+ 479.2

433.1 5-

4+ 250.8

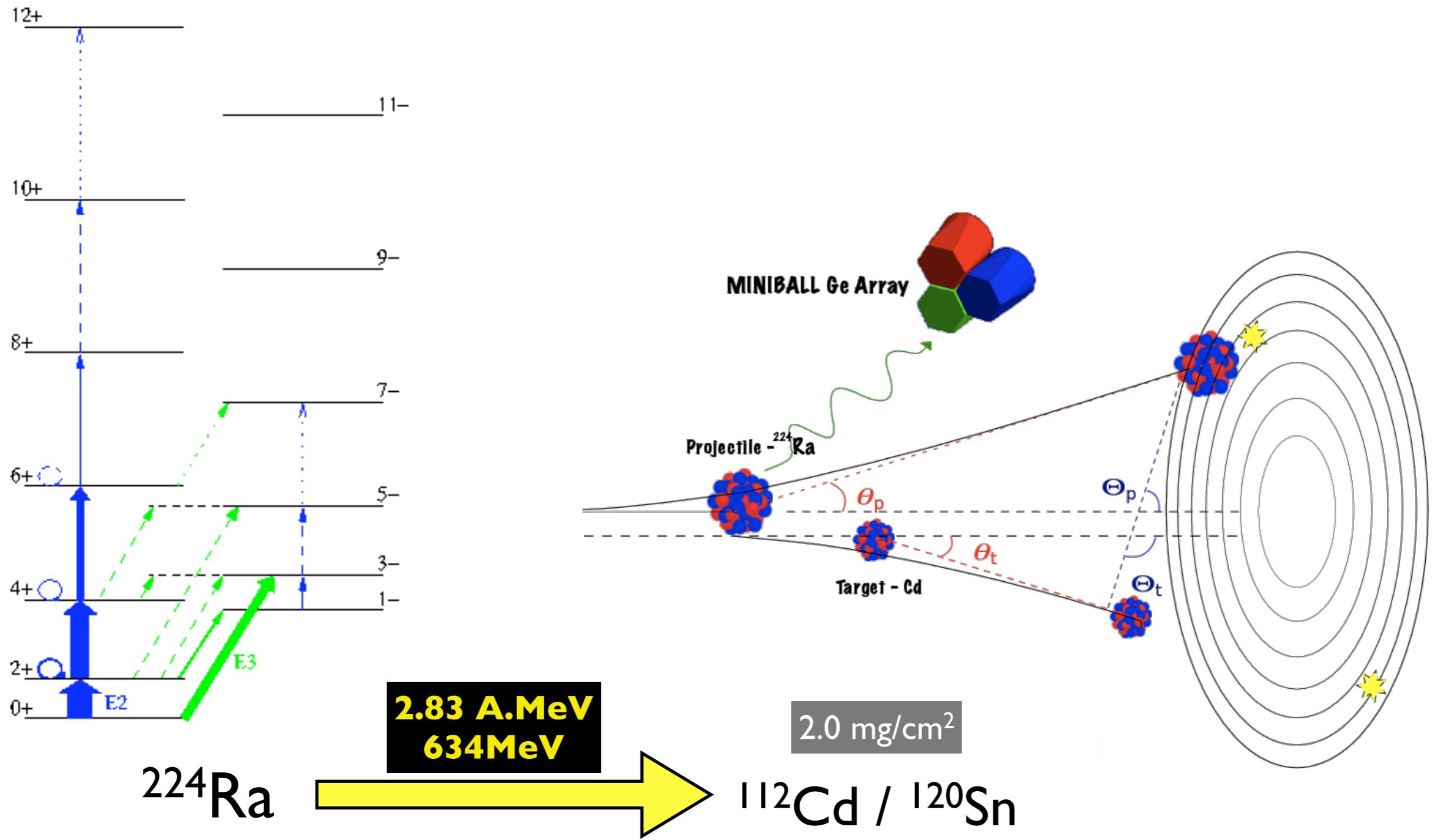
290.4 3-
216.0 1-

2+ 84.4

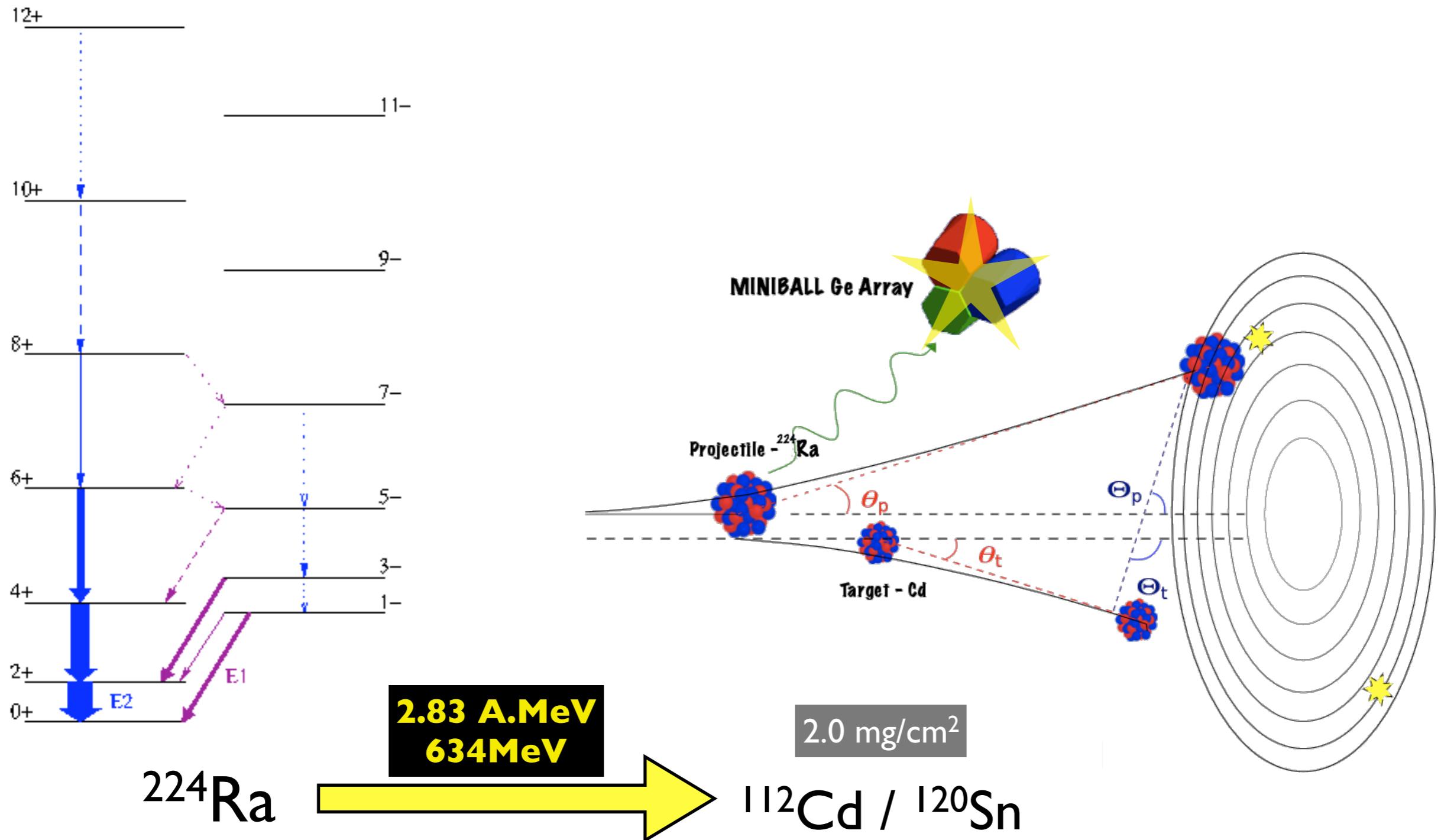
0+ 0.0

^{224}Ra

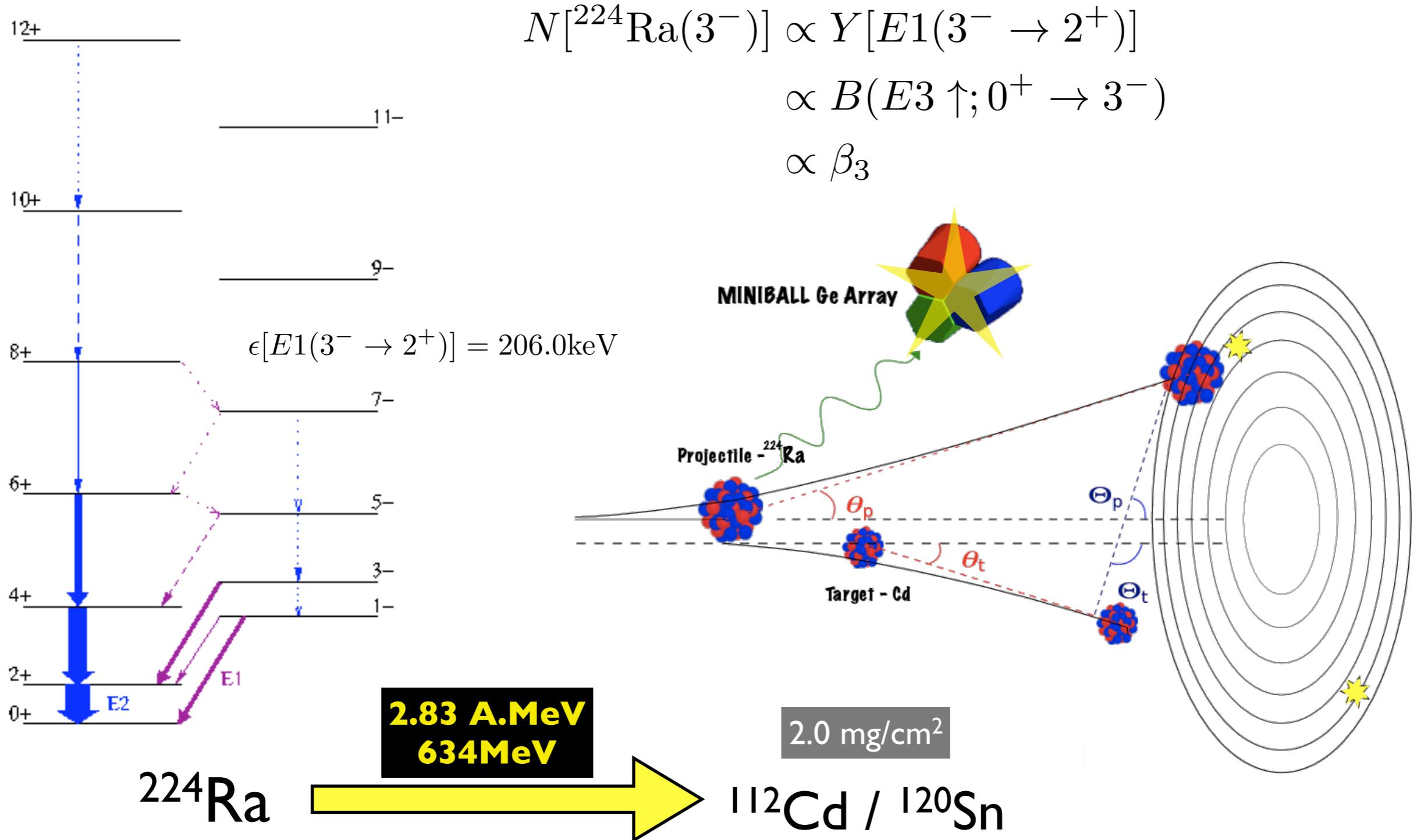
The experiment - ^{224}Ra



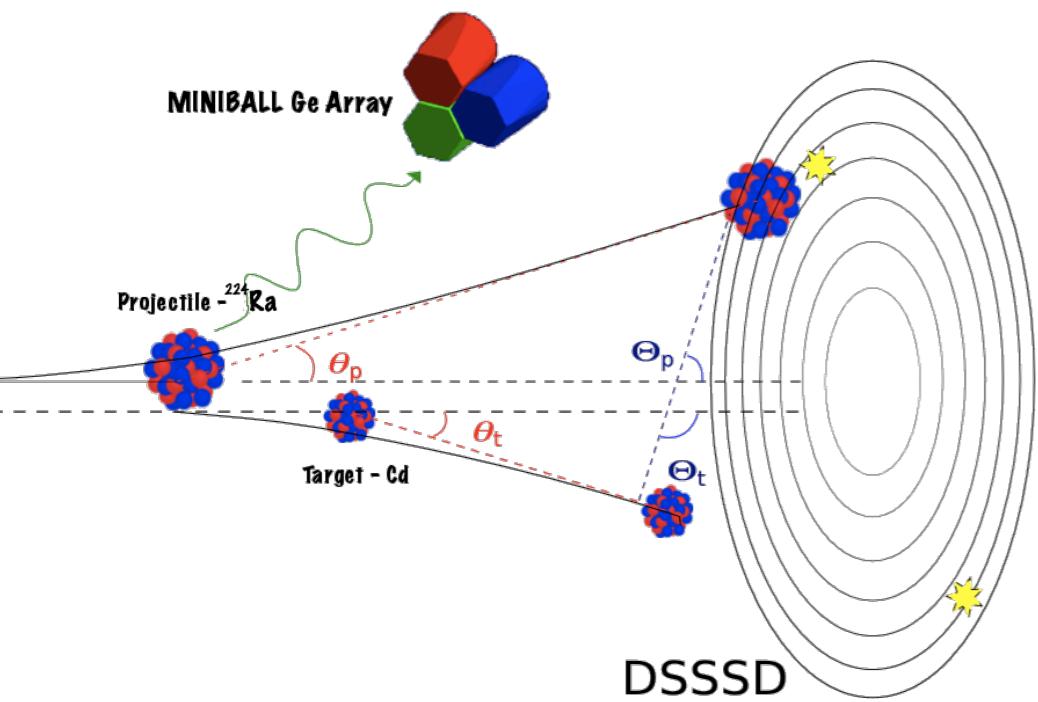
The experiment - ^{224}Ra



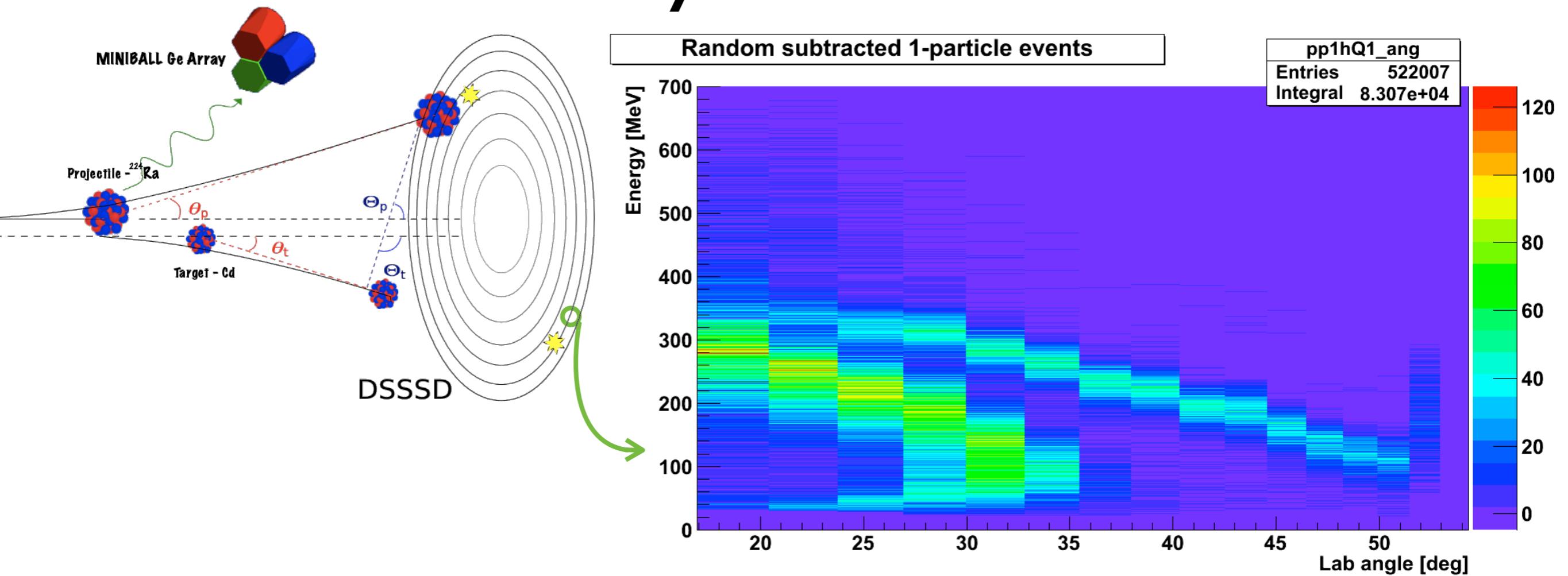
The experiment - ^{224}Ra



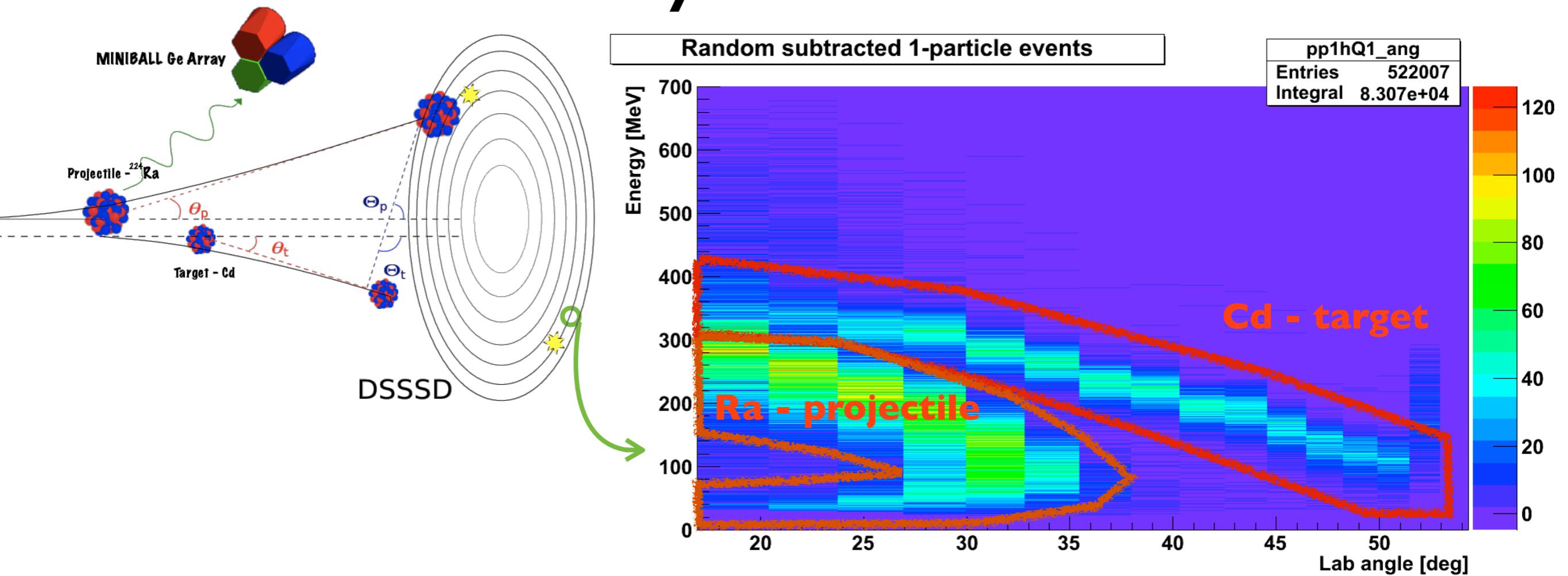
Analysis - ^{224}Ra



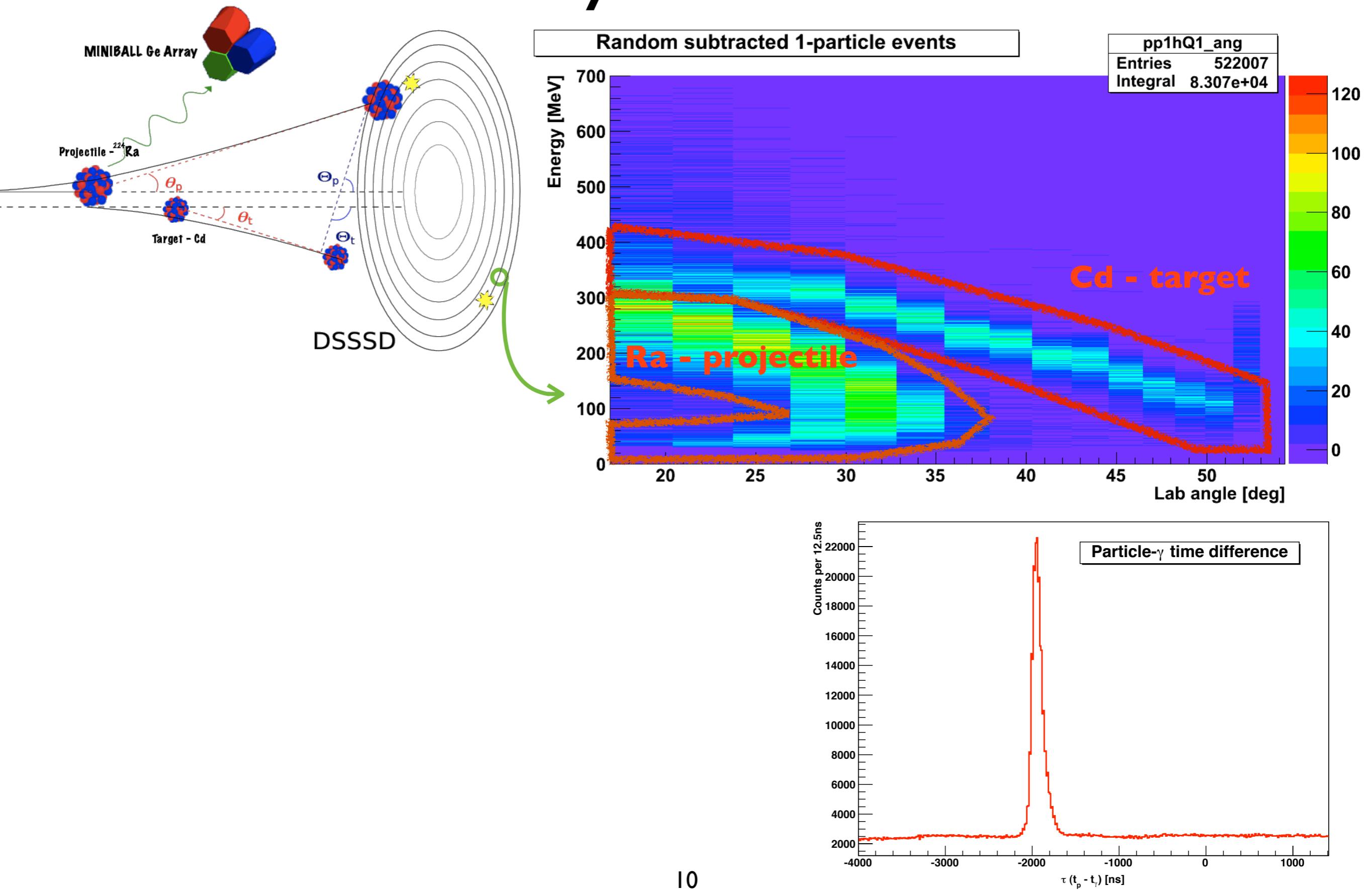
Analysis - ^{224}Ra



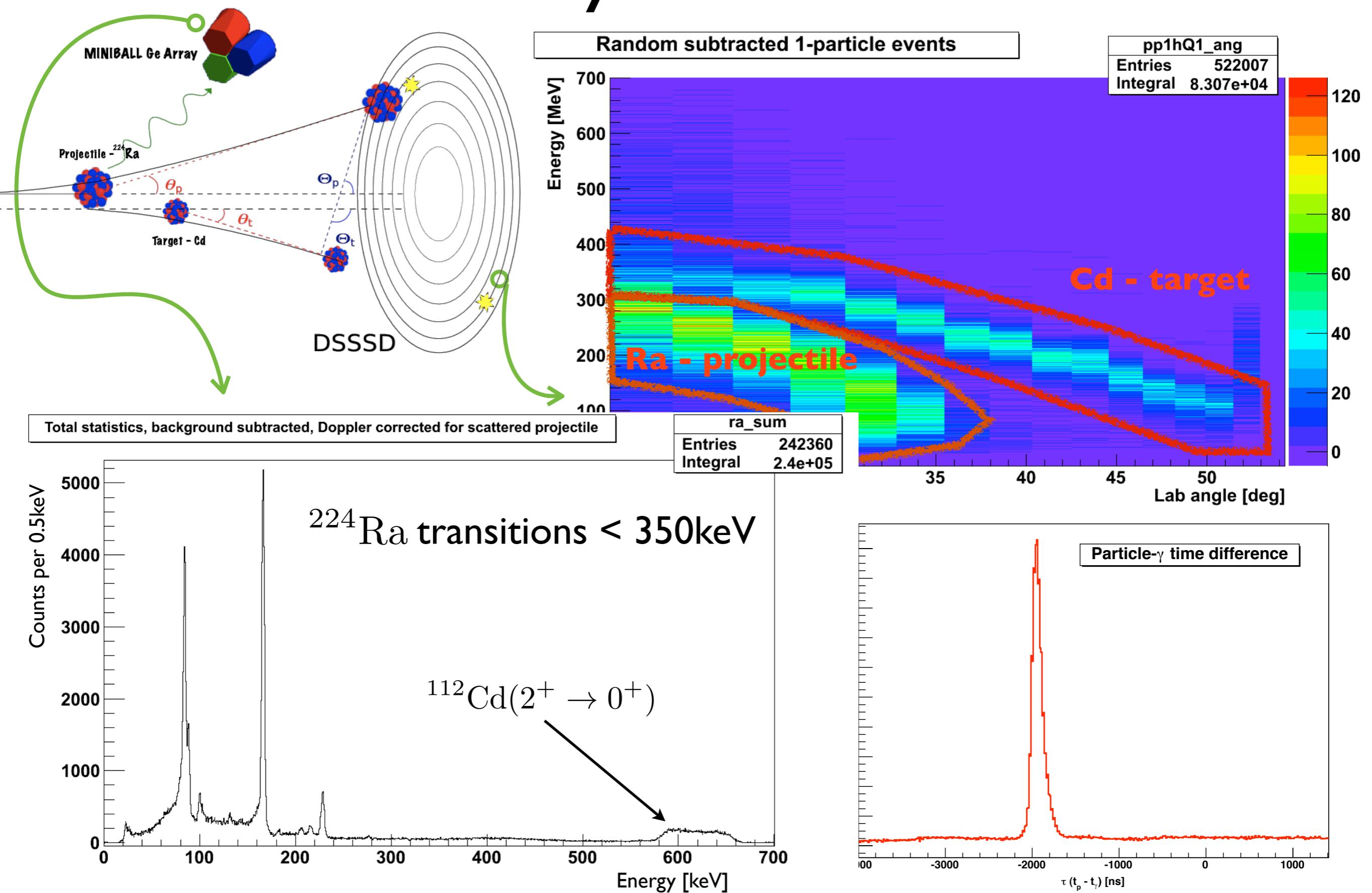
Analysis - ^{224}Ra



Analysis - ^{224}Ra



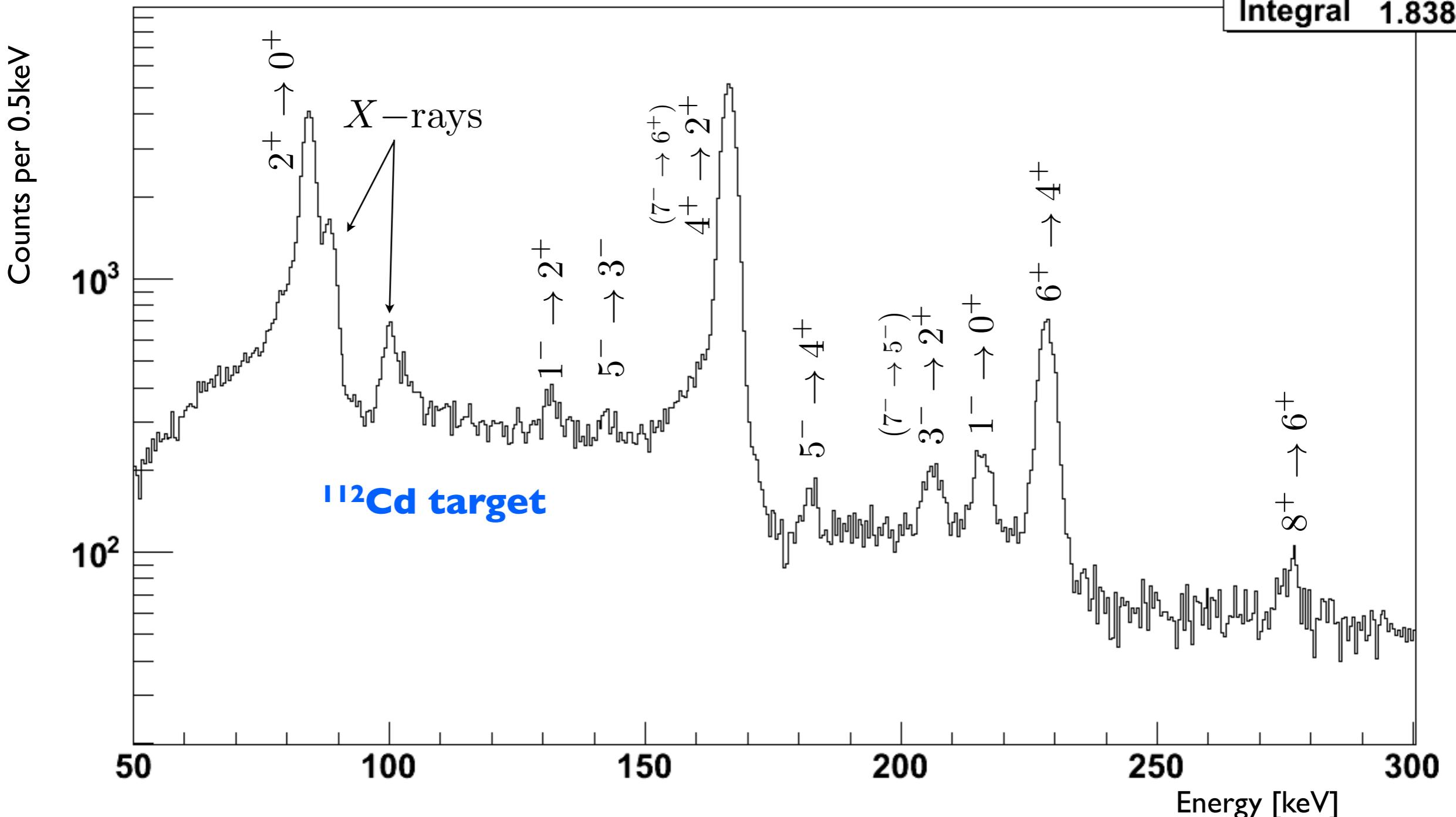
Analysis - ^{224}Ra



Analysis - ^{224}Ra

Total statistics, background subtracted, Doppler corrected for scattered projectile

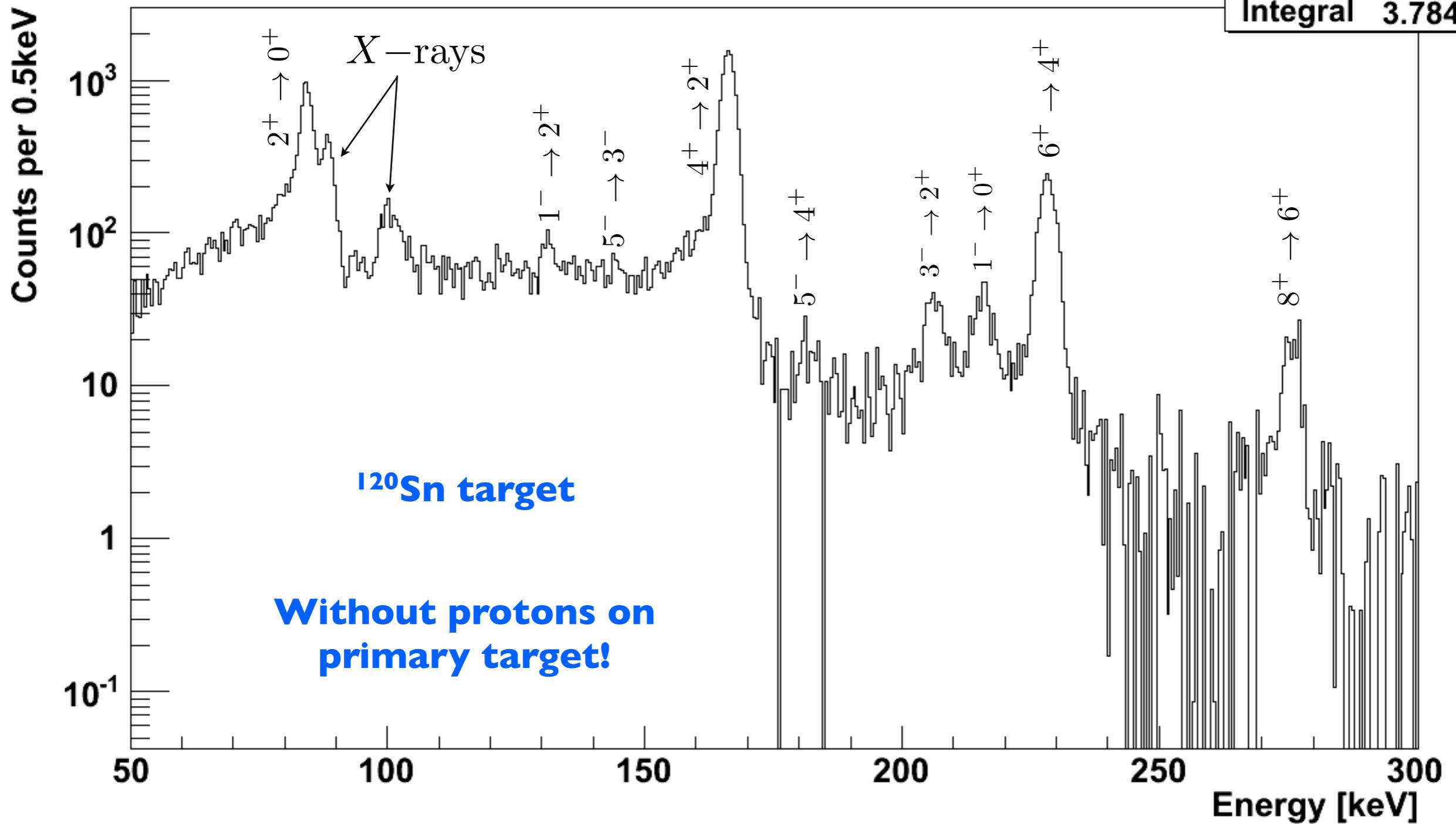
ra_sum	
Entries	242360
Integral	1.838e+05



Analysis - ^{224}Ra

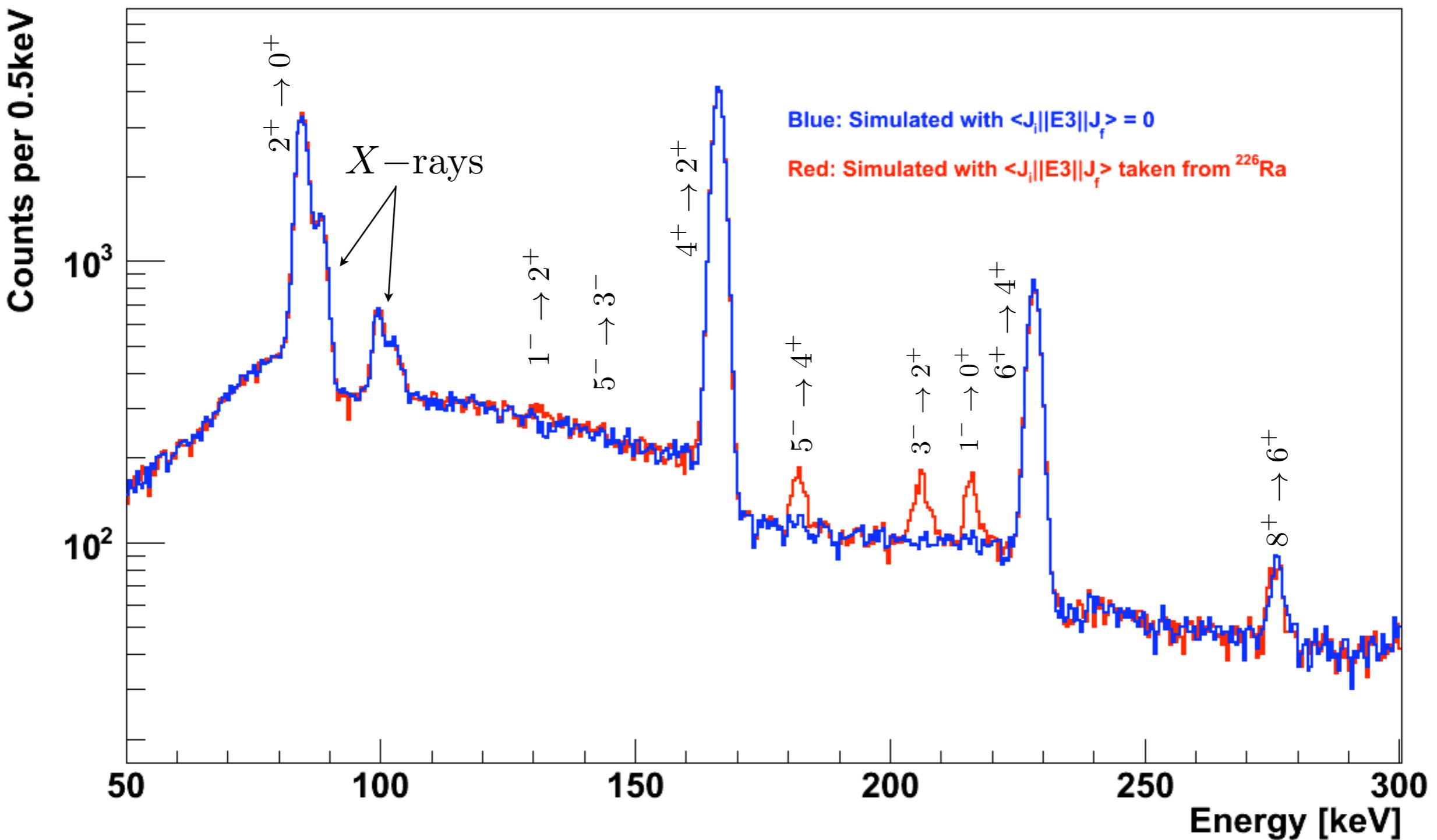
Total statistics, background subtracted, Doppler corrected for scattered projectile

ra_sum
Entries 41221
Integral 3.784e+04



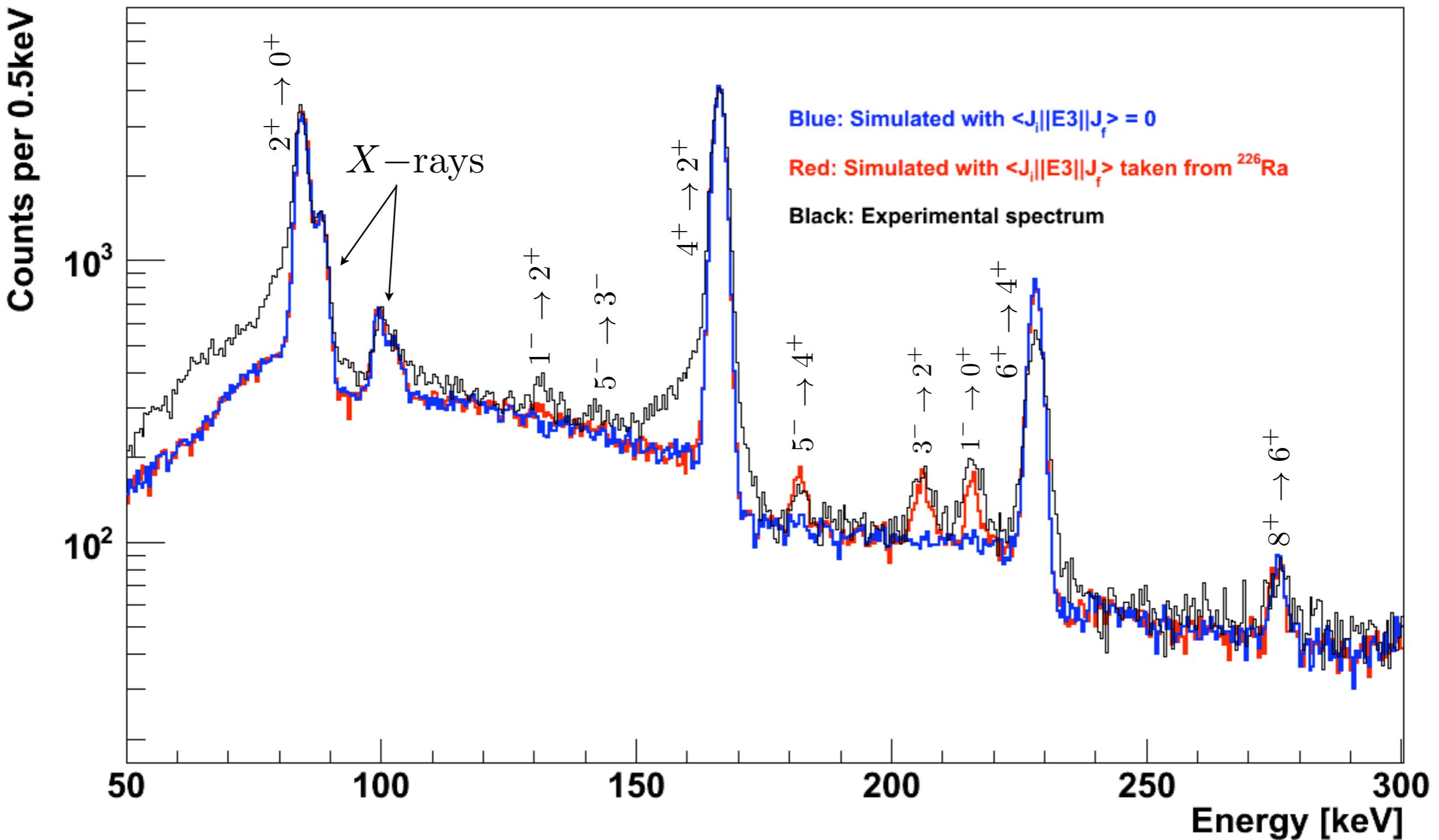
Simulation - ^{224}Ra

^{224}Ra on ^{112}Cd Simulated Yields with background



Simulation - ^{224}Ra

^{224}Ra on ^{112}Cd Simulated Yields with background



Gosia Analysis

72 Matrix elements -- 58 experimental data points

“Experiment”	Number and type of data
Multi-nucleon transfer ^[1,2] $^{226}\text{Ra}(\text{Ni}^{58}, \text{Ni}^{60})^{224}\text{Ra}$ $^{232}\text{Th}(\text{Xe}^{136}, \text{Te}^{128})^{224}\text{Ra}$	Branching ratios (1-, 3-, 5-) -- 3 (+3 limits)
Alpha, alpha-prime ^[3] $^{226}\text{Ra}(\alpha, \alpha' 2n)^{224}\text{Ra}$	
Alpha-decay ^[4] $^{228}\text{Th} \rightarrow \alpha$	
Delayed-coincidence ^[5,6]	Lifetimes (2+, 4+) -- 2
Cd(Sn) only detection $23.9^\circ < \theta_{\text{lab}} < 54.3^\circ$	γ -ray yield -- 9 + 8
Ra, high CoM branch $22.2^\circ < \theta_{\text{lab}} < 29.9^\circ$	γ -ray yield -- 6 + 6
Ra, low CoM branch $23.9^\circ < \theta_{\text{lab}} < 29.9^\circ$	γ -ray yield -- 6 + 6
2-particle events $17.1^\circ < \theta_{\text{lab}} < 54.3^\circ$	γ -ray yield -- 8 + 4
Total	58

Huge parameter space - Reduce number of matrix elements by using rigid rotor

- $\langle I || E\lambda || I' \rangle = (2I + 1)^{\frac{1}{2}} (I0\lambda0 | I'0) Q_\lambda a_\lambda$
- Q_2 coupled for states $I_i > 6\hbar$ -- **-12 MEs**
 - Q_1 coupled for states $I_i > 6\hbar$ -- **-6 MEs**
 - Q_3 coupled for states $I_i > 6\hbar$ -- **-11 MEs**
 - All E4 matrix elements fixed -- **-17 MEs**
 - 26 matrix elements + 4 normalisation constants = **30** parameters in fit

[1] Poynter et al., Phys. Lett. B **232**, 447 (1989)

[2] J.F.C. Cocks et al., Nucl. Phys. A **645**, 61 (1999)

[3] Marten-Tölle et al., Z. Phys. A **336**, 27 (1990)

[4] W. Kurcewicz, et al., Nucl. Phys. A **289** (1977)

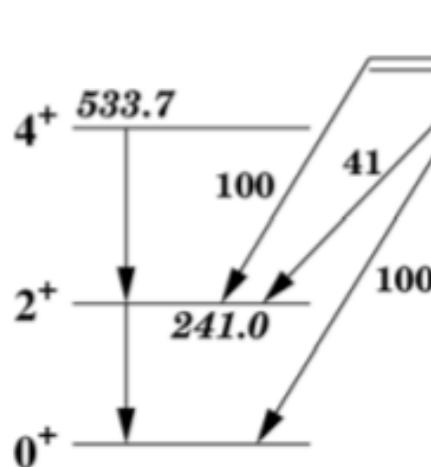
[5] W.R. Neal and H.W. Kraner, Phys. Rev. **137**, B1164 (1965)

[6] H.Ton et al., Nucl. Phys. A **155**, 235 (1970)

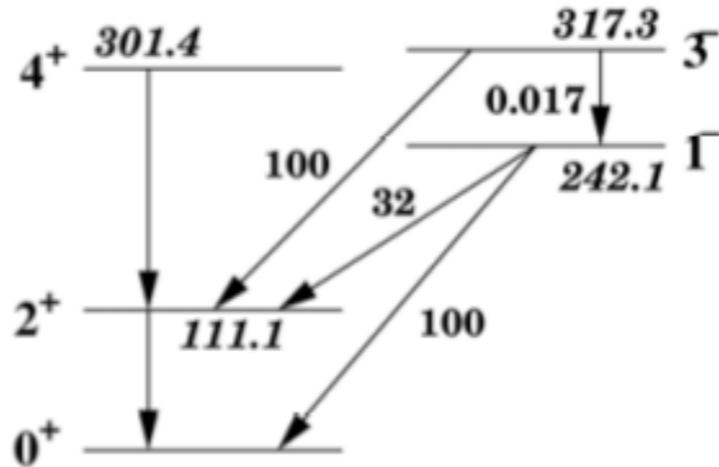
Outlook and “to do’s

Proposal included $^{220,222}\text{Rn}$ and ^{222}Ra

^{220}Rn



^{222}Ra



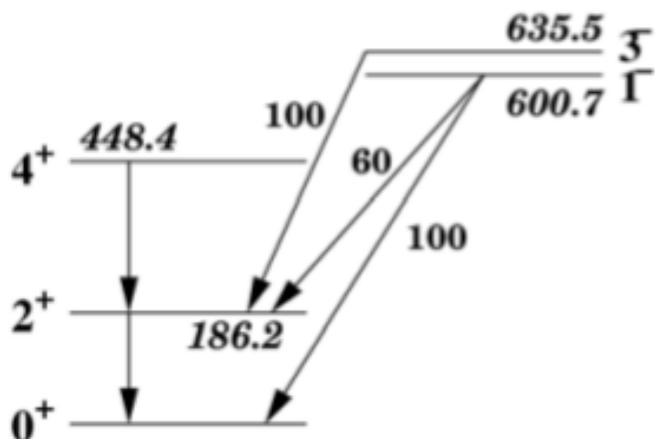
Extract $B(E3; 0^+ \rightarrow 3^-) !!$

^{220}Rn to be studied in July 2011

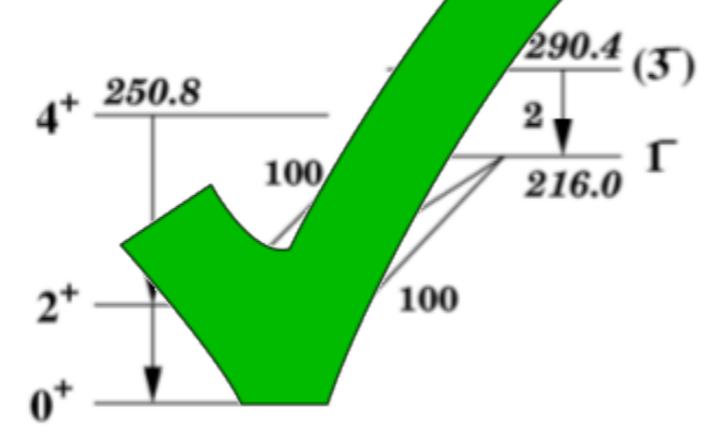
3^- higher in energy, σ is smaller

More time needed

^{222}Rn



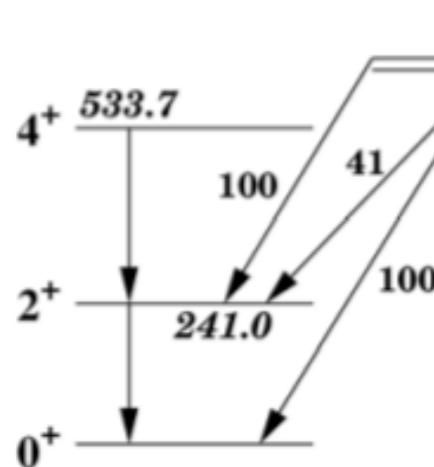
^{224}Ra



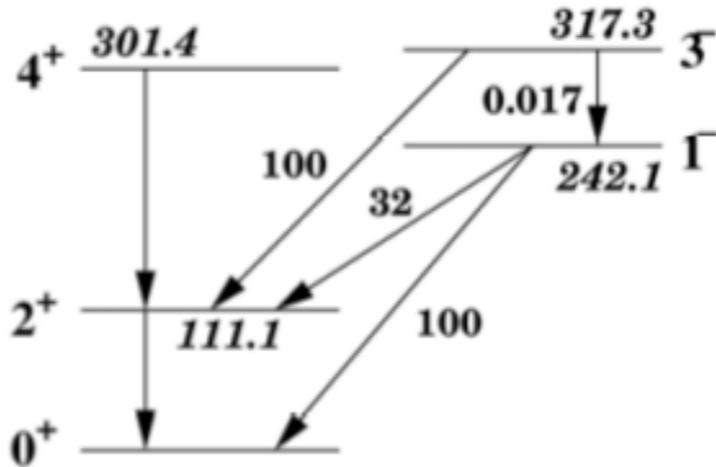
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^{220}Rn



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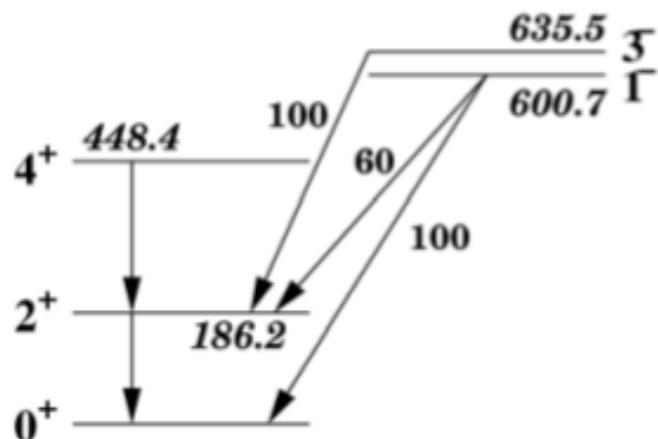
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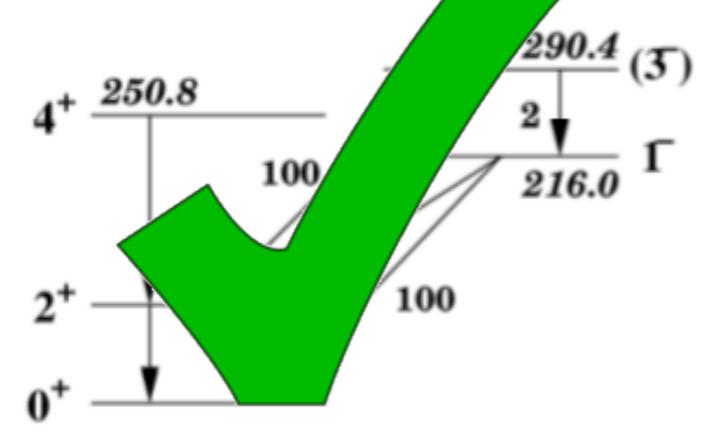
3^- higher in energy, σ is smaller

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^{222}Rn



^{224}Ra



To be continued...

Collaborators

**L. P. Gaffney, P.A. Butler, M. Scheck
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D. Cline
E. Kwan, C.Y.Wu
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A. Blazhev, M. Seidlitz, N.Warr
N. Bree, J. Diriken
T. Grahn
M. Zielinska

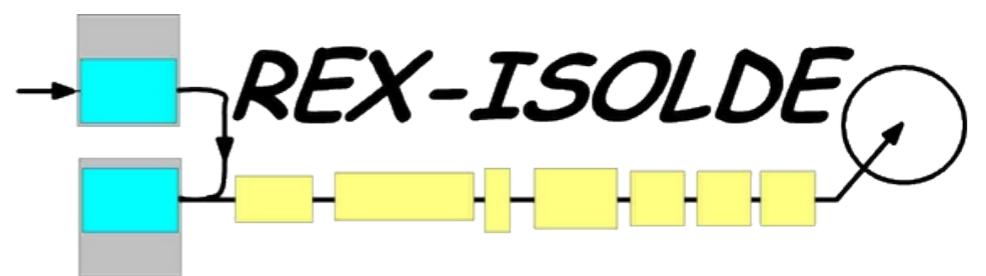
University of Rochester, US
Lawrence Livermore Laboratory, US
CERN-ISOLDE, Switzerland
University of Köln, Germany
KU Leuven, Belgium
University of Jyväskylä, Finland
HIL University of Warsaw, Poland

and the ISOLDE and MINIBALL collaborations

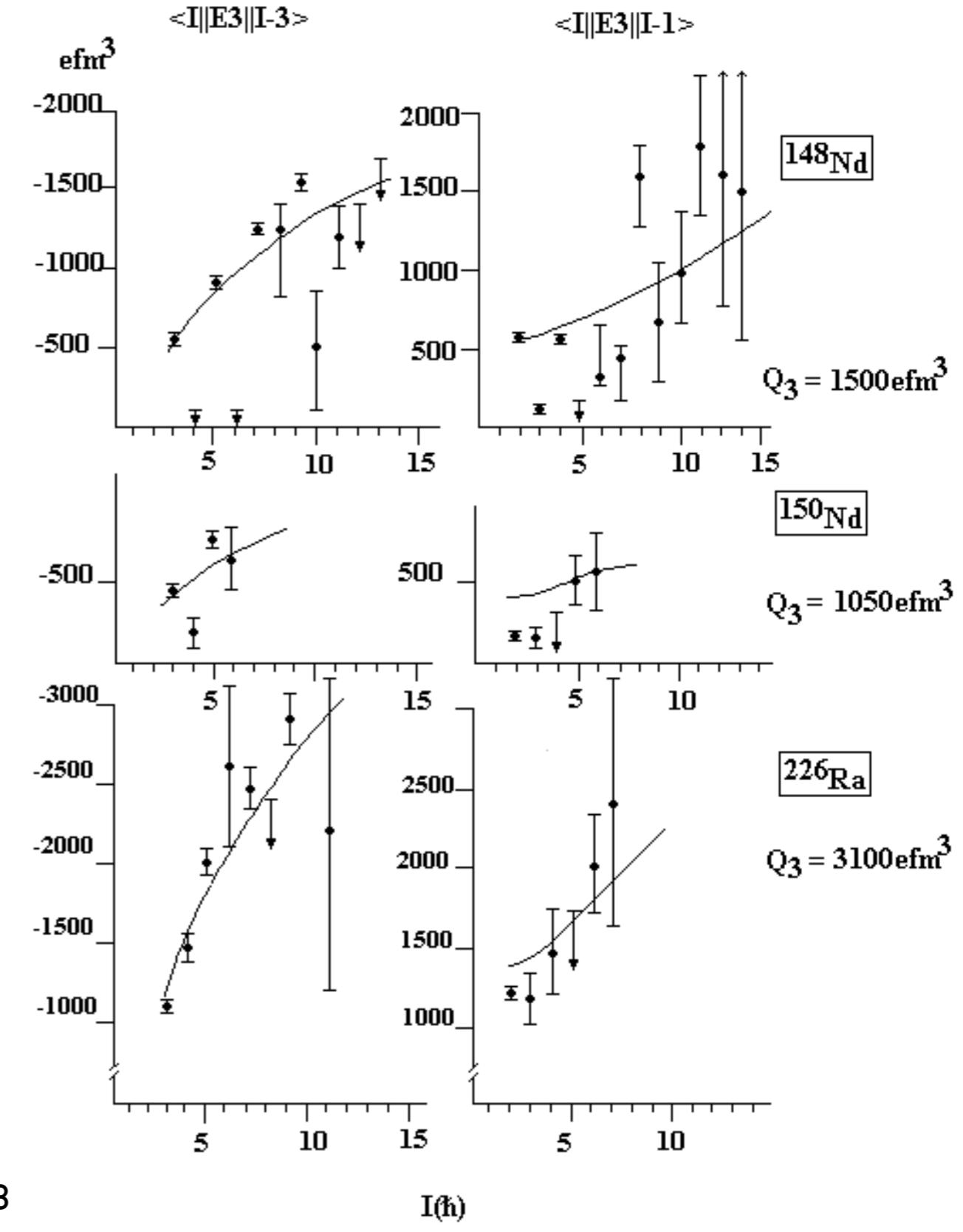
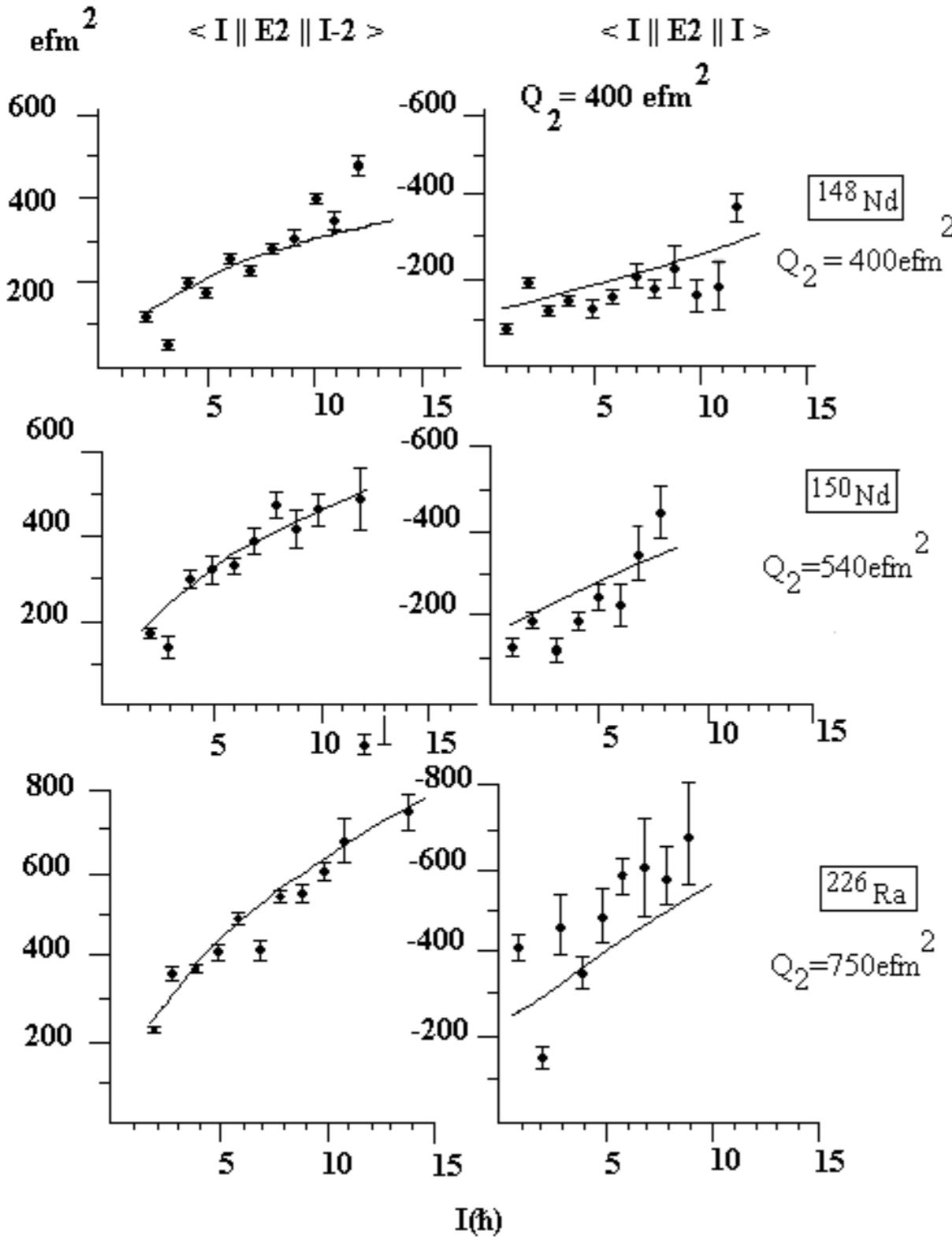
Thank you!



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LIVERPOOL

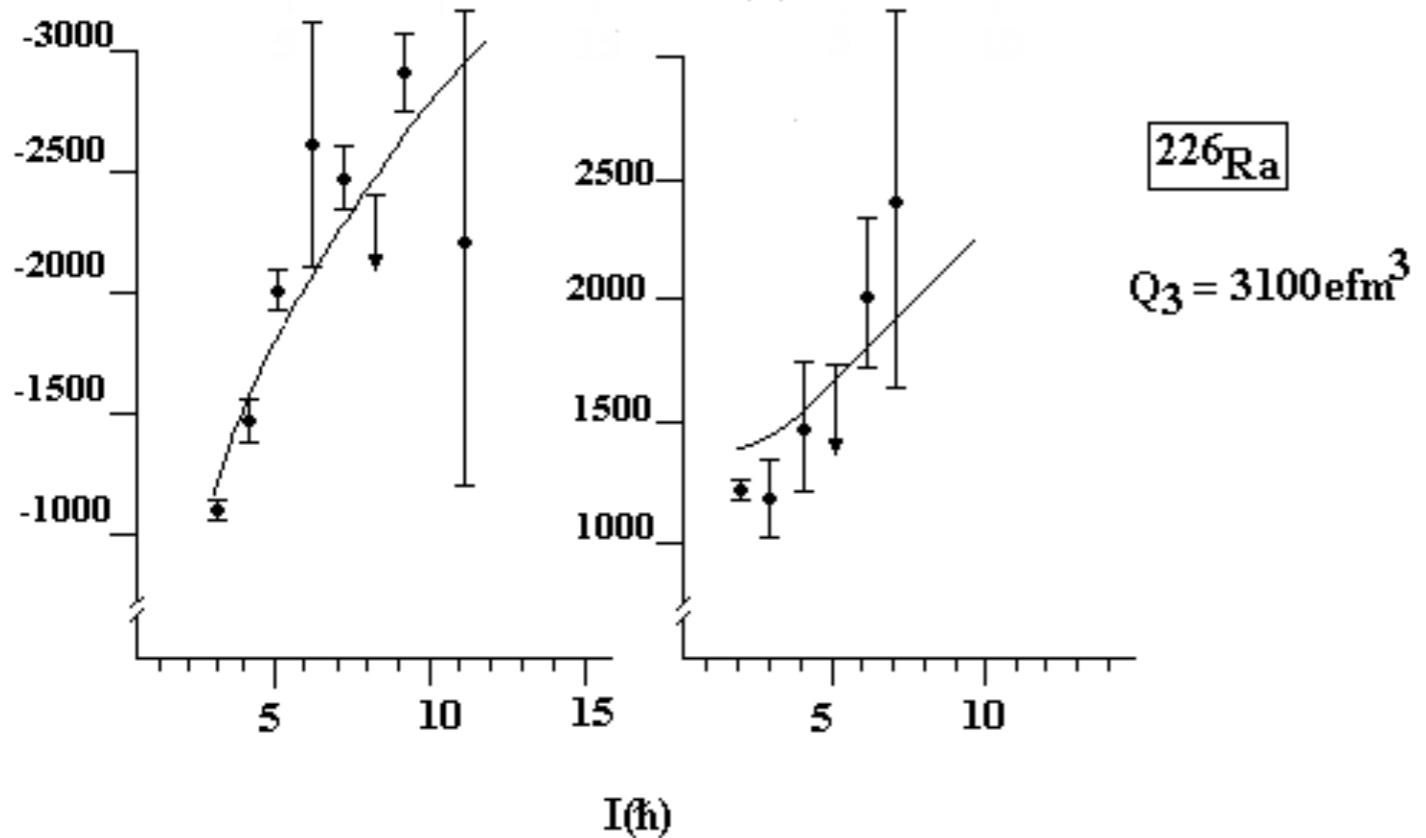


Gosia Analysis



Gosia Analysis

$$\langle I||E3||I-3 \rangle \quad \langle I||E3||I-1 \rangle$$



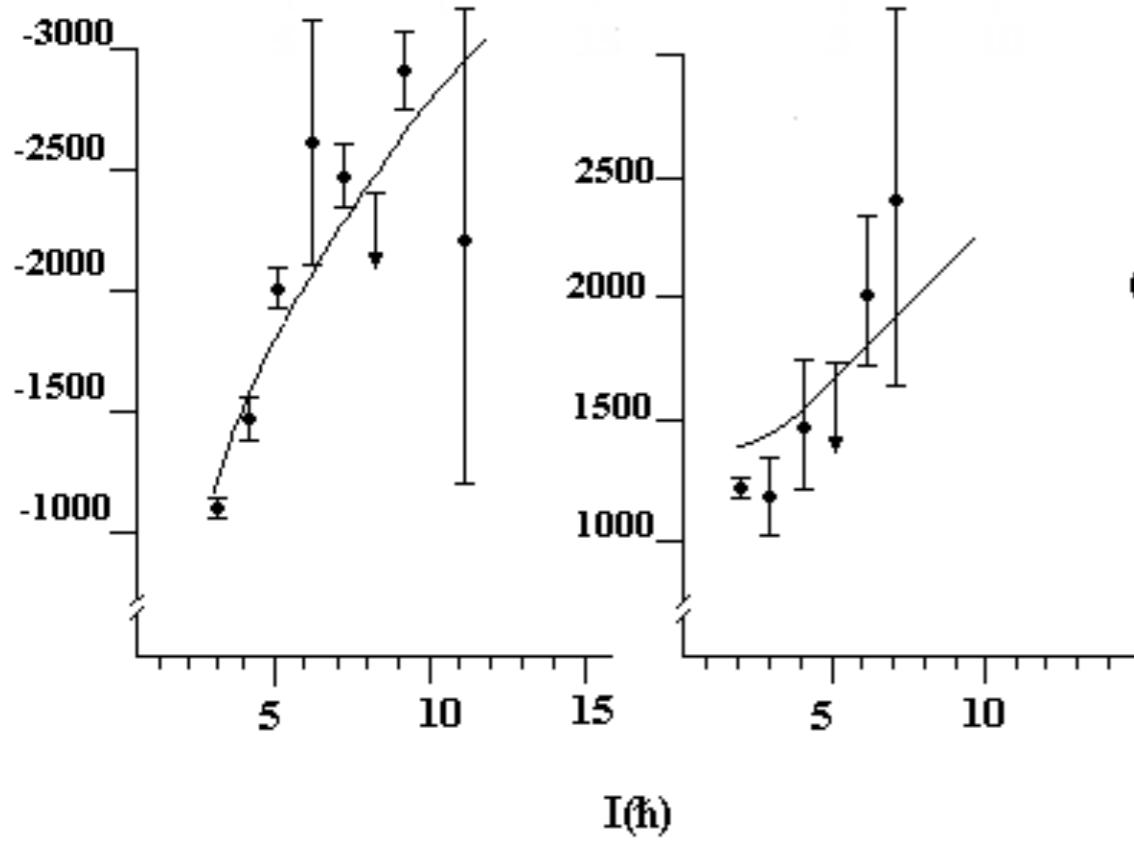
Measured E3 matrix elements [e·fm³]

Stretched: $\langle I||E3||I-3 \rangle$

Un-stretched: $\langle I||E3||I-1 \rangle$

Gosia Analysis

$\langle I||E3||I - 3 \rangle$



Measured E2 matrix elements [e·fm²]

Transitional: $\langle I||E2||I - 2 \rangle$

Diagonal: $\langle I||E2||I \rangle$

$\langle I||E3||I - 1 \rangle$

^{226}Ra
 $Q_3 = 3100 \text{ e fm}^3$

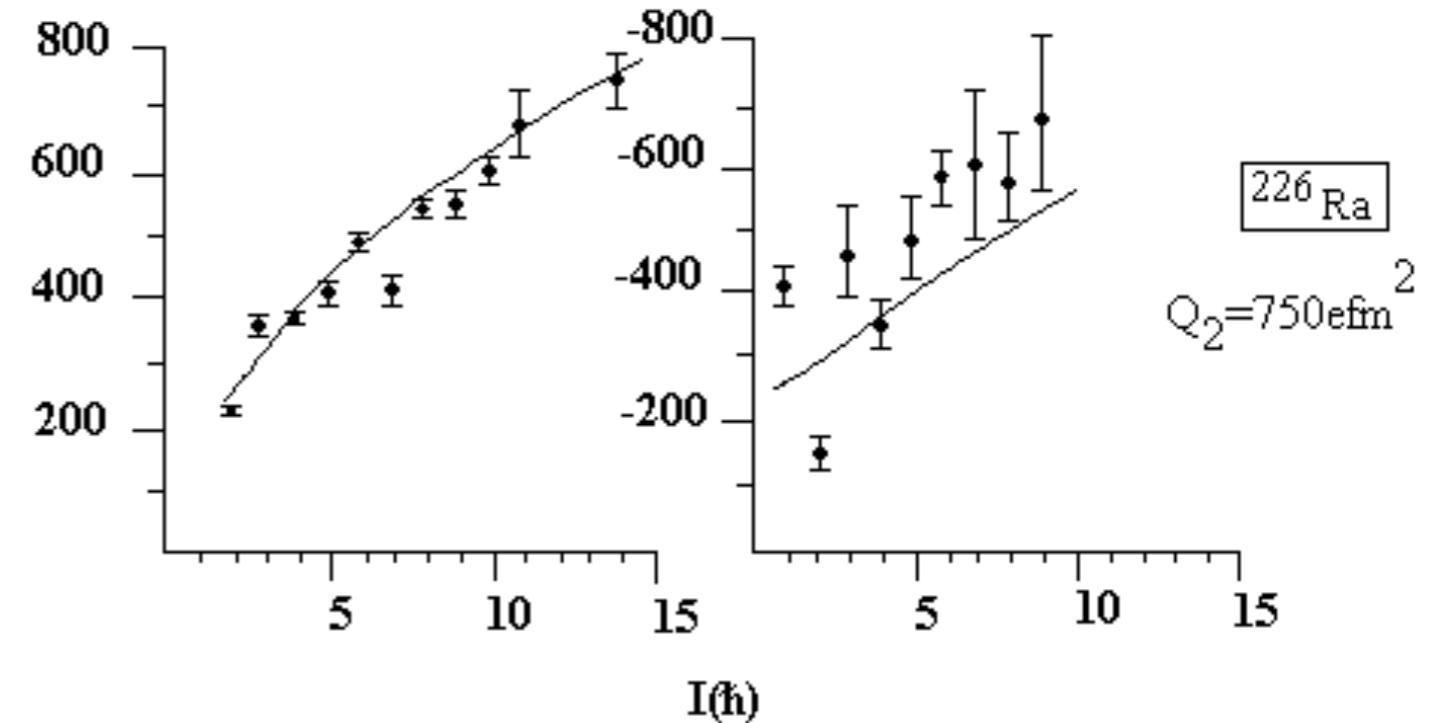
Measured E3 matrix elements [e·fm³]

Stretched: $\langle I||E3||I - 3 \rangle$

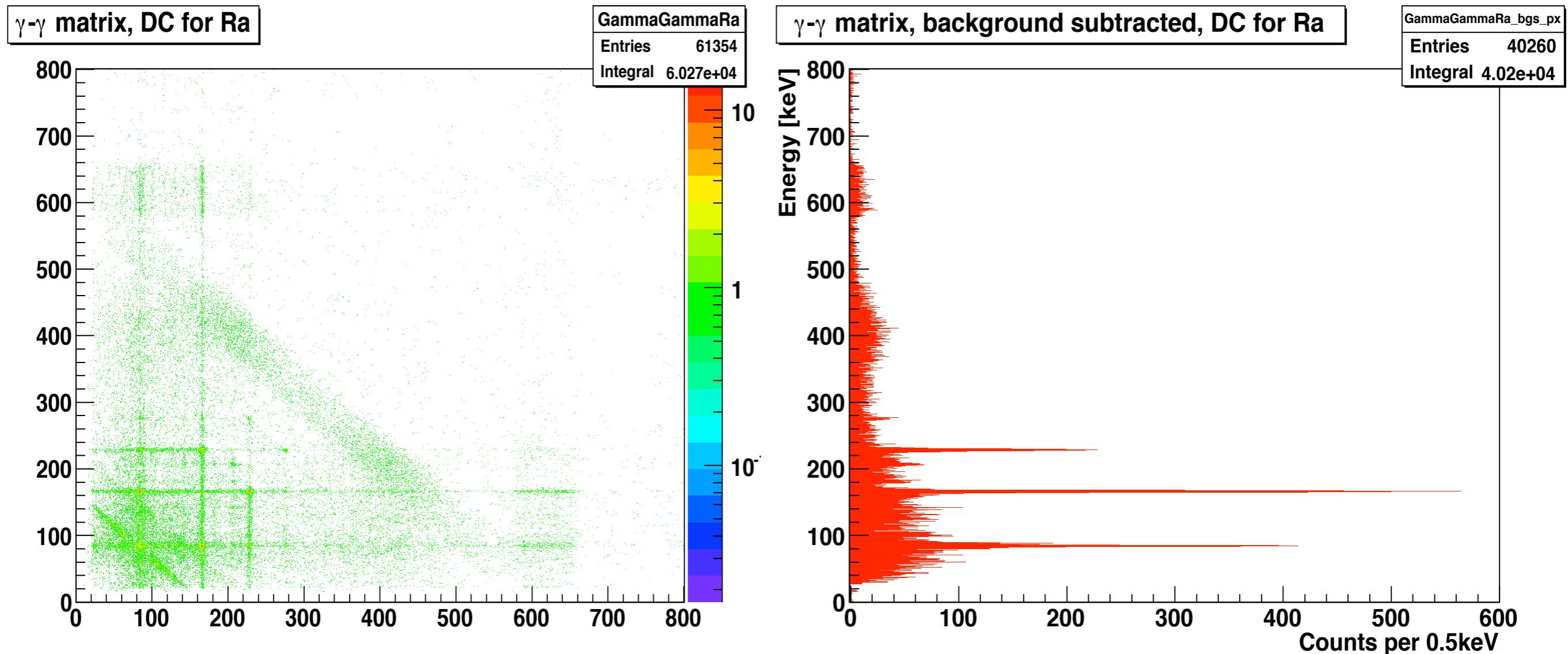
Un-stretched: $\langle I||E3||I - 1 \rangle$

$\langle I||E2||I - 2 \rangle$

$\langle I||E2||I \rangle$



Analysis - ^{224}Ra

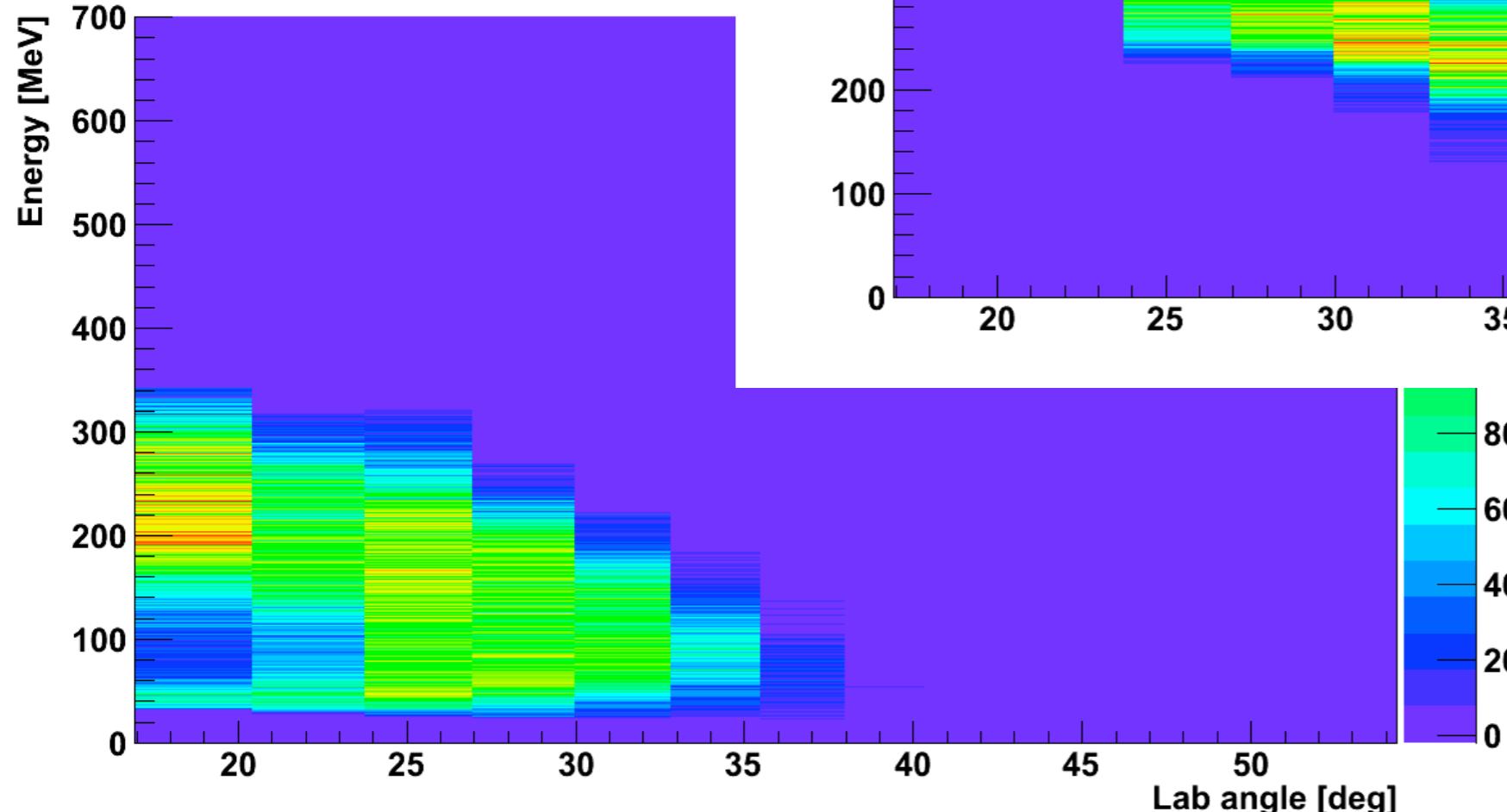


Analysis - ^{224}Ra

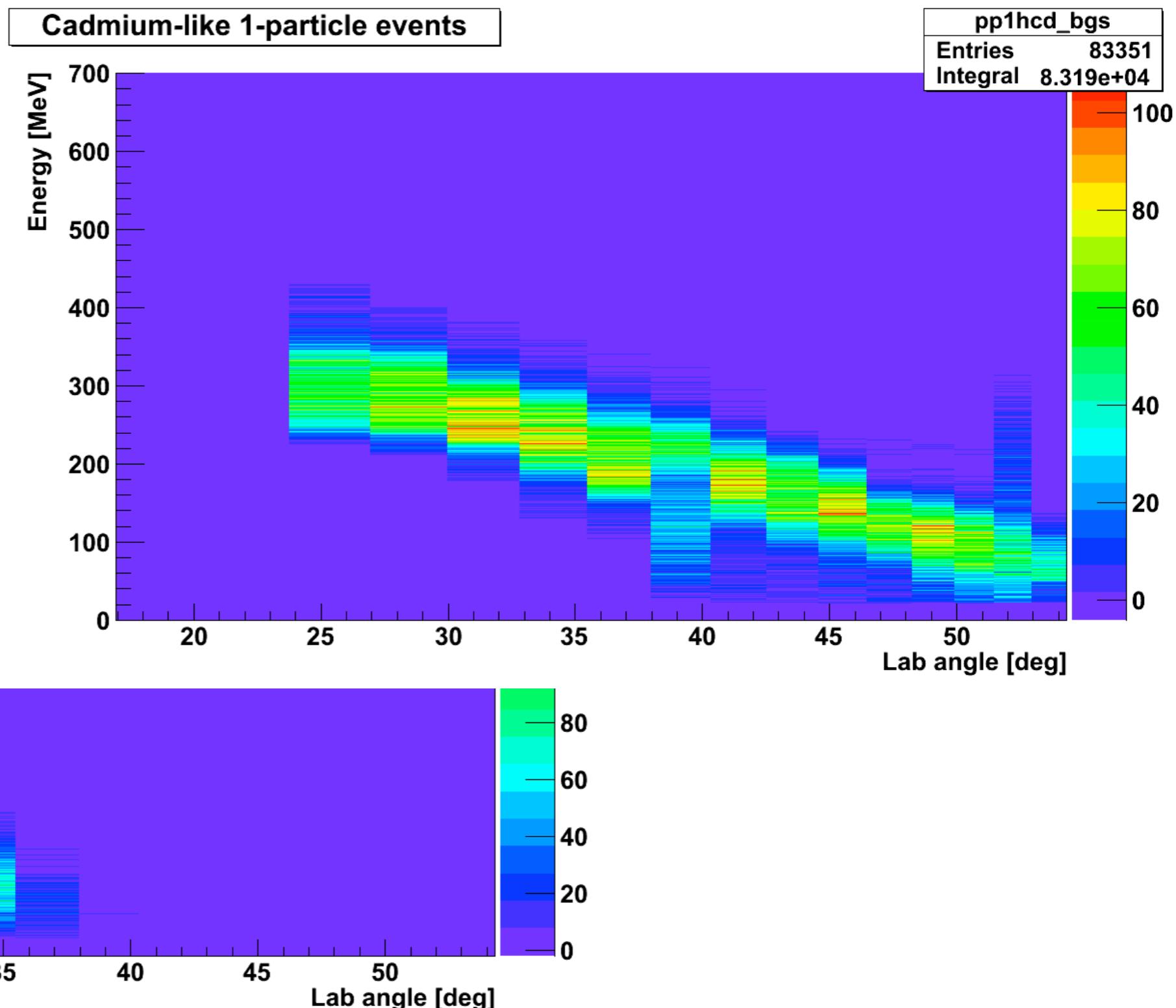
4 “experiments”

- Detection of Cd only
- Detection of Ra at low CoM scattering angle
- Detection of Ra at high CoM
- Detection of Ra and Cd (2-p)

Radium-like 1-particle events



Cadmium-like 1-particle events

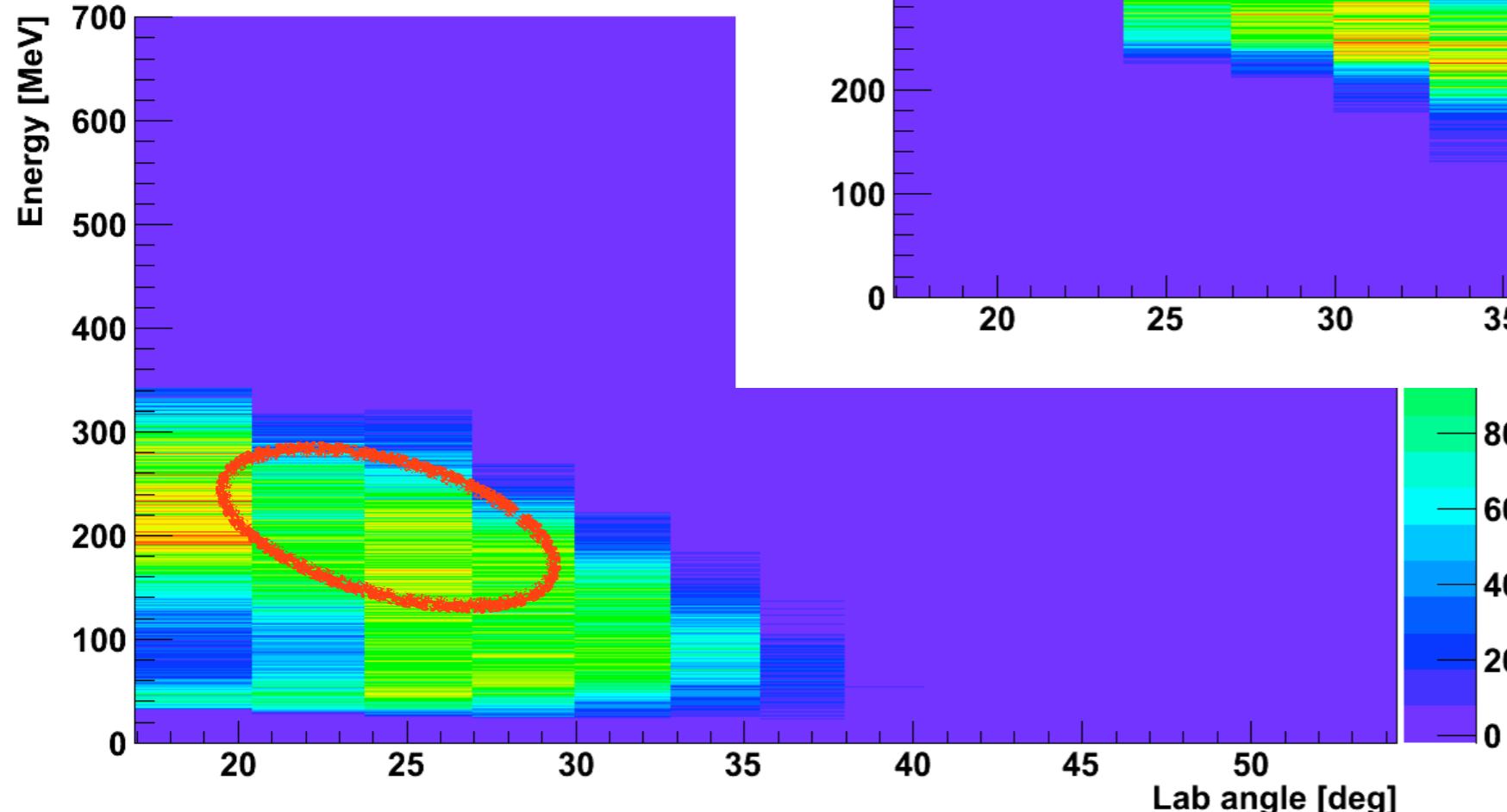


Analysis - ^{224}Ra

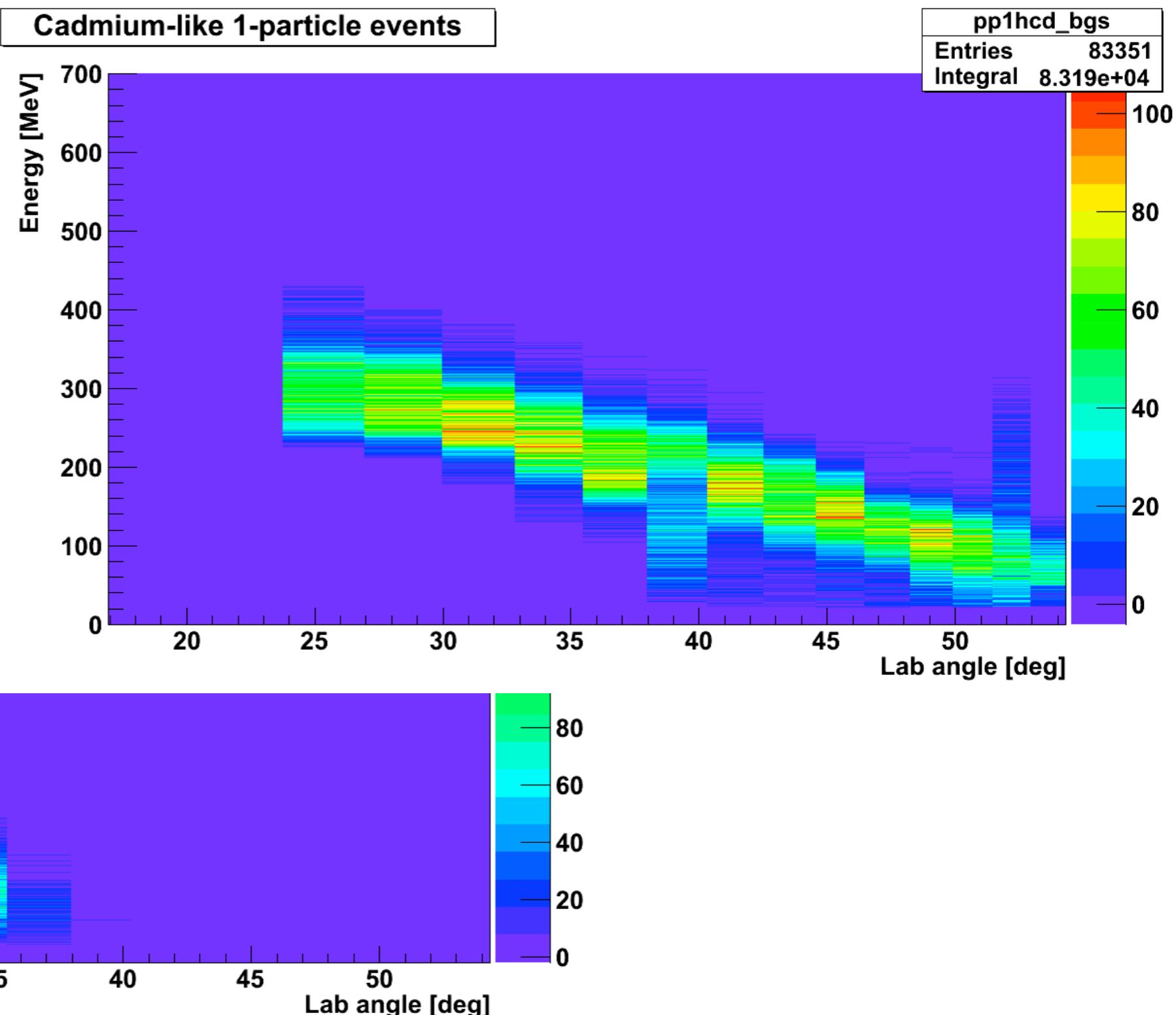
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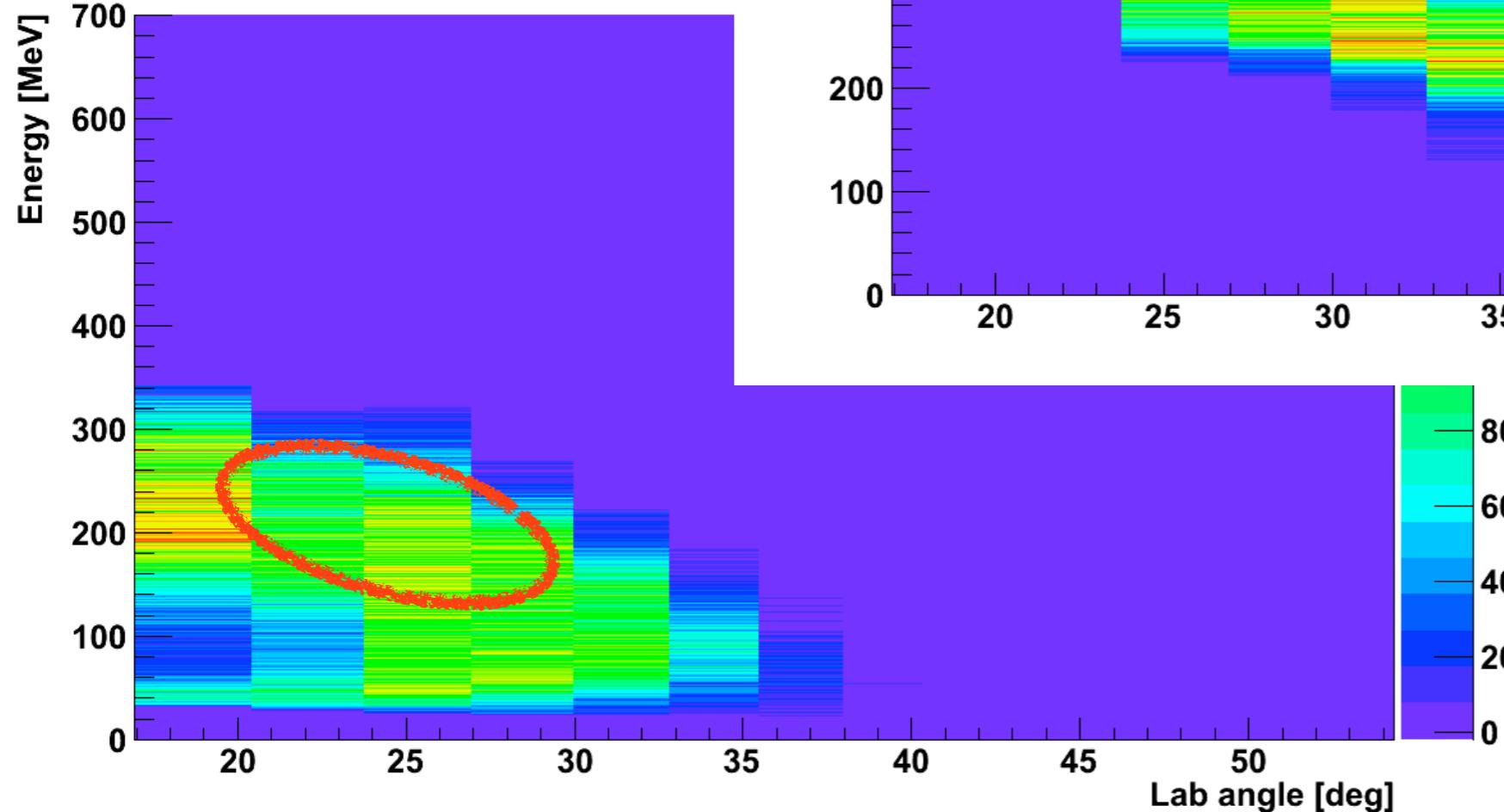


Analysis - ^{224}Ra

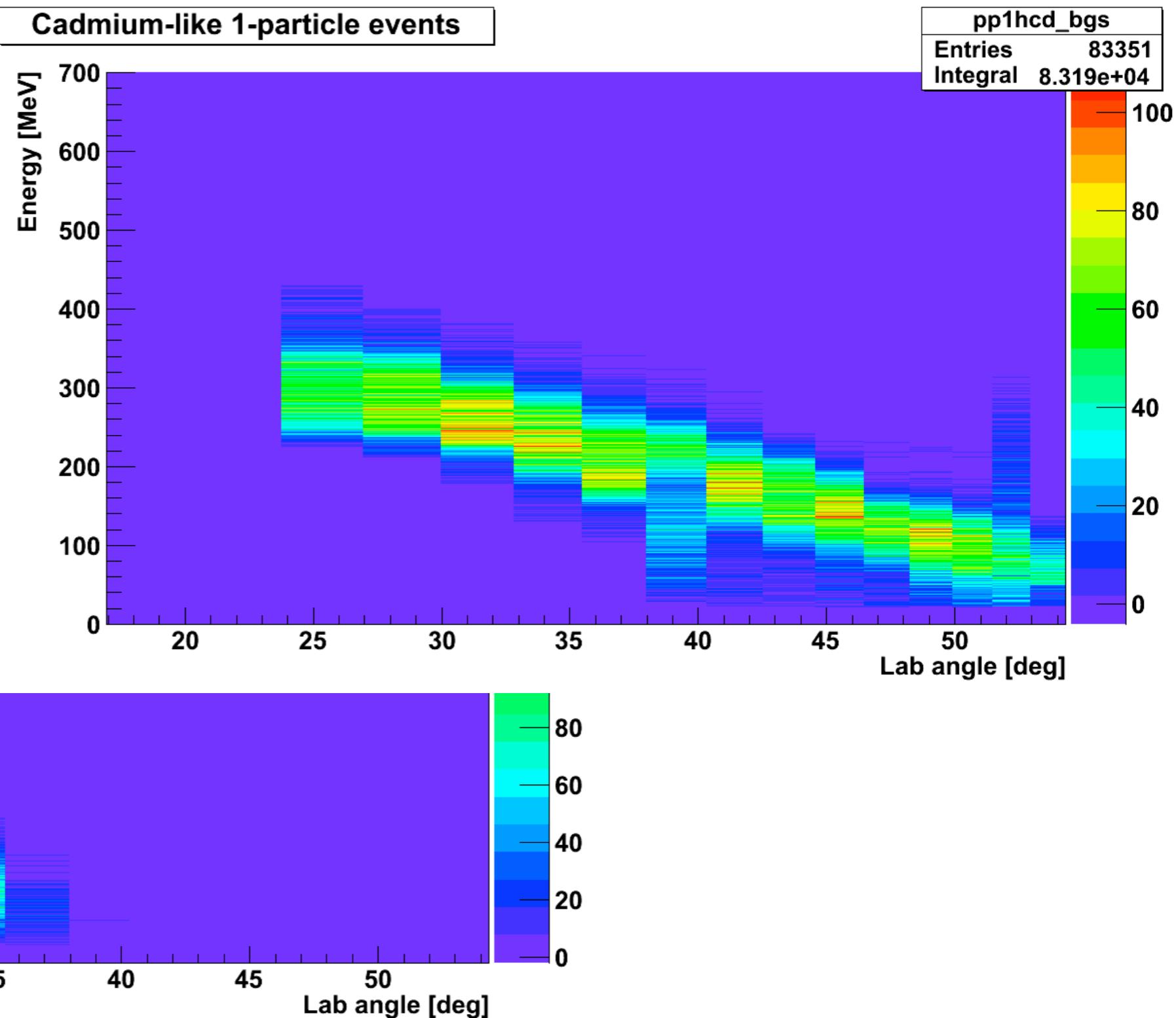
4 “experiments”

- Detection of Cd only
- Detection of Ra at low CoM scattering angle

Radium-like 1-particle events



Cadmium-like 1-particle events

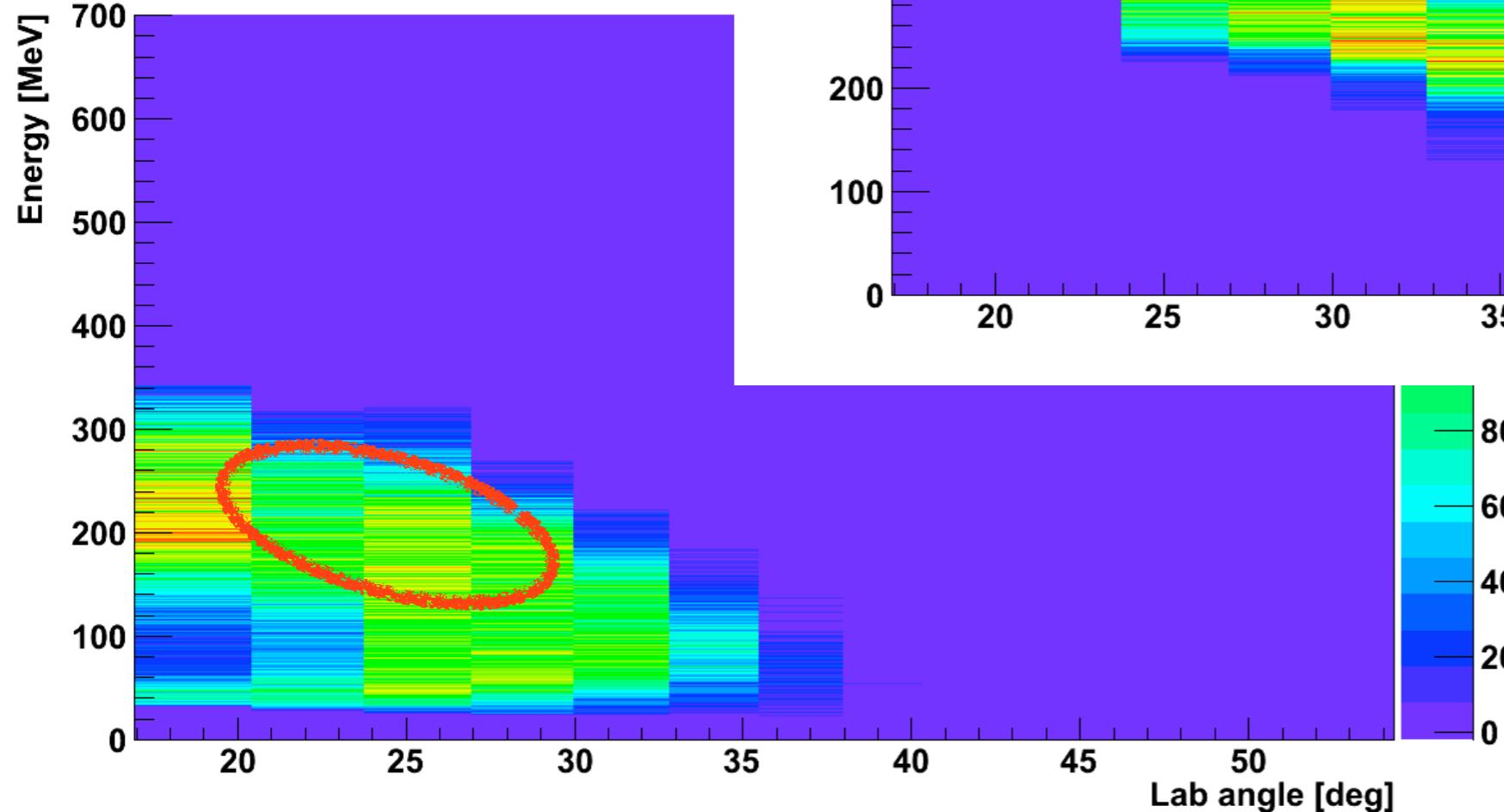


Analysis - ^{224}Ra

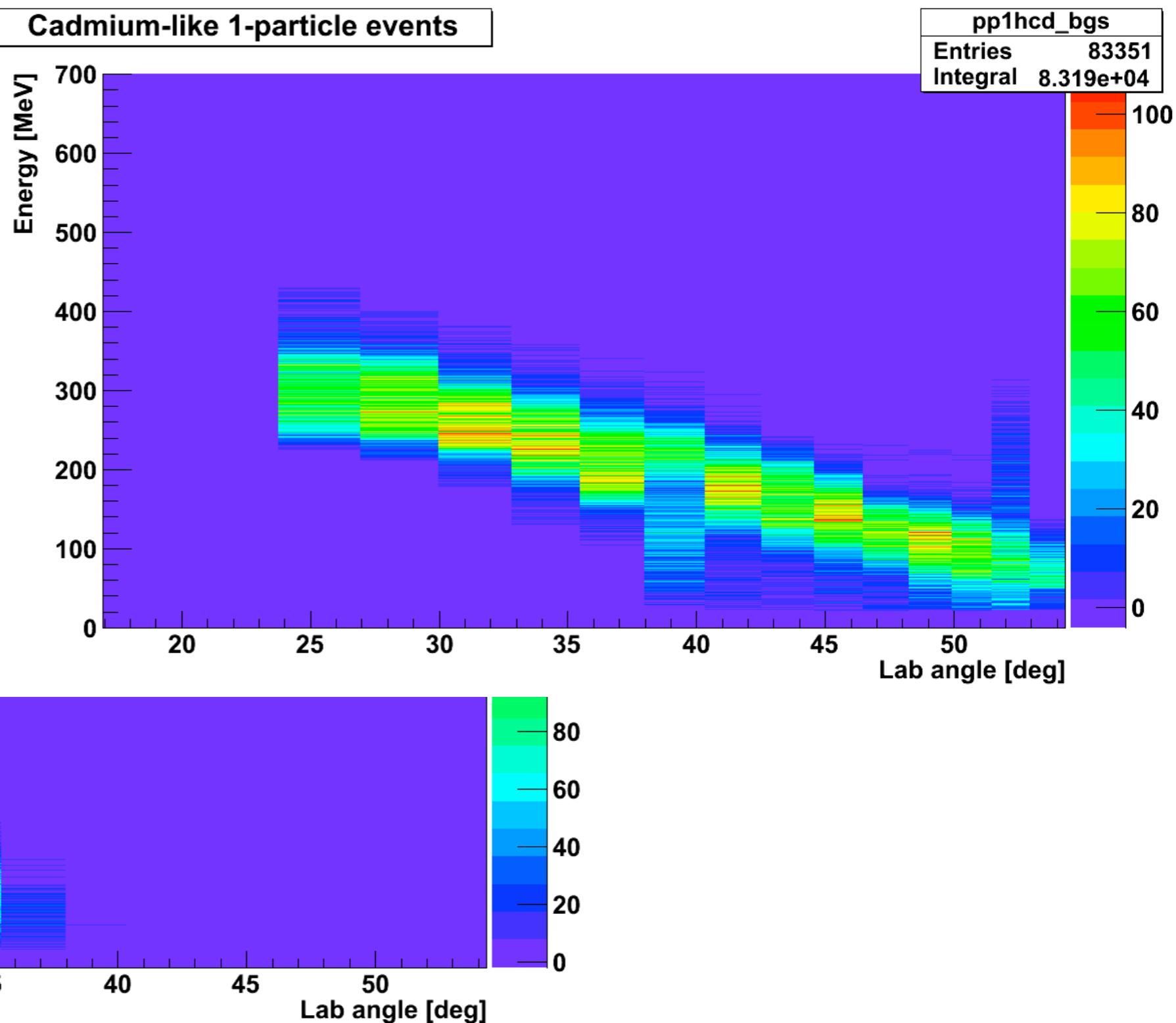
4 “experiments”

- Detection of Cd only
- Detection of Ra at low CoM scattering angle
- Detection of Ra at high CoM

Radium-like 1-particle events



Cadmium-like 1-particle events

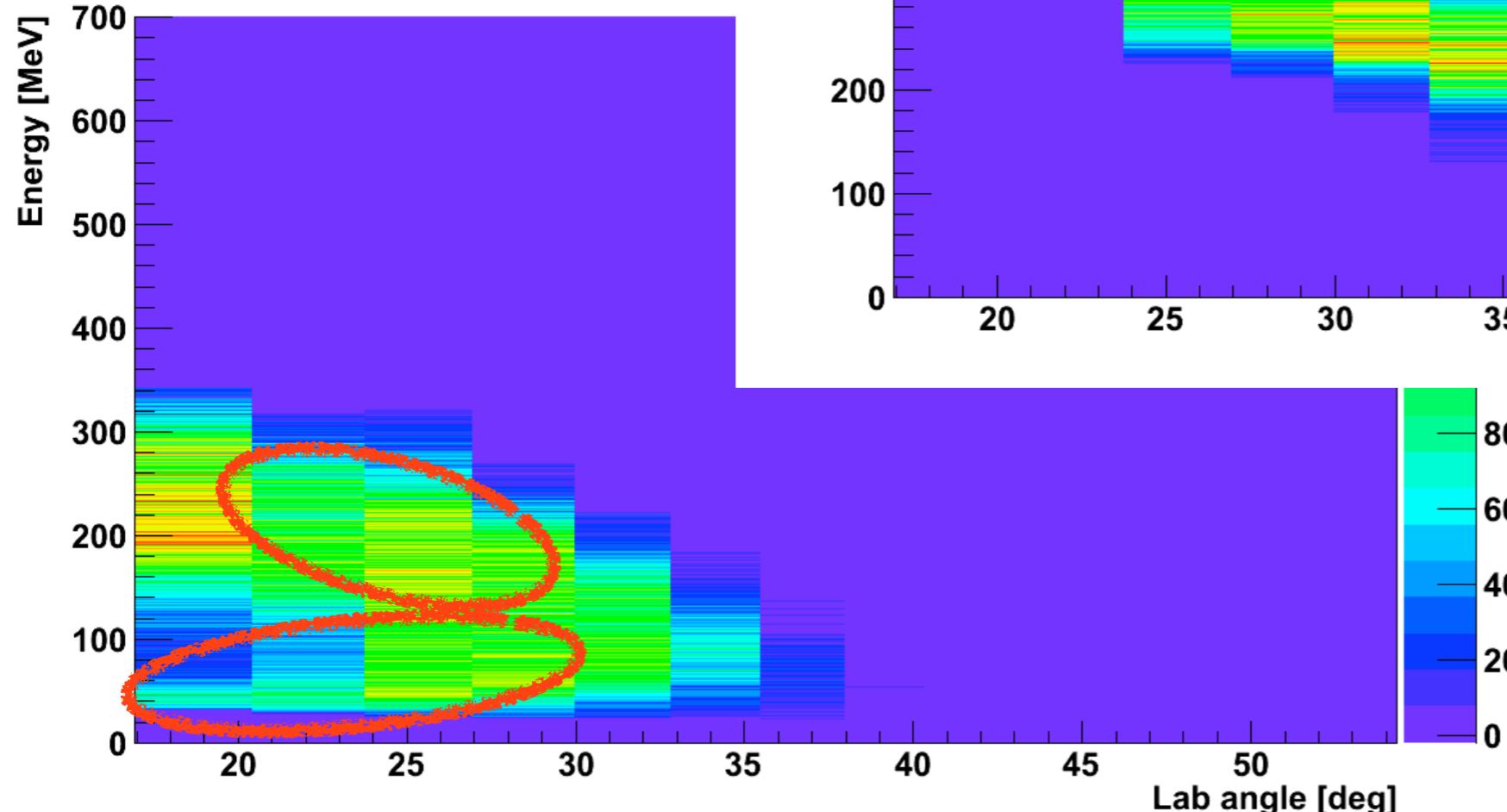


Analysis - ^{224}Ra

4 “experiments”

- Detection of Cd only
- Detection of Ra at low CoM scattering angle
- Detection of Ra at high CoM
- Detection of Ra and Cd (2-p)

Radium-like 1-particle events



Cadmium-like 1-particle events

