Coulomb Excitation Studies at TRIUMF and FRIB

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Nuclear & Chemical Sciences

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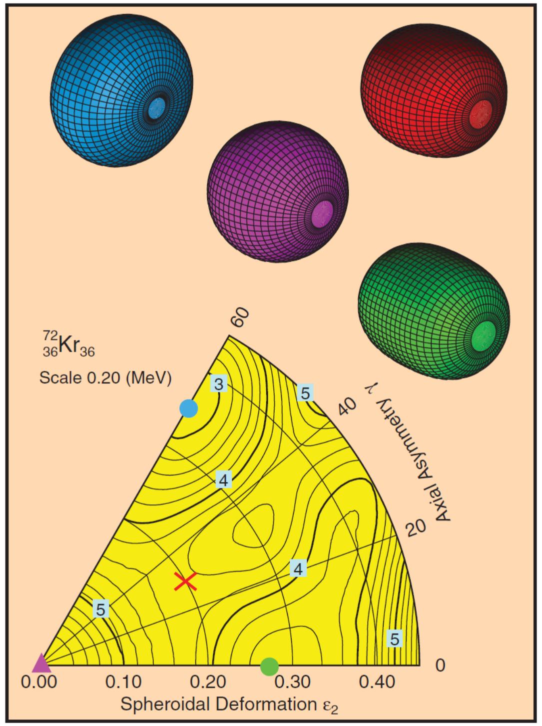
Outline

- Coulomb Excitation of ^{78}Kr (TRIUMF)
  - Motivation
  - Experiment
  - Data Analysis
  - Results and Outlook
- Coulomb Excitation at FRIB (brief)
  - Current status
  - Future plans

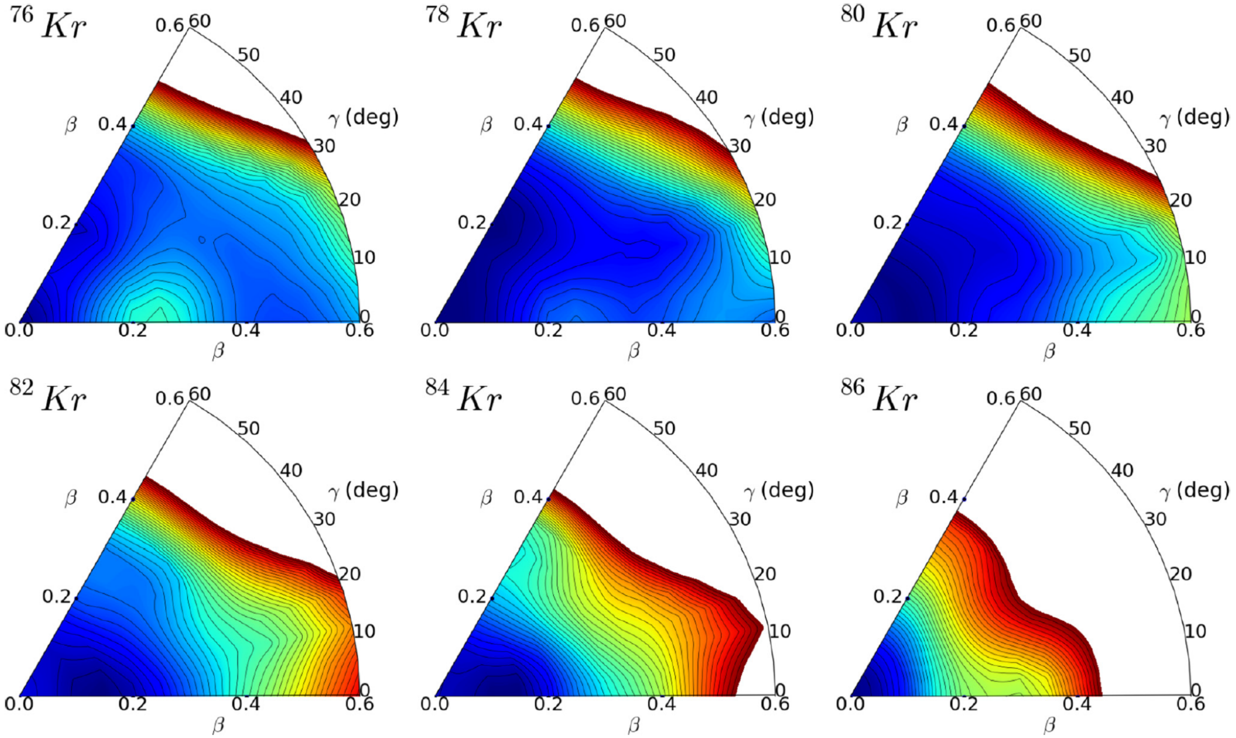
Coulomb Excitation of 78Kr

Nuclear Structure in the Krypton Isotopes

- Shape coexistence in neutron-deficient isotopes
  - Isomerism in N=Z=36 ^{72}Kr
- Shape changes along the isotopic chain
  - Evolution between various symmetries
  - ^{82}Kr suggested as E(5) CPS



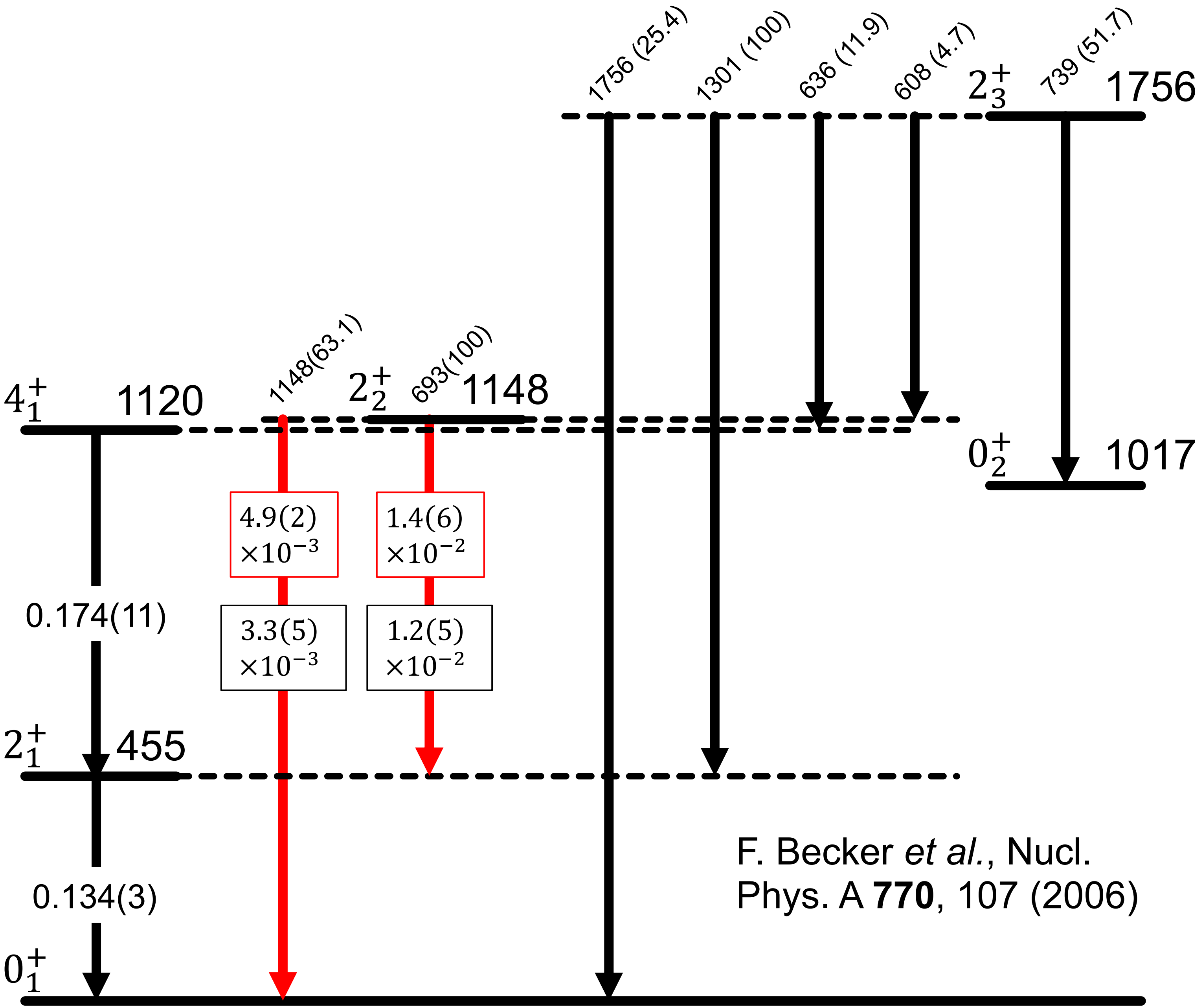
P. Moller *et al.*,
Phys. Rev. Lett. **103**, 212501 (2009)



K. E. Karakatsanis and K. Nomura, Phys. Rev. C **105**, 064310 (2022)

Motivation for ^{78}Kr

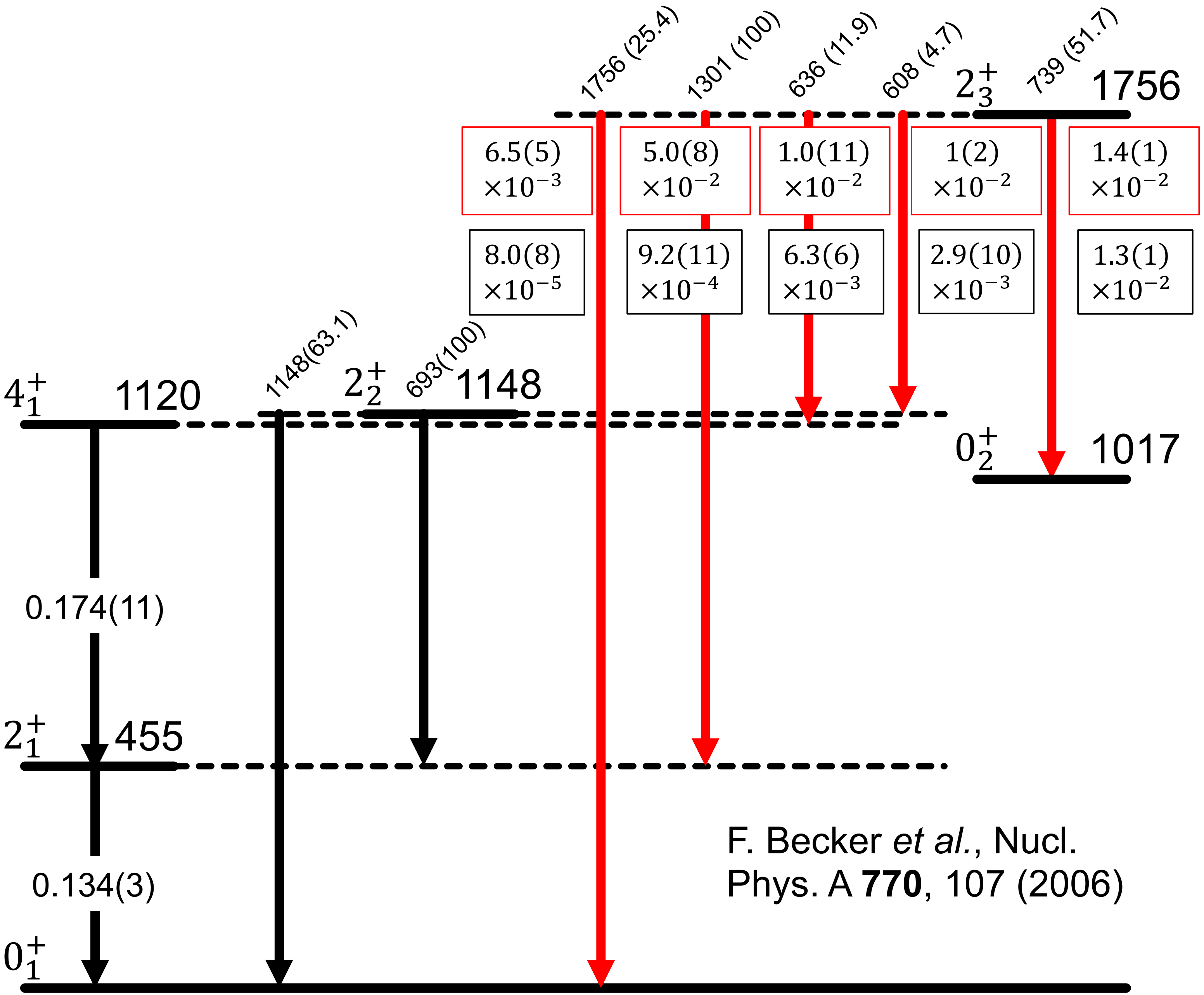
- CoulEx measurement by Becker *et al* inconsistent with decay data
  - Measured Q moments for first time



F. Becker *et al.*, Nucl. Phys. A **770**, 107 (2006)

Motivation for ^{78}Kr

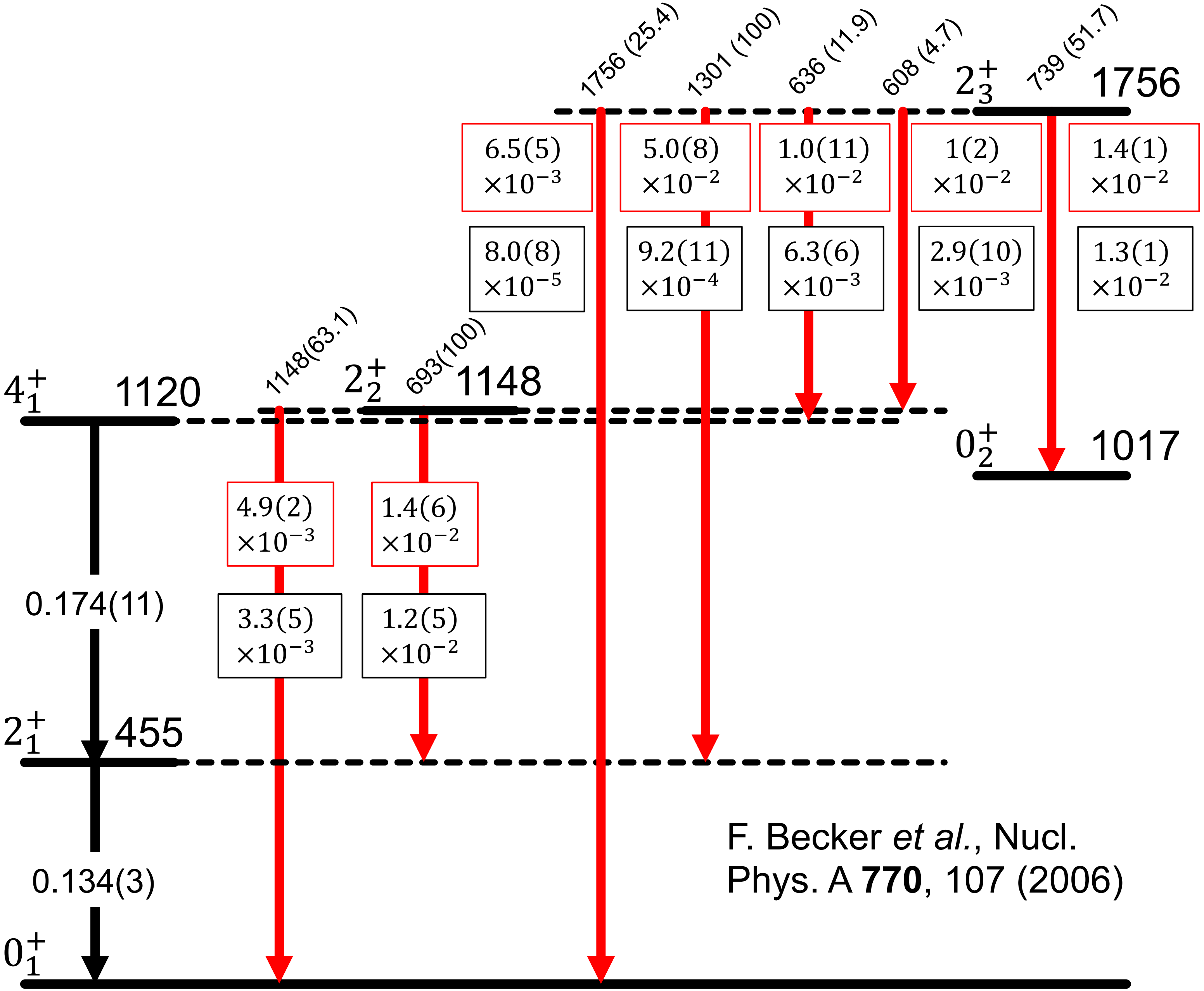
- CoulEx measurement by Becker *et al* inconsistent with decay data
  - Measured Q moments for first time
- 2_3^+ state highly discrepant
  - Lifetime and branching ratios in doubt



F. Becker *et al.*, Nucl. Phys. A **770**, 107 (2006)

Motivation for ^{78}Kr

- CoulEx measurement by Becker *et al* inconsistent with decay data
  - Measured Q moments for first time
- 2_3^+ state highly discrepant
  - Lifetime and branching ratios in doubt
- Proposed band structure based on these results
- Relevant for intrinsic shape parameters



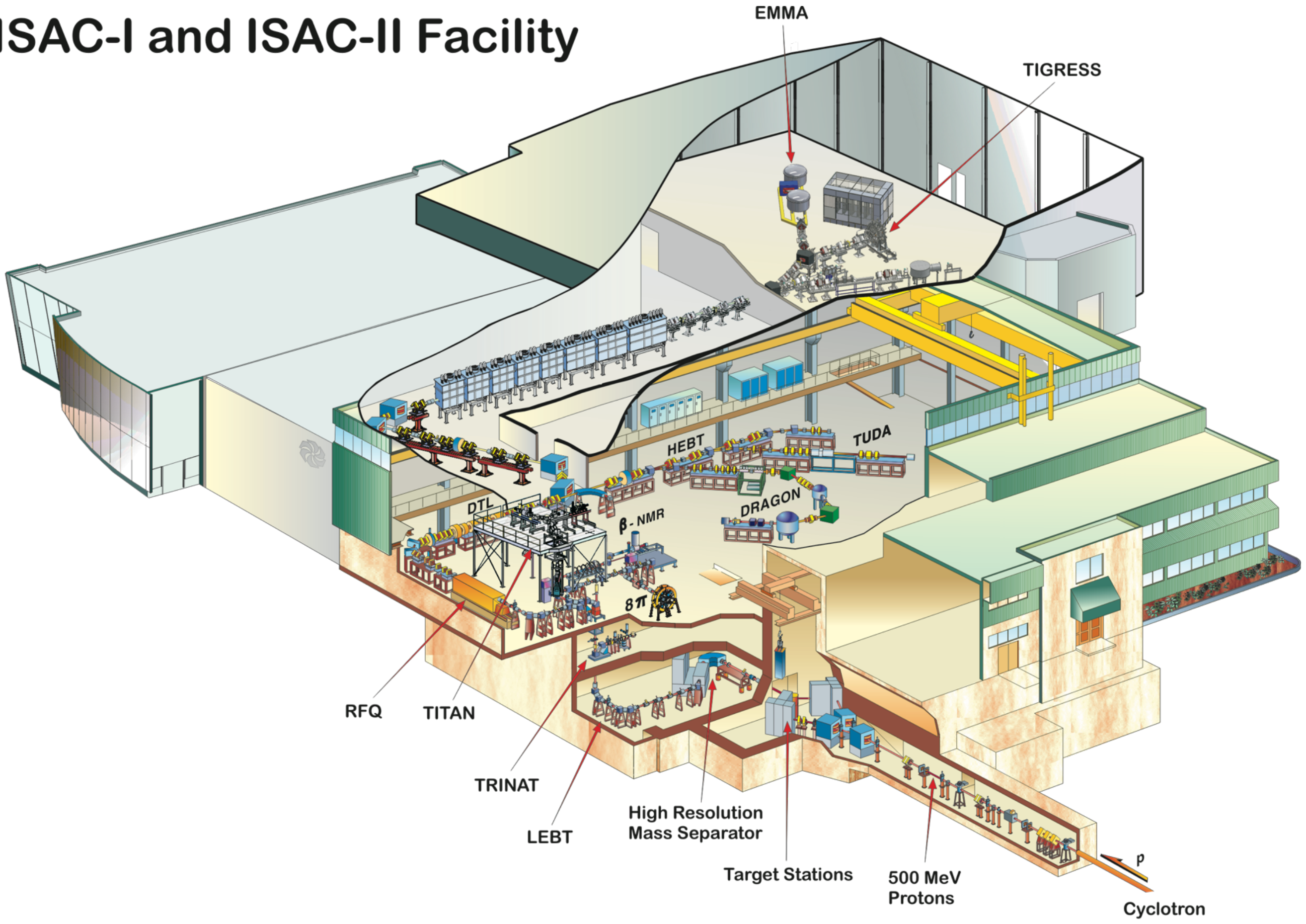
F. Becker *et al.*, Nucl. Phys. A **770**, 107 (2006)

Experimental Details

Experiment Overview

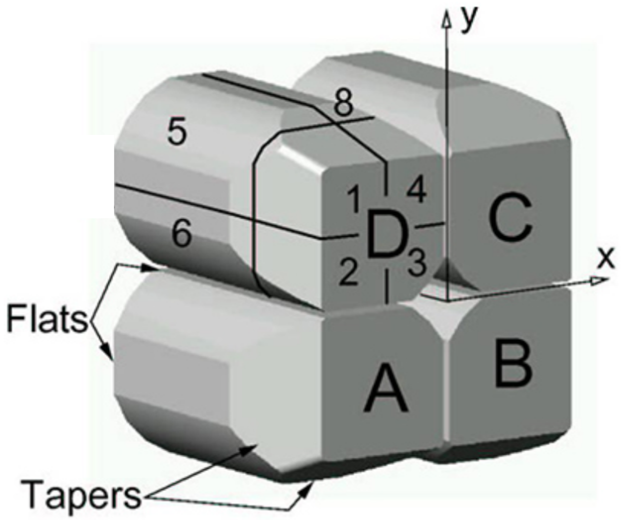
- Experiment was performed at the ISAC-II facility of TRIUMF August 2023
  - Located in Vancouver, BC
  - ISOL RIB Facility
- ^{78,84,86}Kr Off-line ion-source beams
  - Cyclotron not used for stable Kr
- ^{78}Kr delivered to experimental setup at 4.25 MeV/u
  - ^{194,196}Pt and ^{208}Pb reaction targets

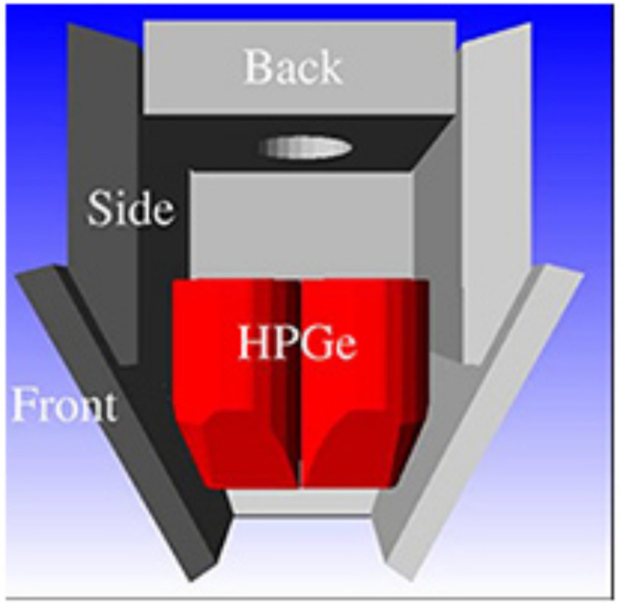
ISAC-I and ISAC-II Facility

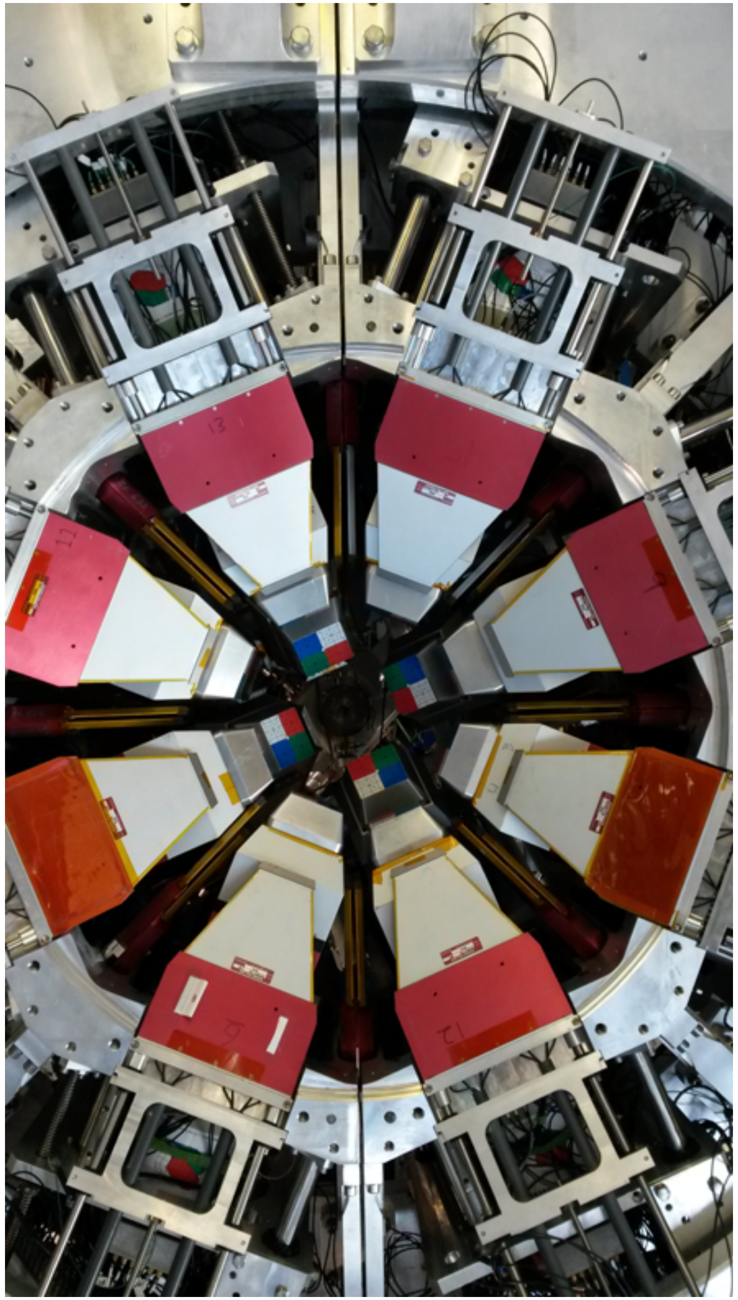


Experimental Setup

- TRIUMF-ISAC Gamma-ray Escape Suppressed Spectrometer (TIGRESS)
  - 16 Compton-suppressed clovers
  - Four 8-fold segmented crystals per clover
  - Two array configurations

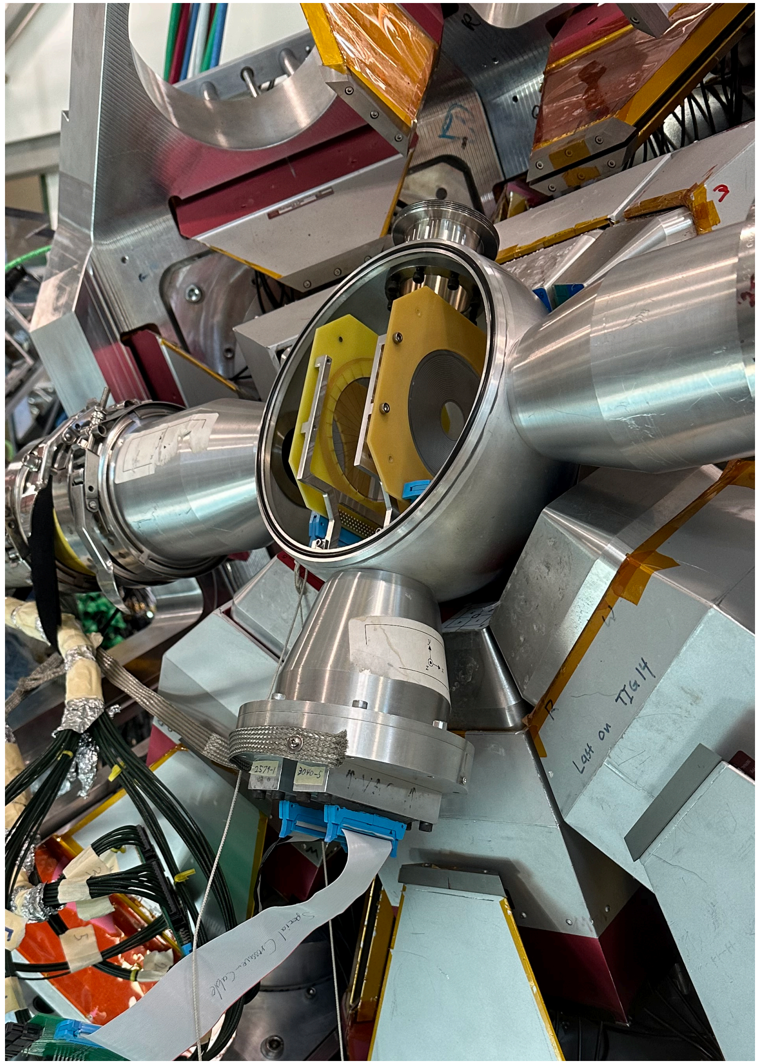


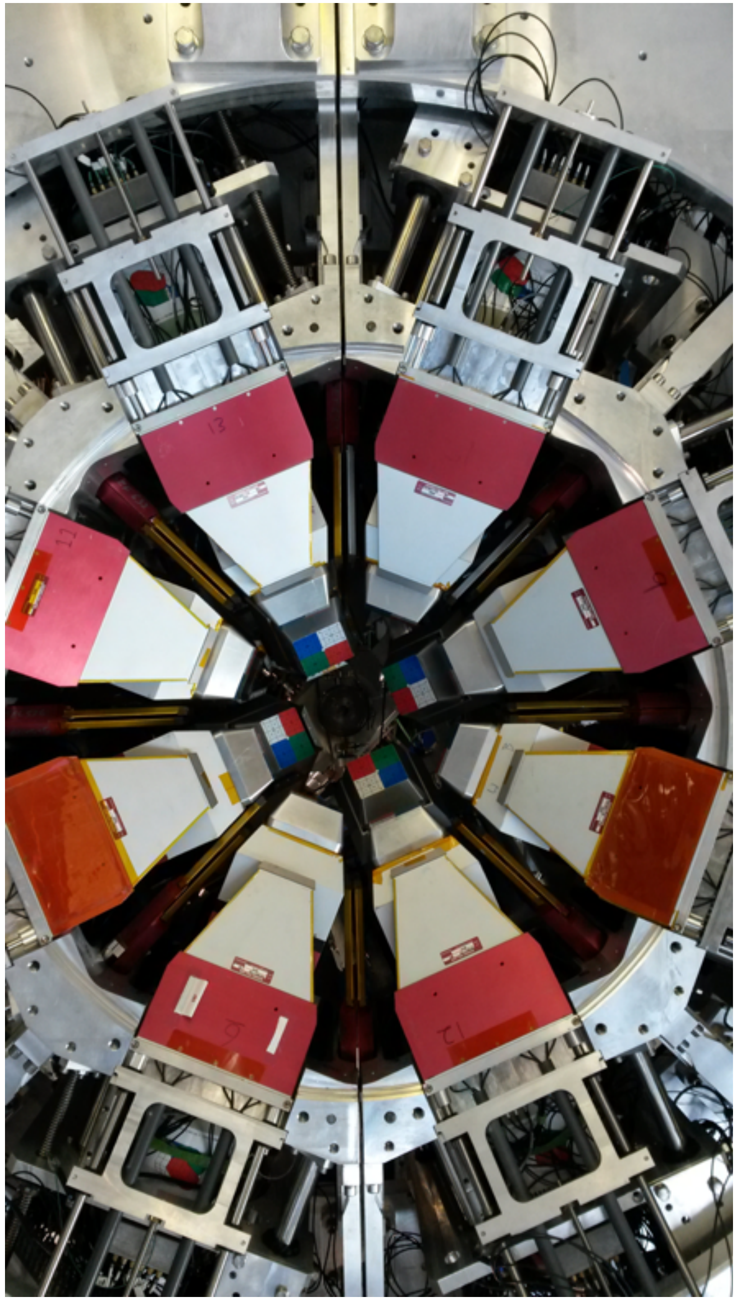




Experimental Setup

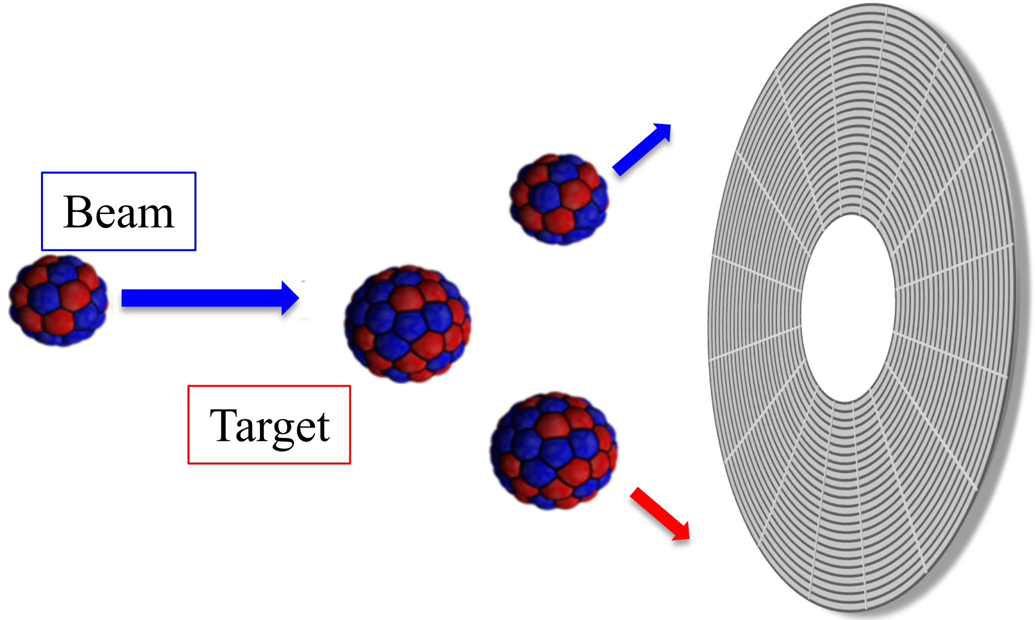
- TIGRESS
  - 16 Compton-suppressed clovers
  - Four 8-fold segmented crystals per clover
  - Two array configurations
- Bambino
  - Two S3 detectors, each 3 cm from target
  - 4 target positions
- Position information from detector segmentation
  - Doppler correction
  - CoulEx analysis

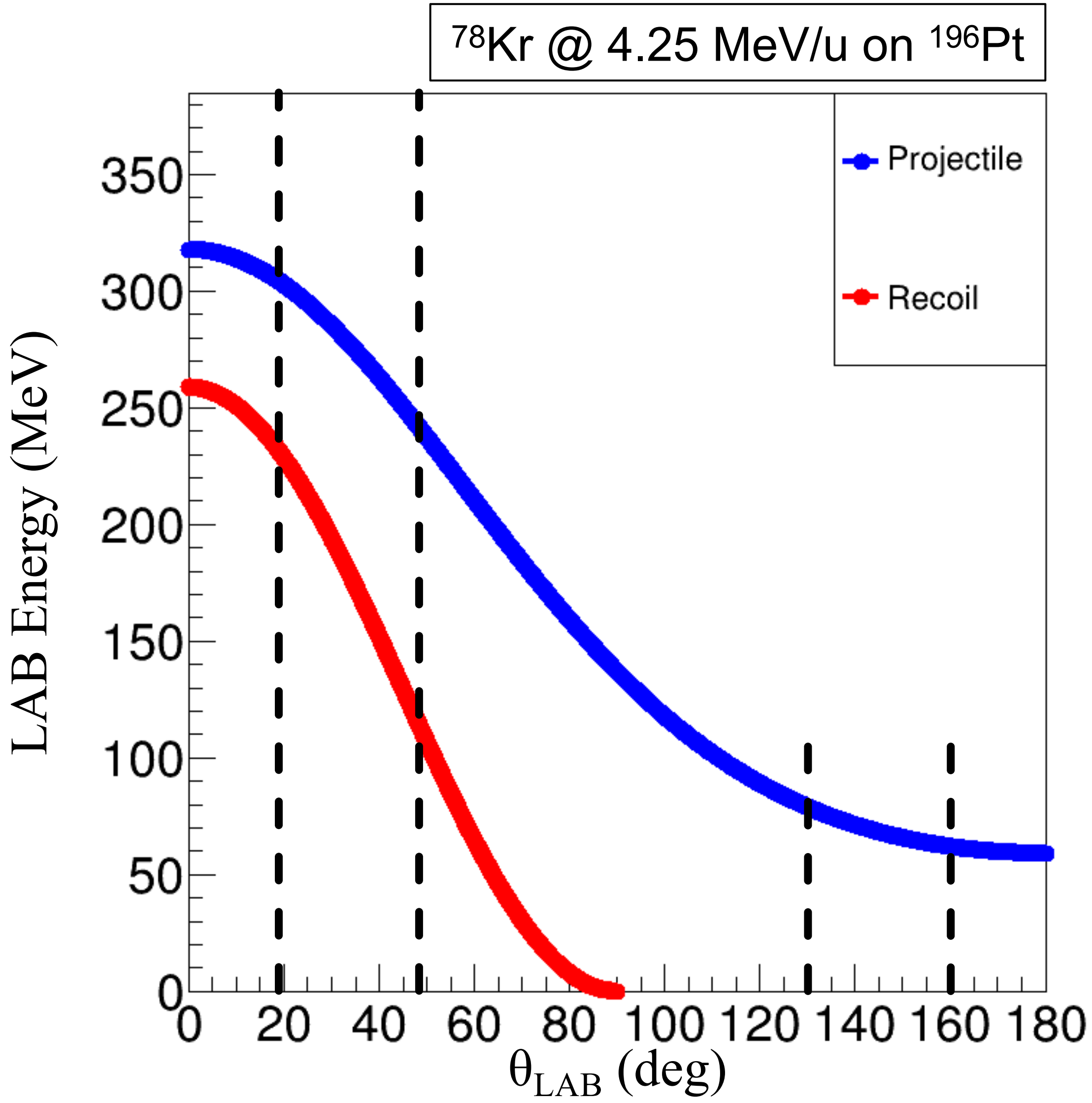




Particle Detection Scheme

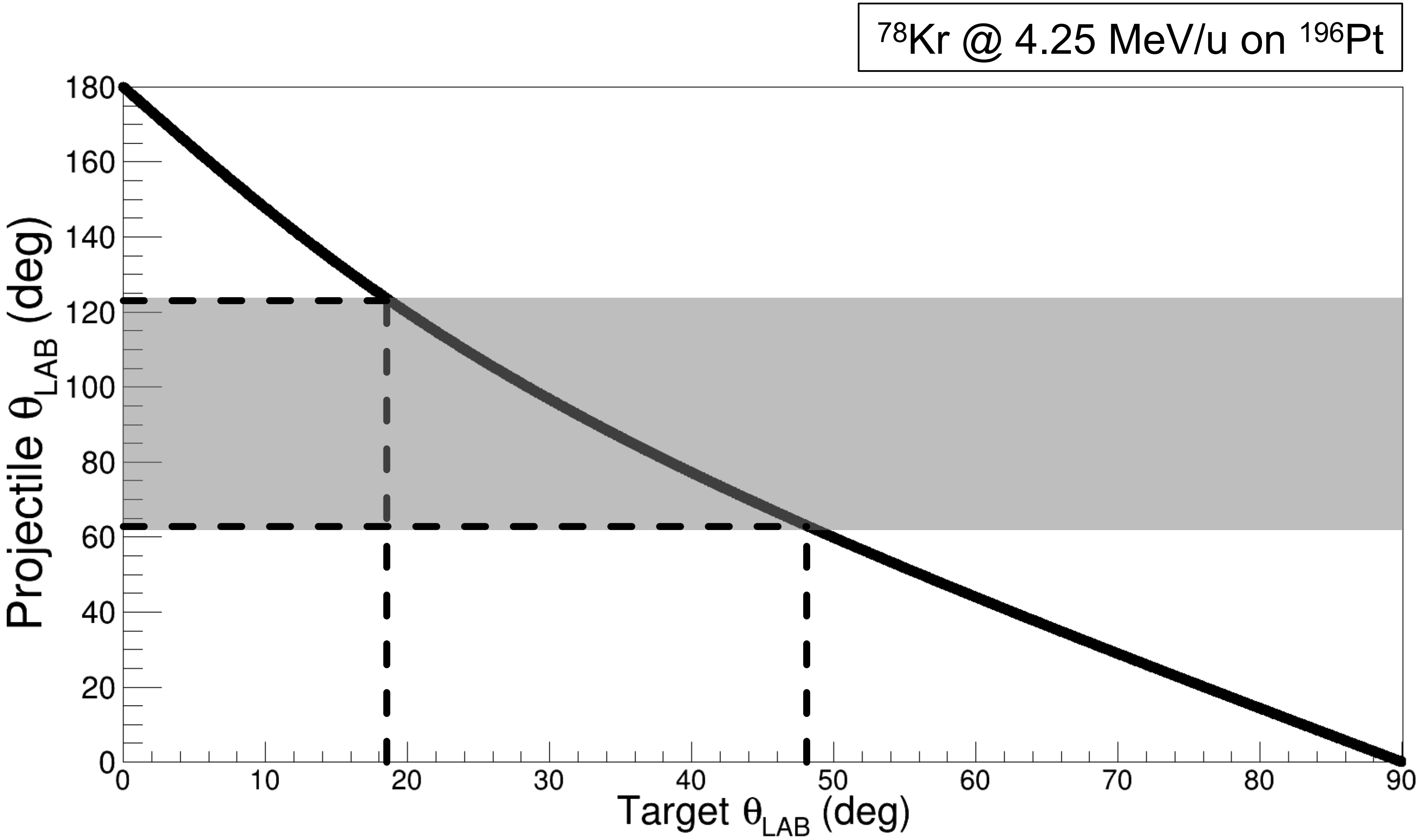
- Kinematic curves provide particle discrimination
  – Forward detector only
- Only 30% of 4π physically covered





Kinematic Reconstruction

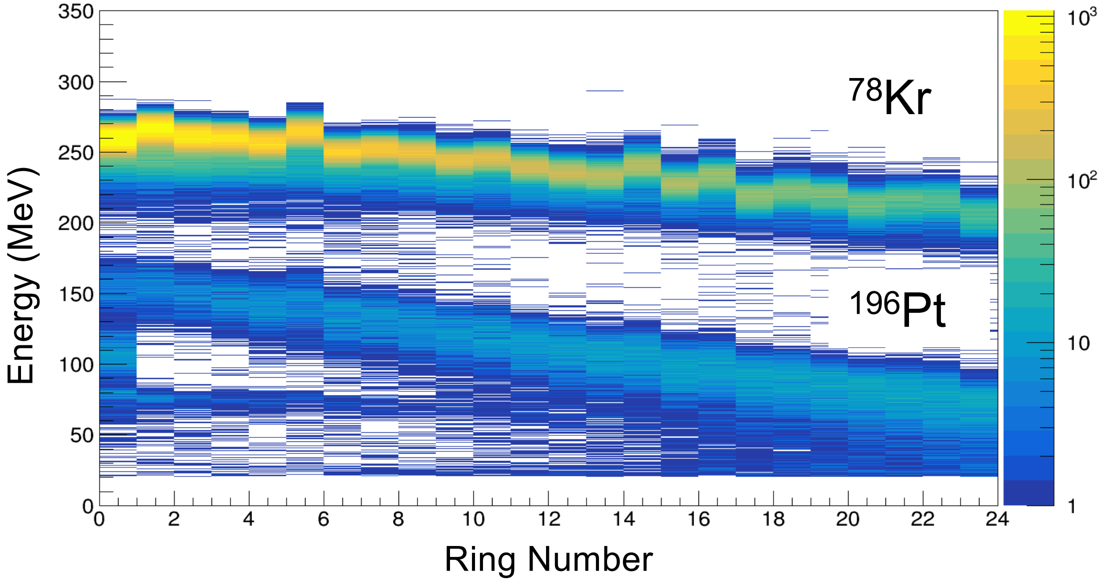
- Reconstruct undetected projectiles scattered near 90° from detected target
- Gain coverage from $62° - 123°$
  - 51% of 4π
- 30% → 81% of 4π

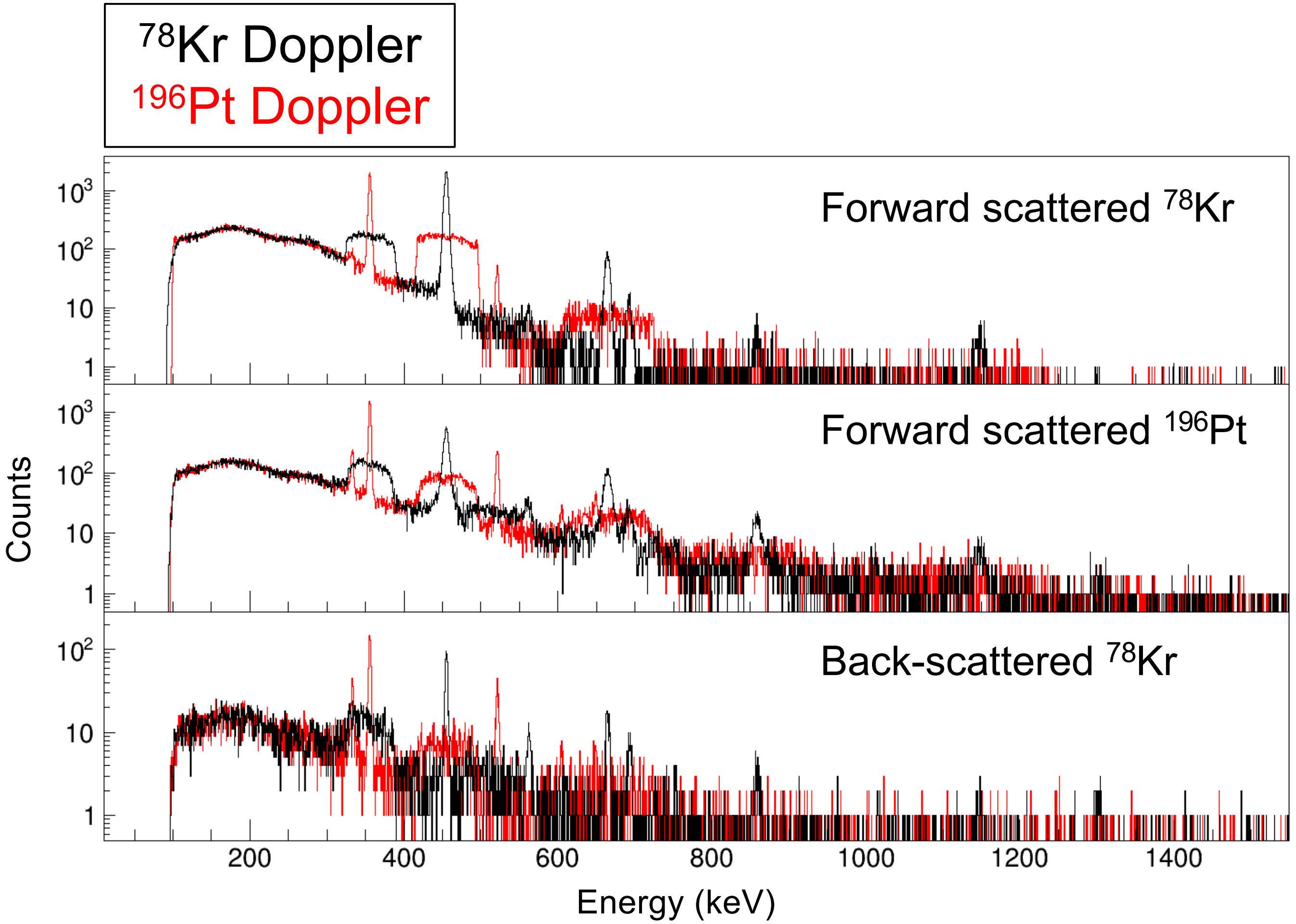


Experimental Spectra I

- ^{194,196}Pt to measure $B(E2; 2_1^+ \rightarrow 0_1^+)$
  - Normalize to target excitations
  - Reduces systematics

^{78}Kr @ 4.25 MeV/u on ^{196}Pt

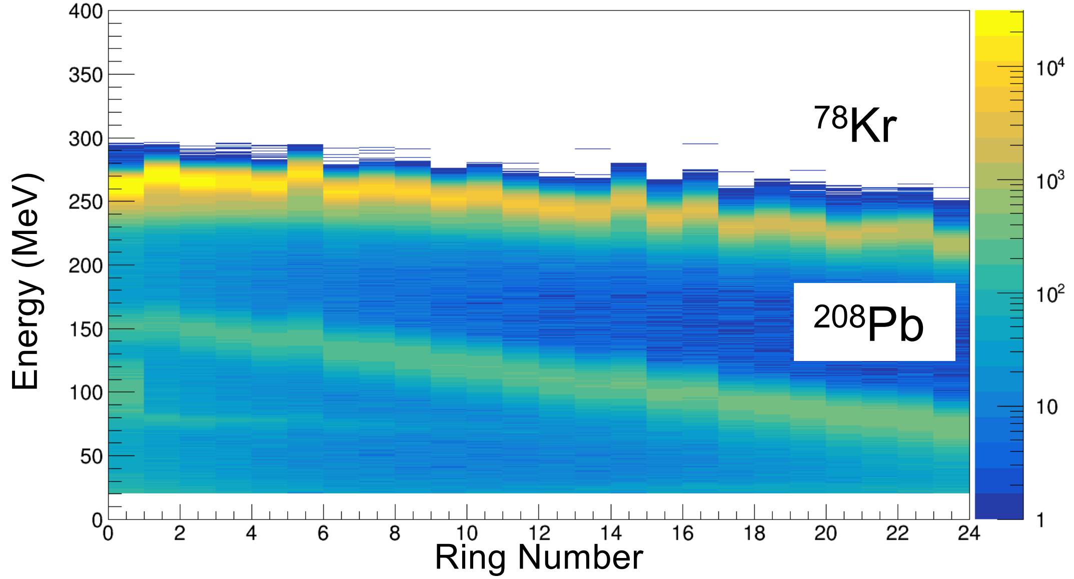


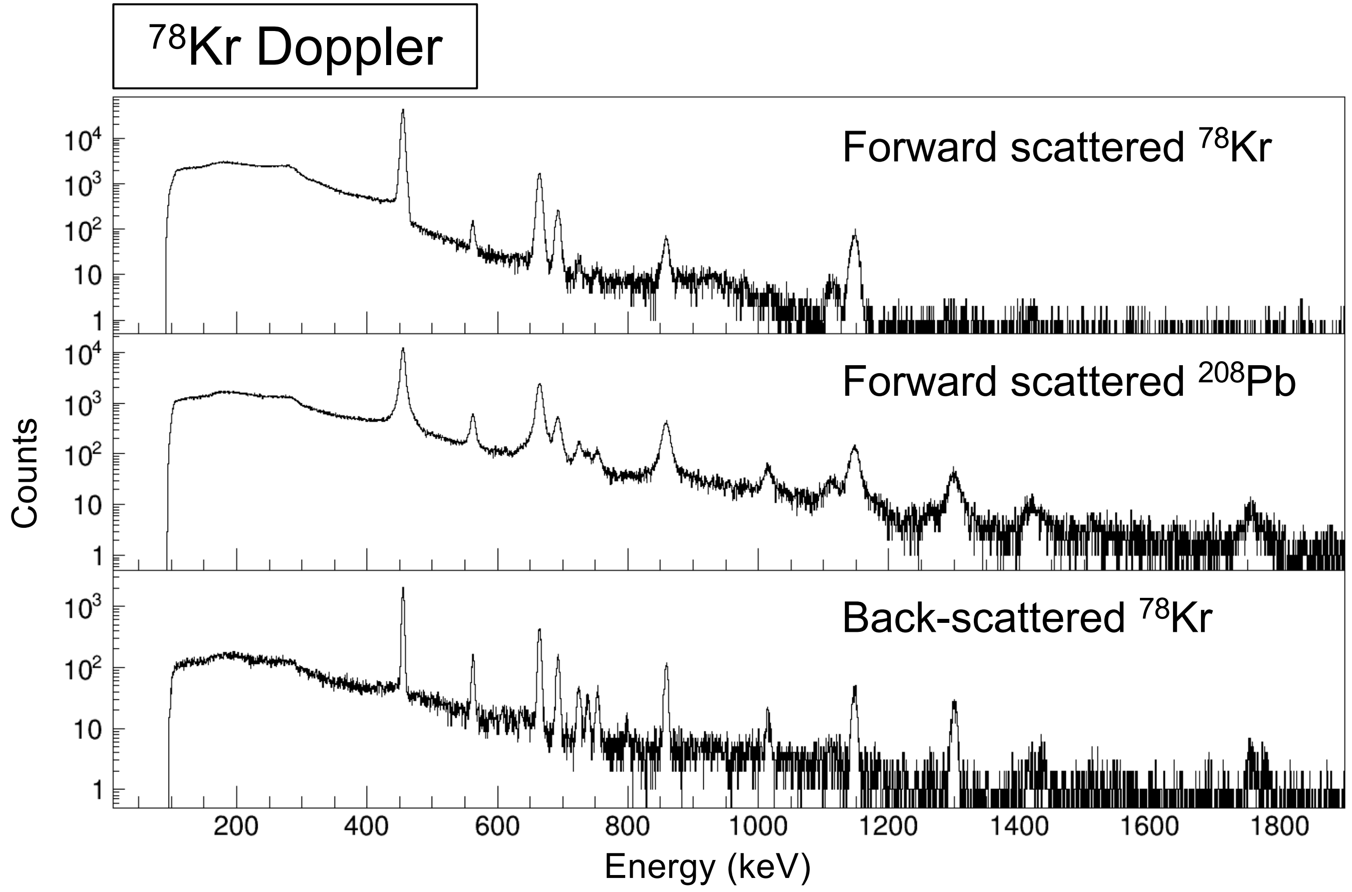


Experimental Spectra II

- ^{208}Pb target provides exceptionally clean spectra
  - No target excitations
  - Higher statistics (more time)

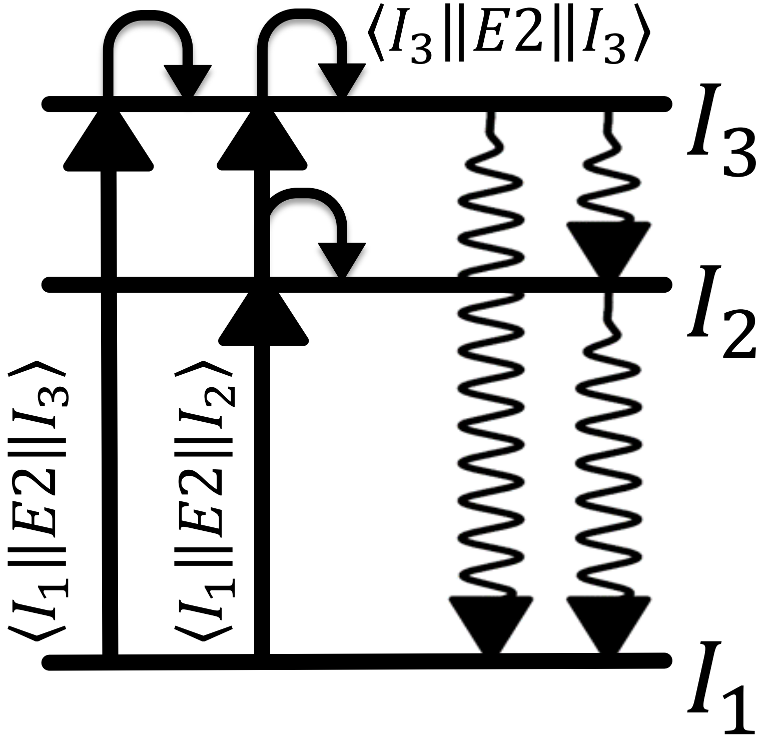
^{78}Kr @ 4.25 MeV/u on ^{208}Pb





Extracting Matrix Elements with GOSIA

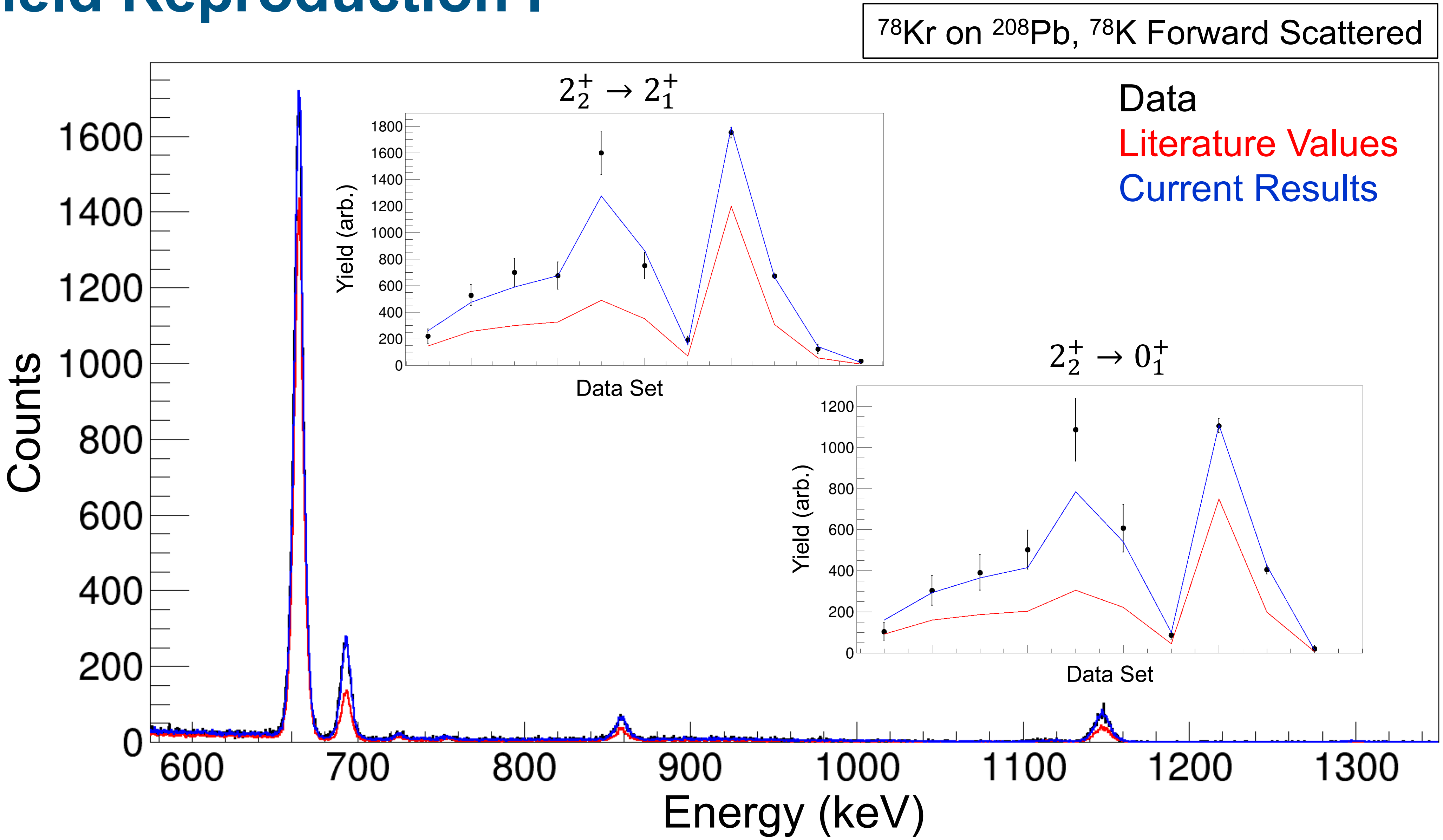
- Many excitation and de-excitation pathways
  - Large network of coupled differential equations
- GOSIA Coulomb excitation code was used
  - Calculates excitation and subsequent decay pattern
  - Fits experimental gamma-ray yields
  - Matrix elements used as parameters in a multi-dimensional least-squares search
- Produces set of best-fit matrix elements
  - Statistical error estimation also possible



$$i\hbar \frac{d}{dt} a_n(t) = \sum_m \langle n | V(t) | m \rangle \exp\left[i \left(E_n - E_m \right) t / \hbar \right] a_m(t)$$

$$P_n = a_n a_n^*$$

Yield Reproduction I



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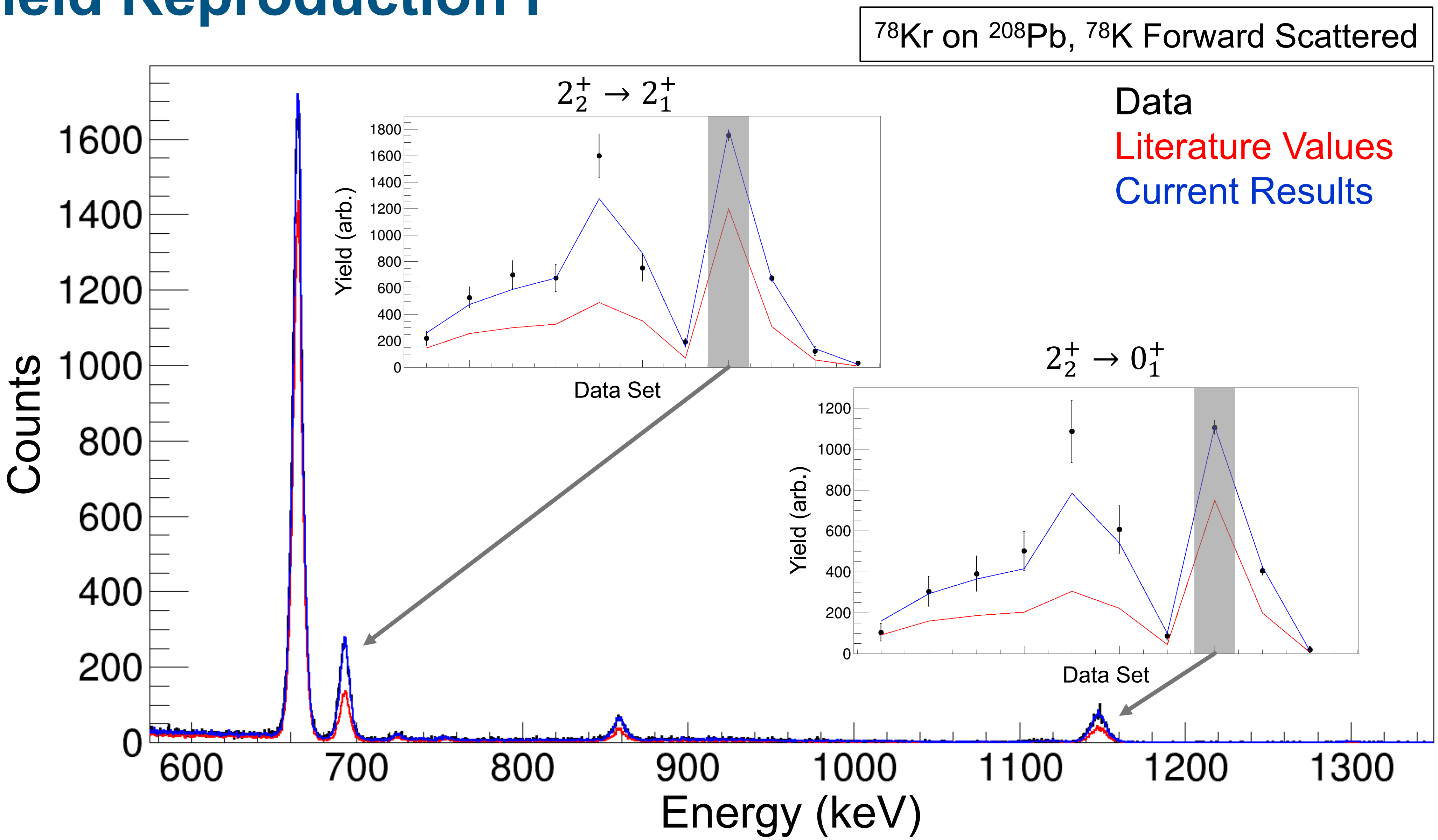
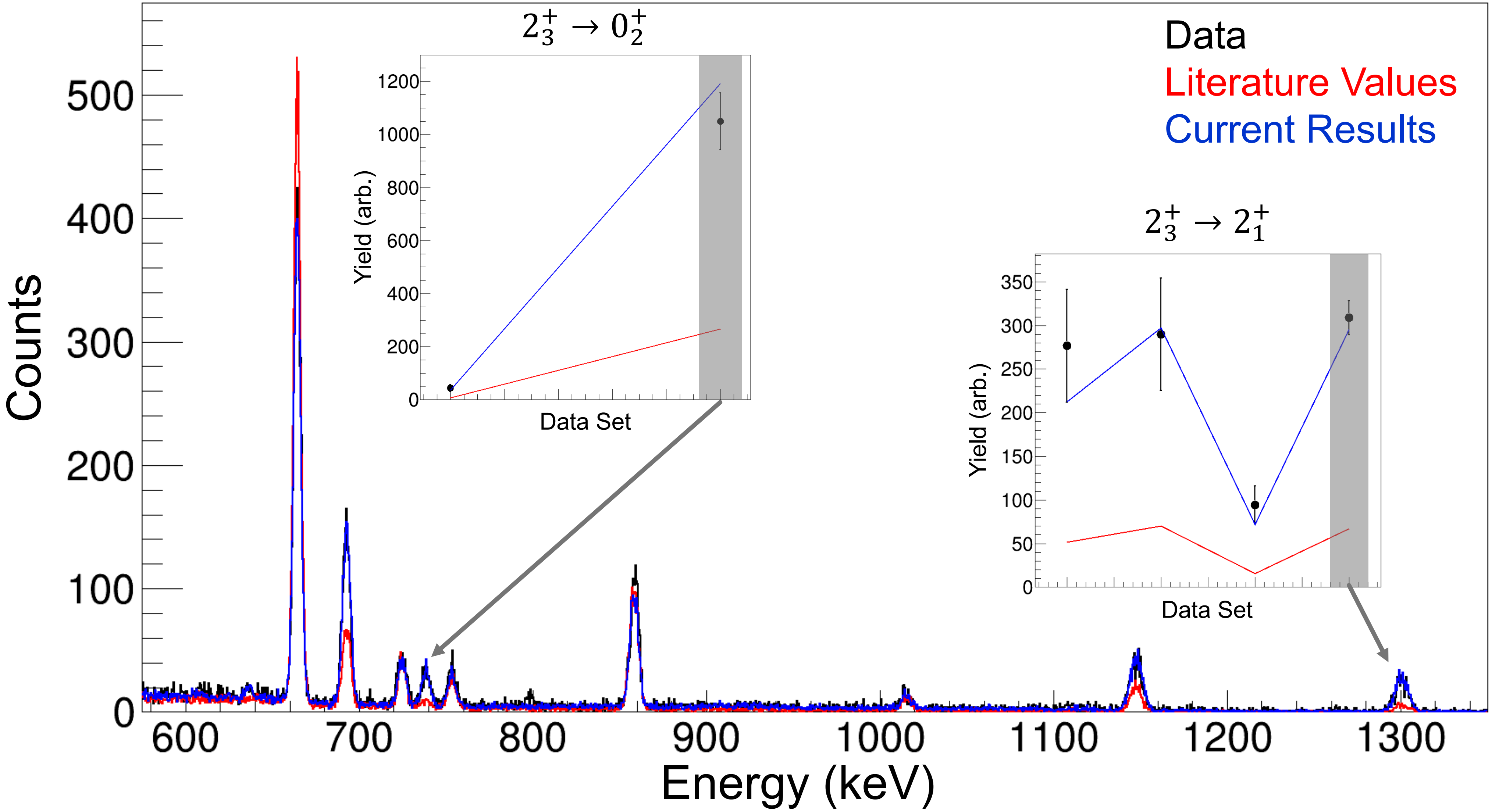


Yield Reproduction II

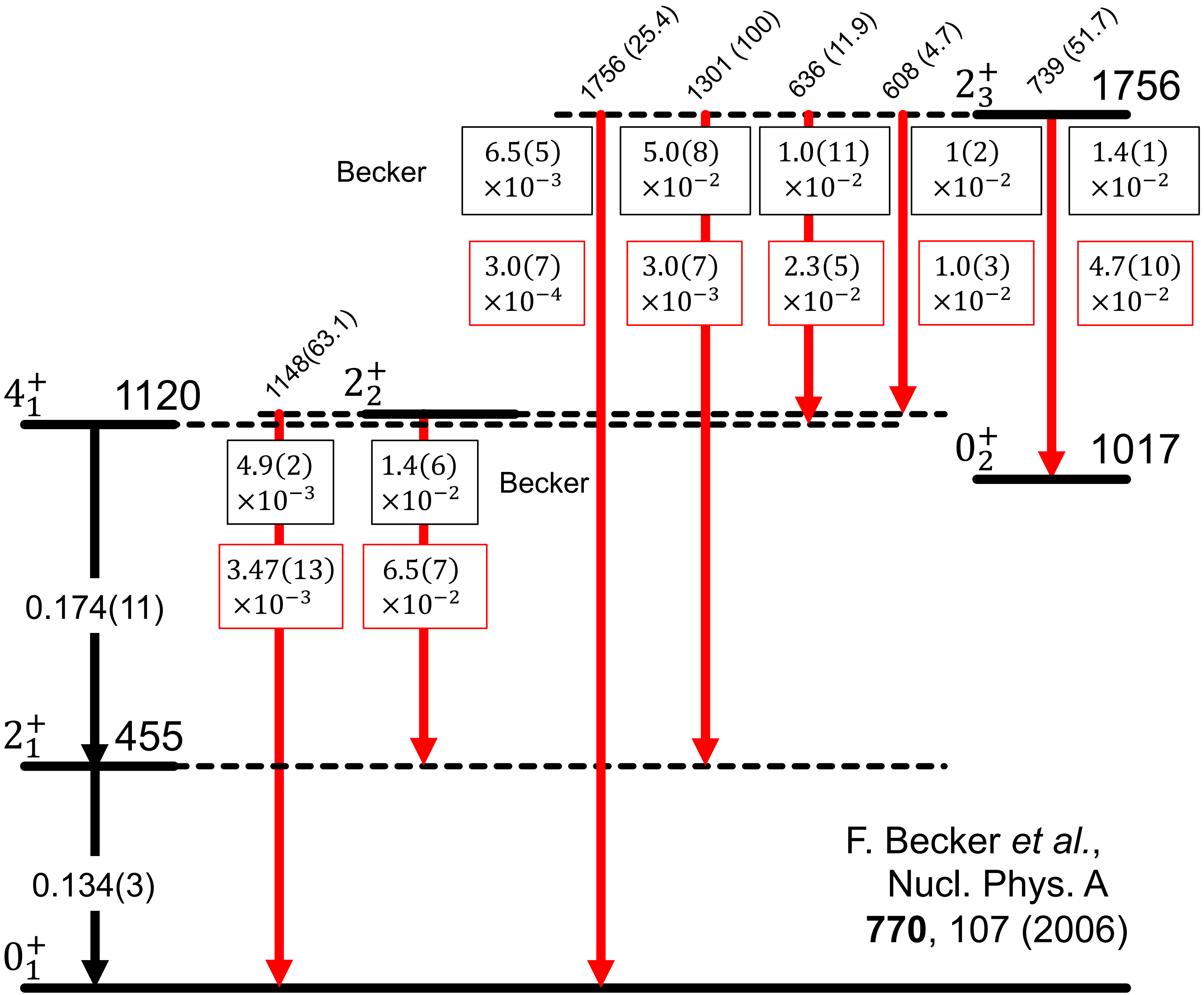
^{78}Kr on ^{208}Pb, ^{78}K Backscattered



Results and Outlook

Results I

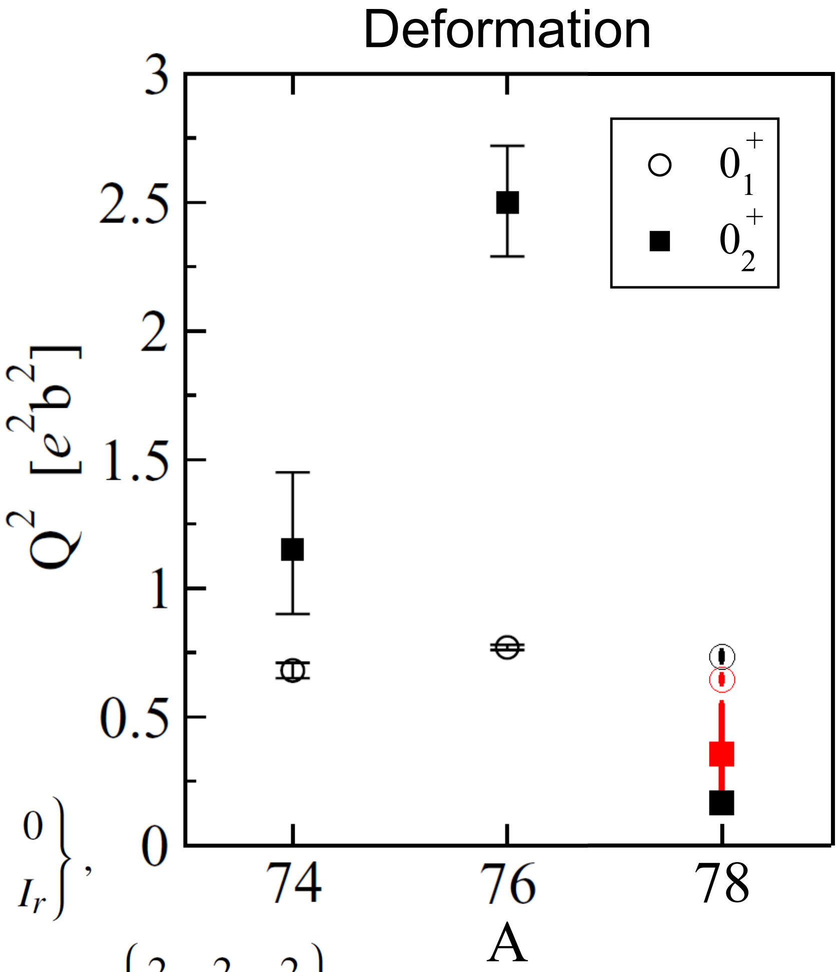
- Transition strengths almost all different from Becker et al.
- All branching ratios agree nicely with adopted values (decay data)
- 2_2^+ lifetime agrees with adopted value
- 2_2^+ mixing ratio is discrepant – 0.45(10) vs 4_2^{30}

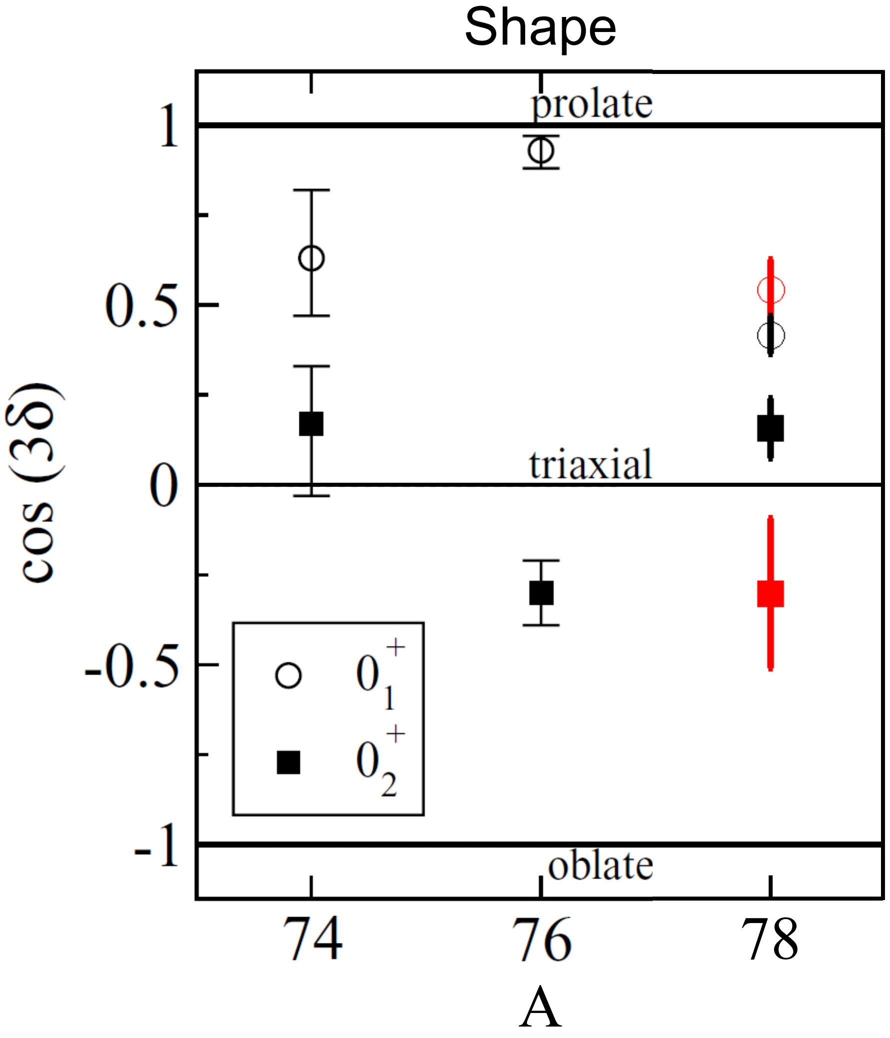


F. Becker *et al.*, Nucl. Phys. A **770**, 107 (2006)

Shape Parameters

- Shape parameters extracted for 0^+ states.
- Small deformations
- Different shapes
  - Largely due to sign of 2_1^+ and 2_3^+ quadrupole moments





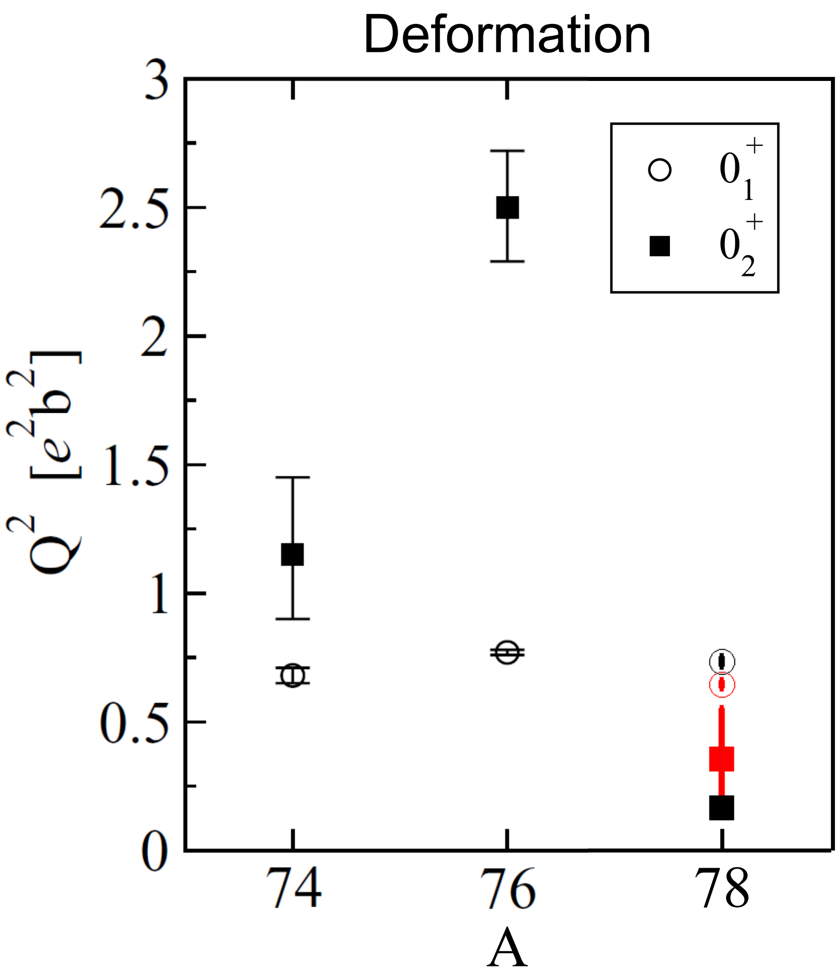
$$\langle Q^2 \rangle = \sqrt{5}\frac{(-1)^{2I_s}}{\sqrt{2I_s+1}}\sum_r M_{sr}M_{rs}\begin{Bmatrix} 2 & 2 & 0 \\ I_s & I_s & I_r \end{Bmatrix},$$

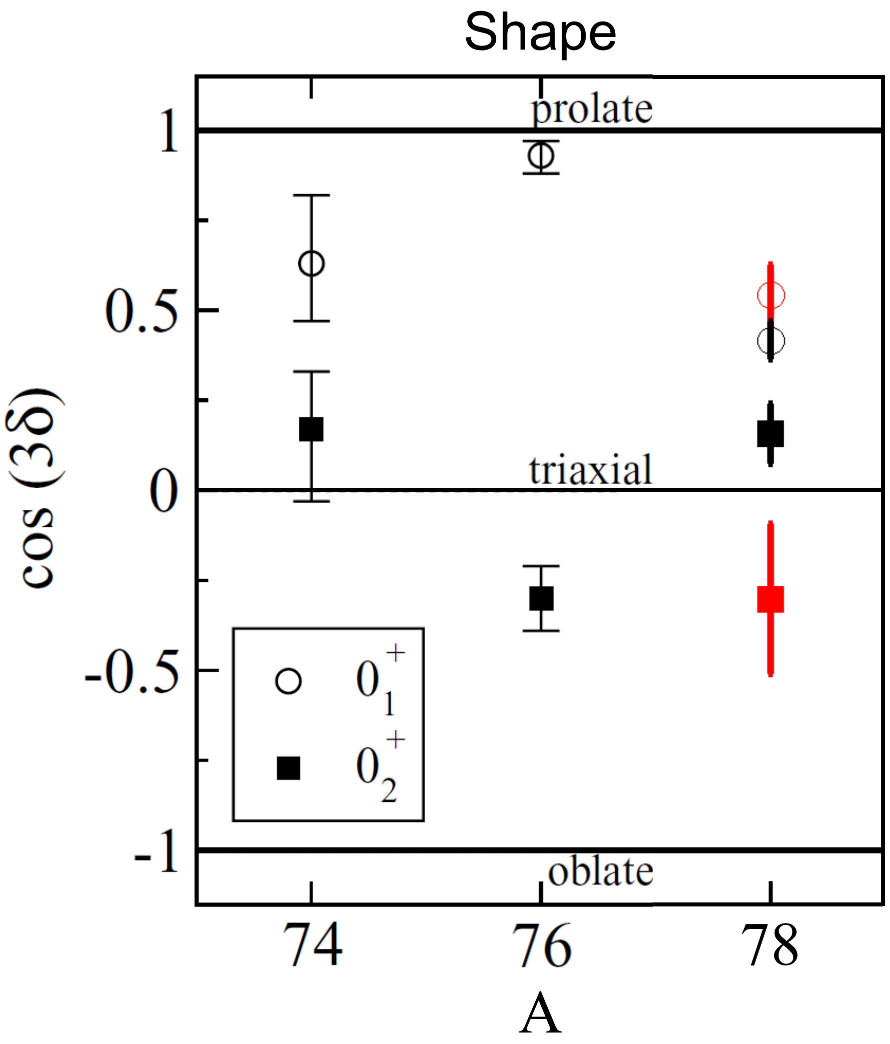
$$\langle Q^3 \cos(3\delta) \rangle = \frac{\sqrt{35}}{\sqrt{2}}\frac{(-1)^{2I_s+1}}{2I_s+1}\sum_{tu} M_{su}M_{ut}M_{ts}\begin{Bmatrix} 2 & 2 & 2 \\ I_s & I_t & I_u \end{Bmatrix}.$$

E. Clement *et al.*, Phys. Rev. C **75**, 054313 (2007)

Shape Parameters

- Shape parameters extracted for 0^+ states.
- Small deformations
- Different shapes
  - Largely due to sign of 2_1^+ and 2_3^+ quadrupole moments
- Note: No information (yet) on variances of the statistical moments





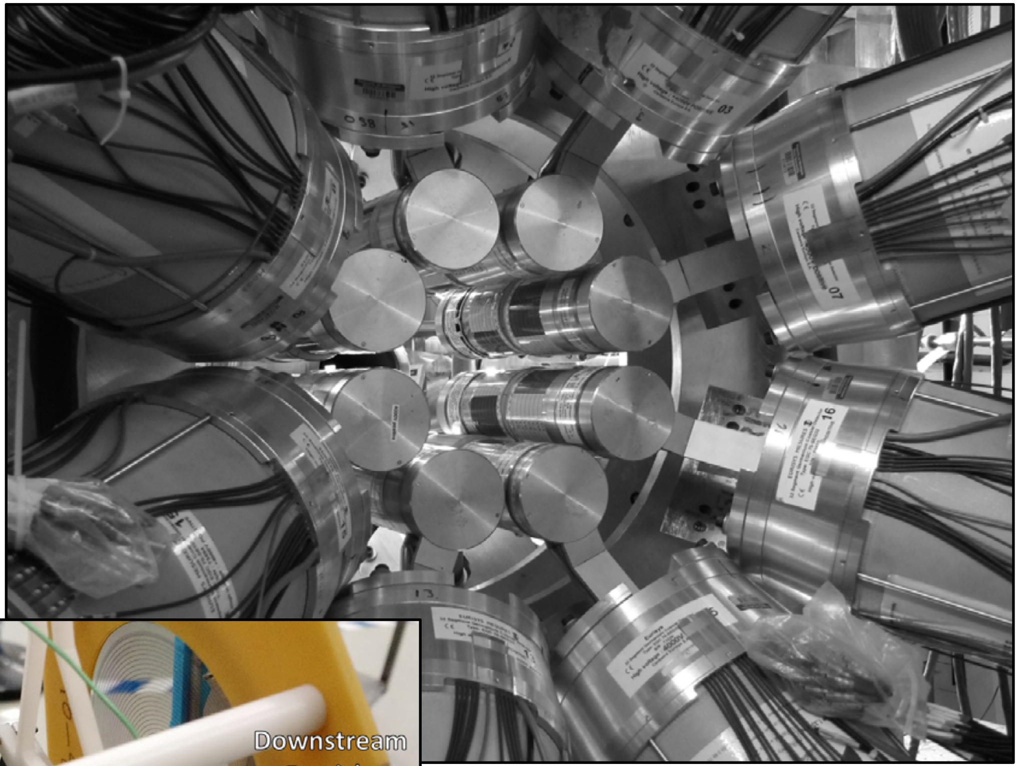
E. Clement *et al.*, Phys. Rev. C **75**, 054313 (2007)

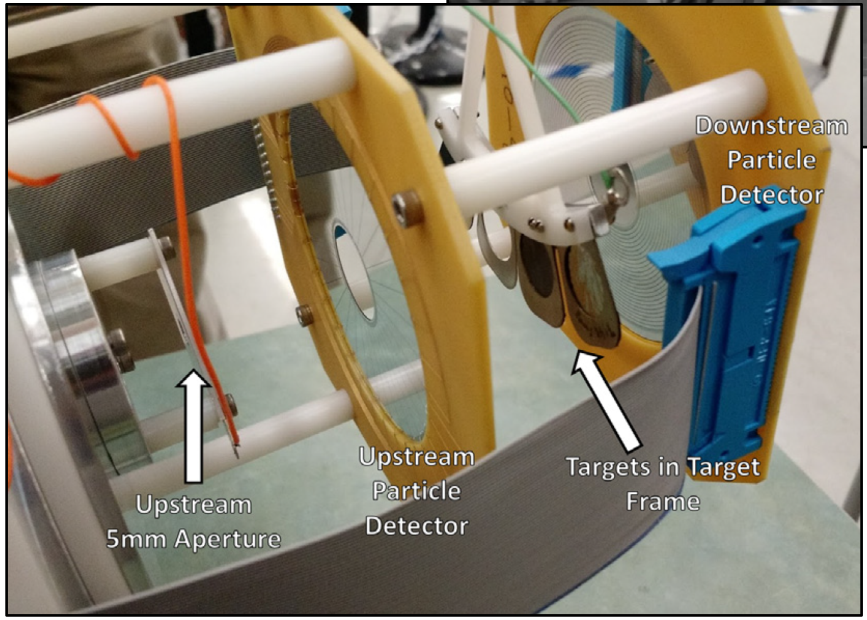
Experimental Collaboration

- S1937, S1576, and S1866 experimental collaborations
  - TRIUMF, Vancouver, BC V6T 2A3, Canada
  - Department of Physics, University of Surrey, Guildford, United Kingdom
  - Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom
  - Department of Physics, University of Guelph, Guelph, ON N1G 2W1, Canada
  - Science Technical Center, Simon Fraser University, Burnaby, BC V5A 1S6, Canada
  - Advanced Science Research Center, Japanese Atomic Energy Agency, 2-4 Shirakata Shirane, Tokai, Ibaraki 319-1195 Japan
  - Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Coulomb Excitation at FRIB

- ReAccelerator (ReA6) Facility provides RIB and stable beams at ~few MeV/u
  - Stop fast RIB in gas cell, extract
  - Ion source for stable beams
- Currently employ JANUS setup
  - SeGA with two S3 detectors
  - Many stable and RIB experiments successfully performed
- Beam development underway for two approved RIB experiments
  - ^{46}Ar and ^{44}Ti

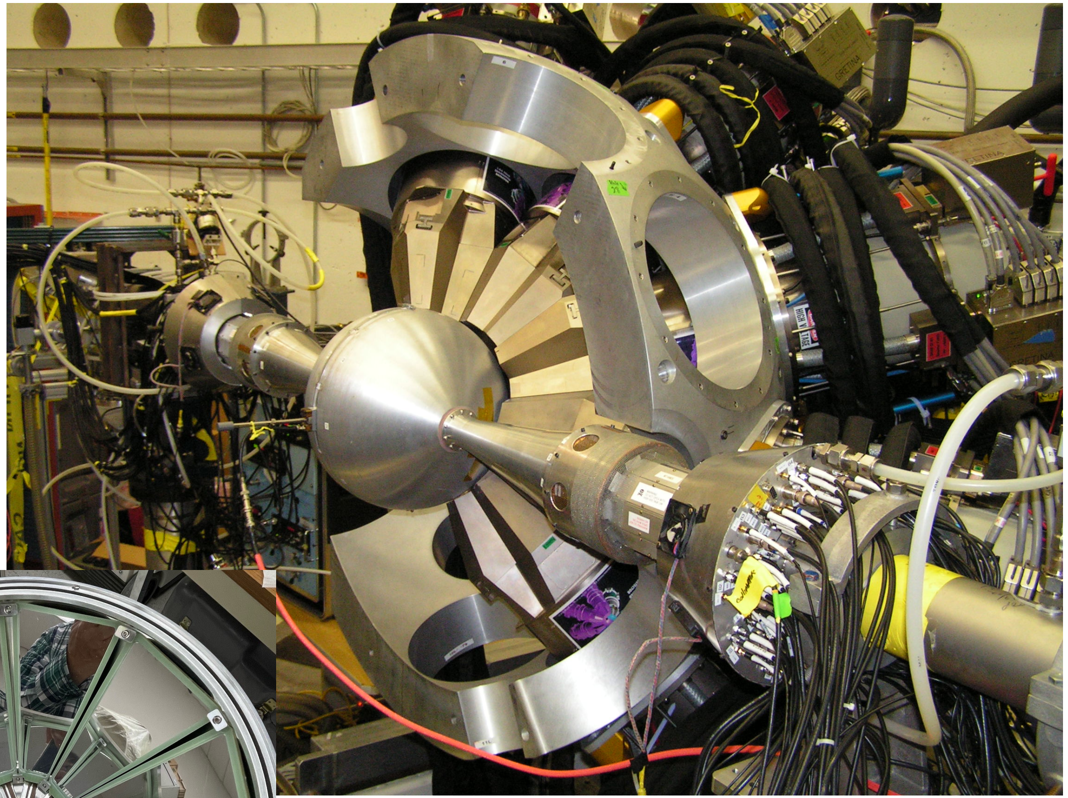




E. Lunderberg *et al.*, NIM A **885**, 30 (2018)

Future Plans for CoulEx at FRIB

- Two complimentary arrays for charged particle detection in anticipation of GRETA @ ReA6
  - CHICOX for Z > 20 nuclei
  - BambinoX for Z < 20 nuclei
- CHICOX is the upgrade of CHICO2 PPAC array
  - Assembly and initial tests completed
  - Will be used first with GRETINA at Argonne next year
- BambinoX houses two S3 detectors similar to JANUS and Bambino
  - Starting manufacturing process
  - Will be ready for GRETA at FRIB



CHICO2 @ Argonne

C. Y. Wu *et al.*, NIM A **814**, 6 (2016)

Thank You!

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Extra Slides

Extracted Matrix Elements I

Matrix Element	This Work	Lunderberg	Becker	Adopted
$\langle 0_1^+ \vert\vert E2 \vert\vert 2_1^+ \rangle$	0.788_5^5	0.81_1^1	0.82_2^2	0.82_1^1
$\langle 2_1^+ \vert\vert E2 \vert\vert 2_1^+ \rangle$	-0.78_8^8	-0.96_{47}^{11}	-0.80_4^4	-
$\langle 2_1^+ \vert\vert E2 \vert\vert 4_1^+ \rangle$	1.38_1^1	1.30_2^2	1.27_2^5	1.25_4^4
$\langle 4_1^+ \vert\vert E2 \vert\vert 4_1^+ \rangle$	-1.34_{10}^{11}	$-1.2_{10}^{2.4}$	-0.73_{14}^{15}	-
$\langle 4_1^+ \vert\vert E2 \vert\vert 6_1^+ \rangle$	1.87_2^2	1.63_7^7	1.61_8^6	1.56_9^9
$\langle 6_1^+ \vert\vert E2 \vert\vert 6_1^+ \rangle$	-1.0_2^2	-0.8_{13}^{22}	-0.87_{12}^{16}	-
$\langle 6_1^+ \vert\vert E2 \vert\vert 8_1^+ \rangle$	2.26_5^5	-	1.80_8^{15}	1.82_{14}^{14}

F. Becker *et al.*, Nucl. Phys. A **770**, 107 (2006)

E. Lunderberg *et al.*, NIM A **885**, 30 (2018)

E. Lunderberg, PhD Thesis, Michigan State University (2017).

Extracted Matrix Elements II

Matrix Element	This Work	Lunderberg	Becker	Adopted
$\langle 0_1^+ \|\| E2 \|\| 2_2^+ \rangle$	0.132_3^2	0.159(5)	0.157(4)	0.13(1)
$\langle 2_1^+ \|\| E2 \|\| 2_2^+ \rangle$	0.57_3^2	0.43(3)	0.26(6)	0.24(5)
$\langle 2_2^+ \|\| E2 \|\| 2_2^+ \rangle$	0.88_{17}^{22}	1.0_7^3	0.58_8^4	-
$\langle 0_2^+ \|\| E2 \|\| 2_2^+ \rangle$	-0.06_{10}^{10}	-	-0.03_1^2	-
$\langle 2_1^+ \|\| M1 \|\| 2_2^+ \rangle$	0.08_7^7	0.33(2)	0.38(3)	0.30(3)
$\langle 0_1^+ \|\| E2 \|\| 2_3^+ \rangle$	0.039_4^5	0.0384(7)	0.180(8)	0.020(1)
$\langle 2_1^+ \|\| E2 \|\| 2_3^+ \rangle$	0.123_{16}^{14}	0.084(5)	0.50_5^2	0.068(4)
$\langle 2_2^+ \|\| E2 \|\| 2_3^+ \rangle$	0.23_{16}^4	0.15_{37}^2	0.19_5^{32}	0.12(2)
$\langle 0_2^+ \|\| E2 \|\| 2_3^+ \rangle$	0.48_5^6	0.48(1)	0.26(1)	0.25(1)
$\langle 4_1^+ \|\| E2 \|\| 2_3^+ \rangle$	0.34_4^4	0.330(6)	0.22_5^{20}	0.178(8)
$\langle 2_3^+ \|\| E2 \|\| 2_3^+ \rangle$	0.7_4^4	1.6_5^{18}	-0.22_{14}^9	-
$\langle 2_1^+ \|\| M1 \|\| 2_3^+ \rangle$	-0.12_3^3	-0.149(3)	-0.41_4^{12}	0.057(4)
$\langle 2_2^+ \|\| M1 \|\| 2_3^+ \rangle$	0.03_3^3	0.09(2)	-	0.016_8^{14}

F. Becker *et al.*, Nucl. Phys. A **770**, 107 (2006)

E. Lunderberg *et al.*, NIM A **885**, 30 (2018)

E. Lunderberg, PhD Thesis, Michigan State University (2017).

Extracted Matrix Elements III

Matrix Element	This Work	Lunderberg	Becker	Adopted
$\langle 2_1^+ \| E2 \| 4_2^+ \rangle$	0.0542^{13}_{13}	0.074^{5}_{6}	0.073^{2}_{5}	0.069^{5}_{5}
$\langle 2_2^+ \| E2 \| 4_2^+ \rangle$	0.740^{16}_{16}	0.89^{5}_{7}	0.91^{6}_{4}	0.95^{6}_{6}
$\langle 4_1^+ \| E2 \| 4_2^+ \rangle$	0.504^{13}_{13}	-	-0.60^{2}_{3}	0.66^{8}_{8}
$\langle 4_2^+ \| E2 \| 4_2^+ \rangle$	1.27^{23}_{21}	-	-	-
$\langle 4_1^+ \| M1 \| 4_2^+ \rangle$	0.10^{1}_{1}	-	-0.12^{5}_{7}	0.2^{3}_{3}
$\langle 0_2^+ \| E2 \| 2_1^+ \rangle$	0.33^{2}_{2}	0.243^{16}_{7}	0.30^{1}_{1}	0.31^{1}_{1}
$\langle 0_1^+ \| E3 \| 3_1^- \rangle$	0.22^{4}_{4}	-	-	0.20^{3}_{3}
$\langle 2_1^+ \| E3 \| 5_1^- \rangle$	0.43^{2}_{2}	-	-	-
$\langle 3_1^- \| E2 \| 3_1^- \rangle$	-3.1^{25}_{25}	-	-	-
$\langle 3_1^- \| E2 \| 5_1^- \rangle$	-0.3^{21}_{21}	-	-	-

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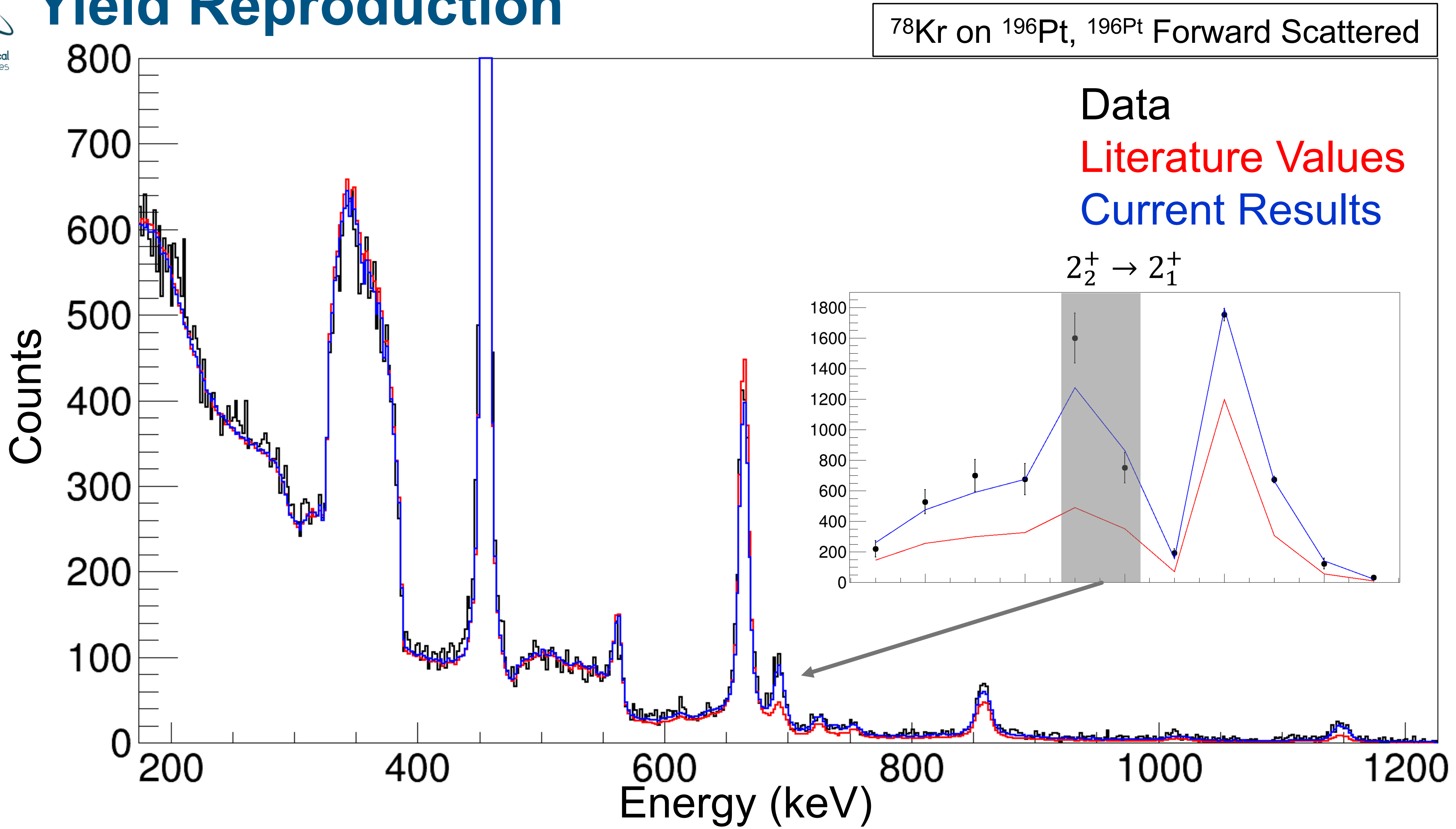
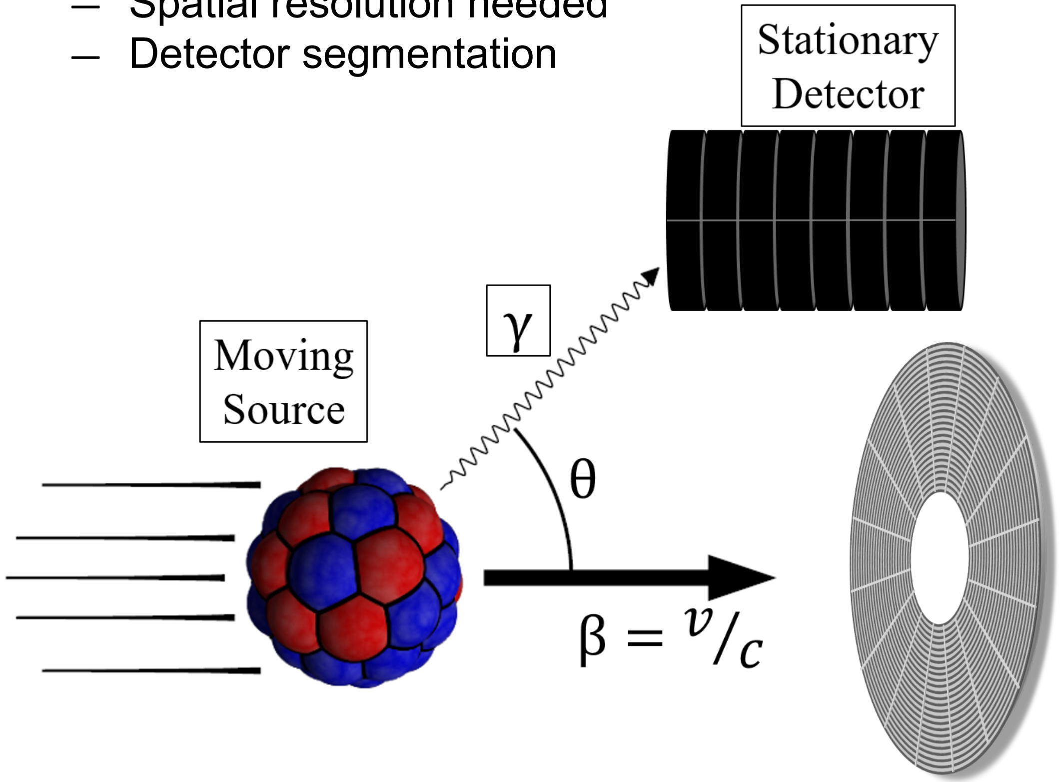
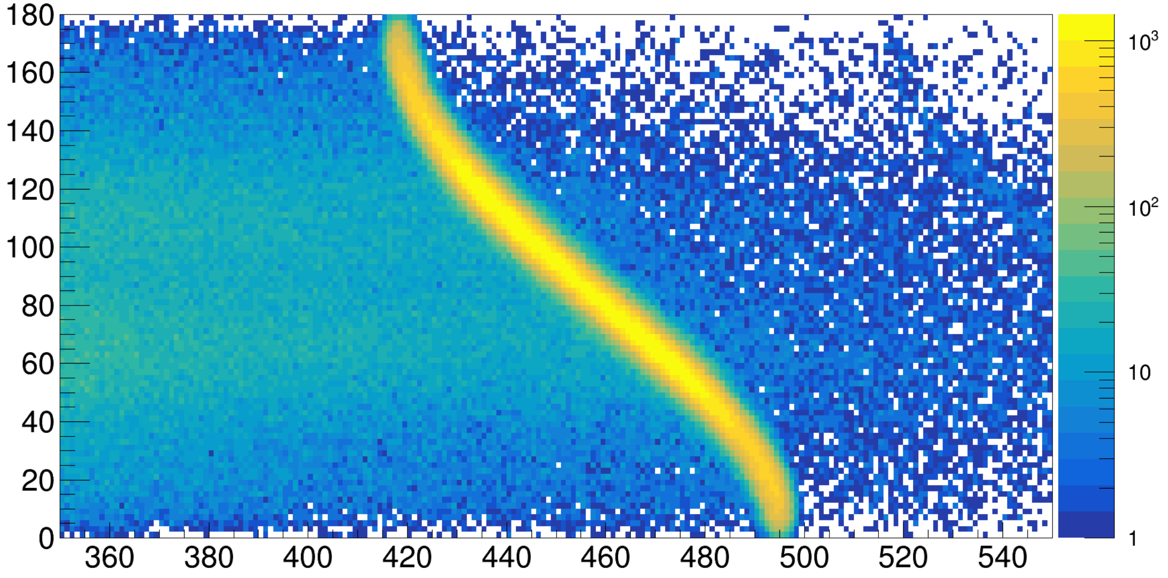
Yield Reproduction

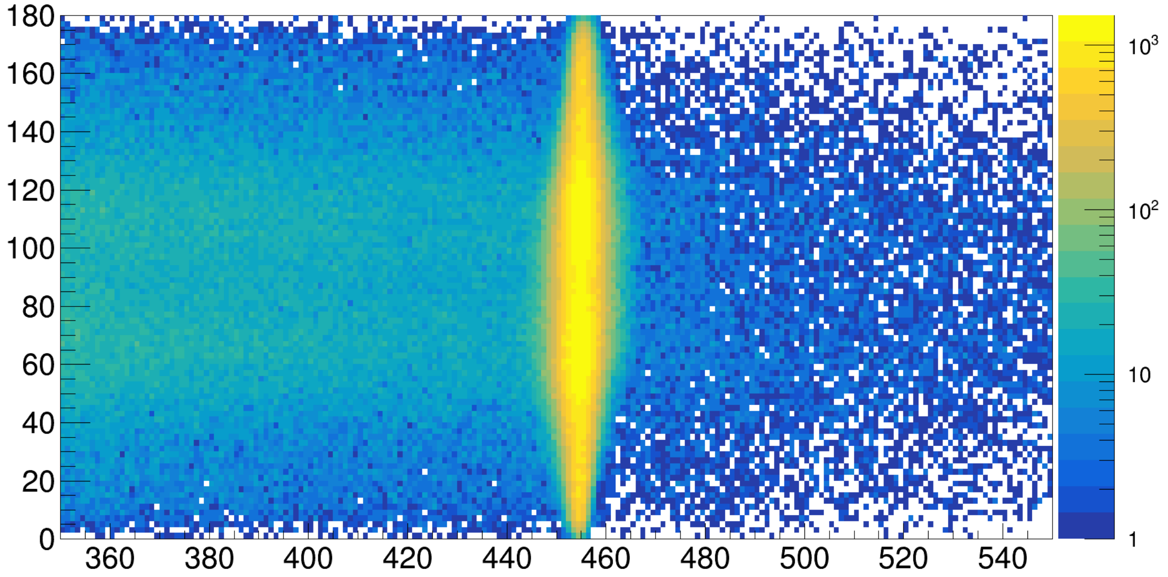


Doppler Correction

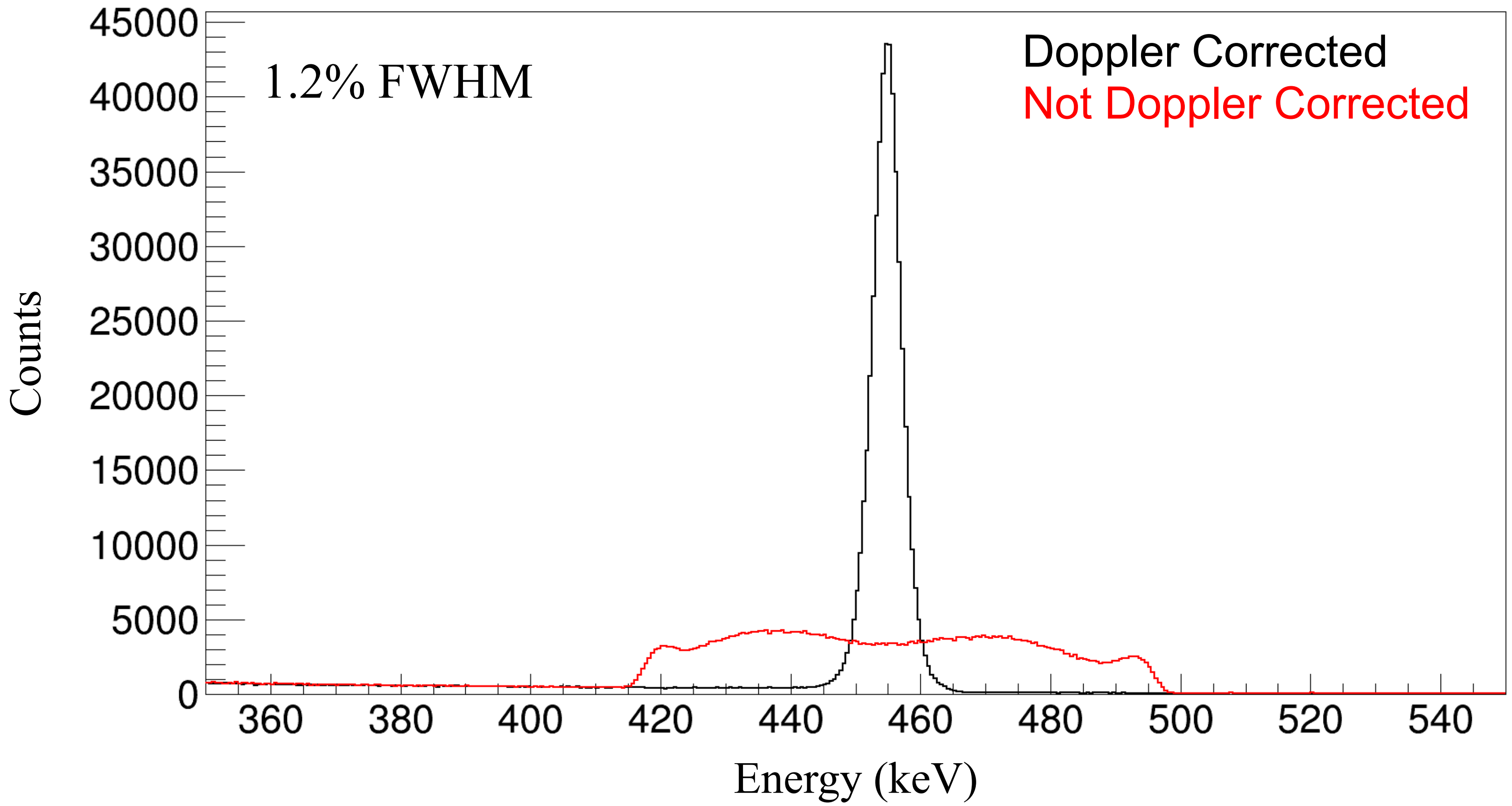
- $E_{LAB} = \frac{E_{REST}}{\gamma(1-\beta\cos\theta)}$
- $\beta = \frac{v}{c}$ depends on scattering angle
  - β range: 0.075 to 0.090
  - Spatial resolution needed
  - Detector segmentation







Doppler Correction



Results I

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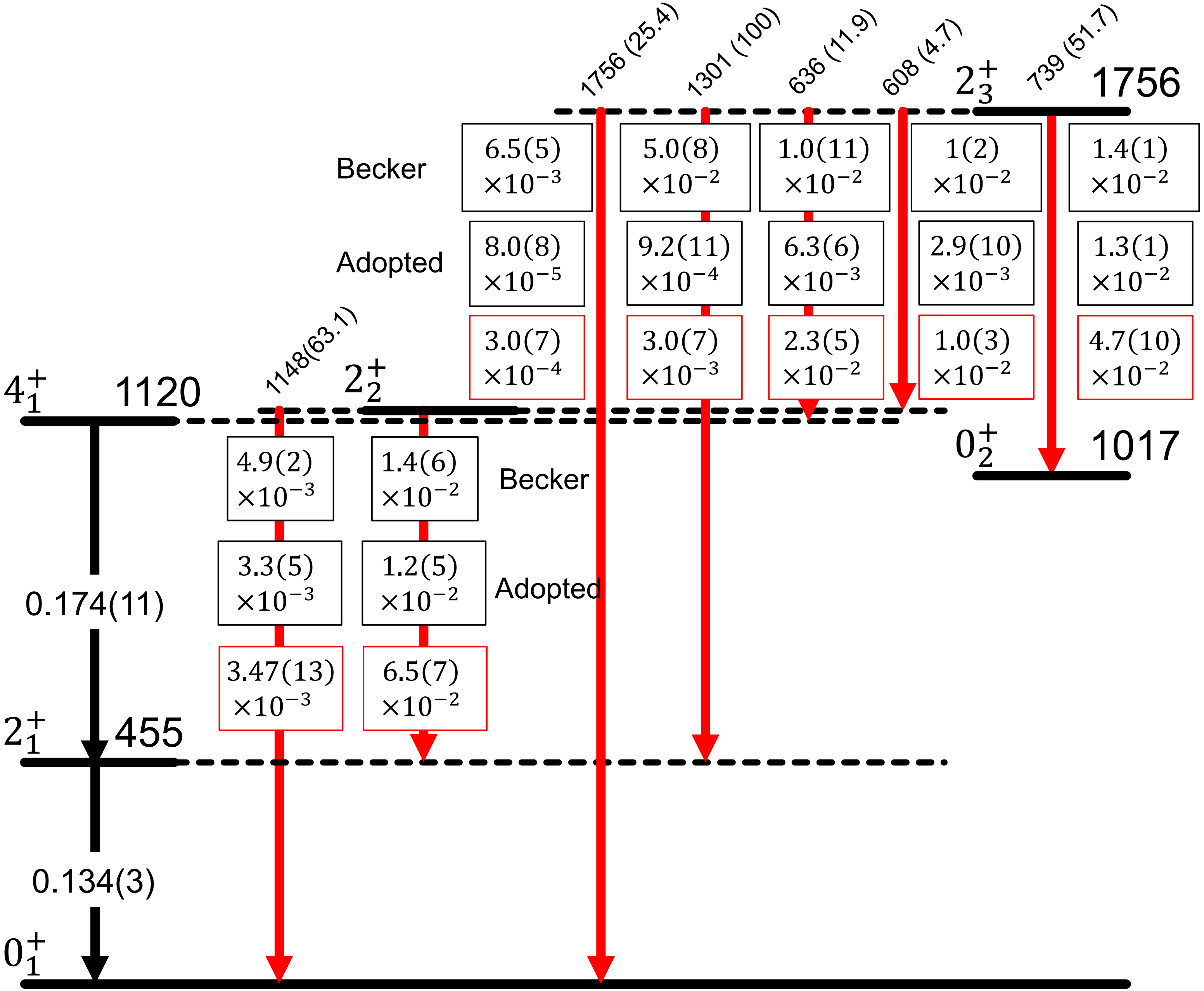
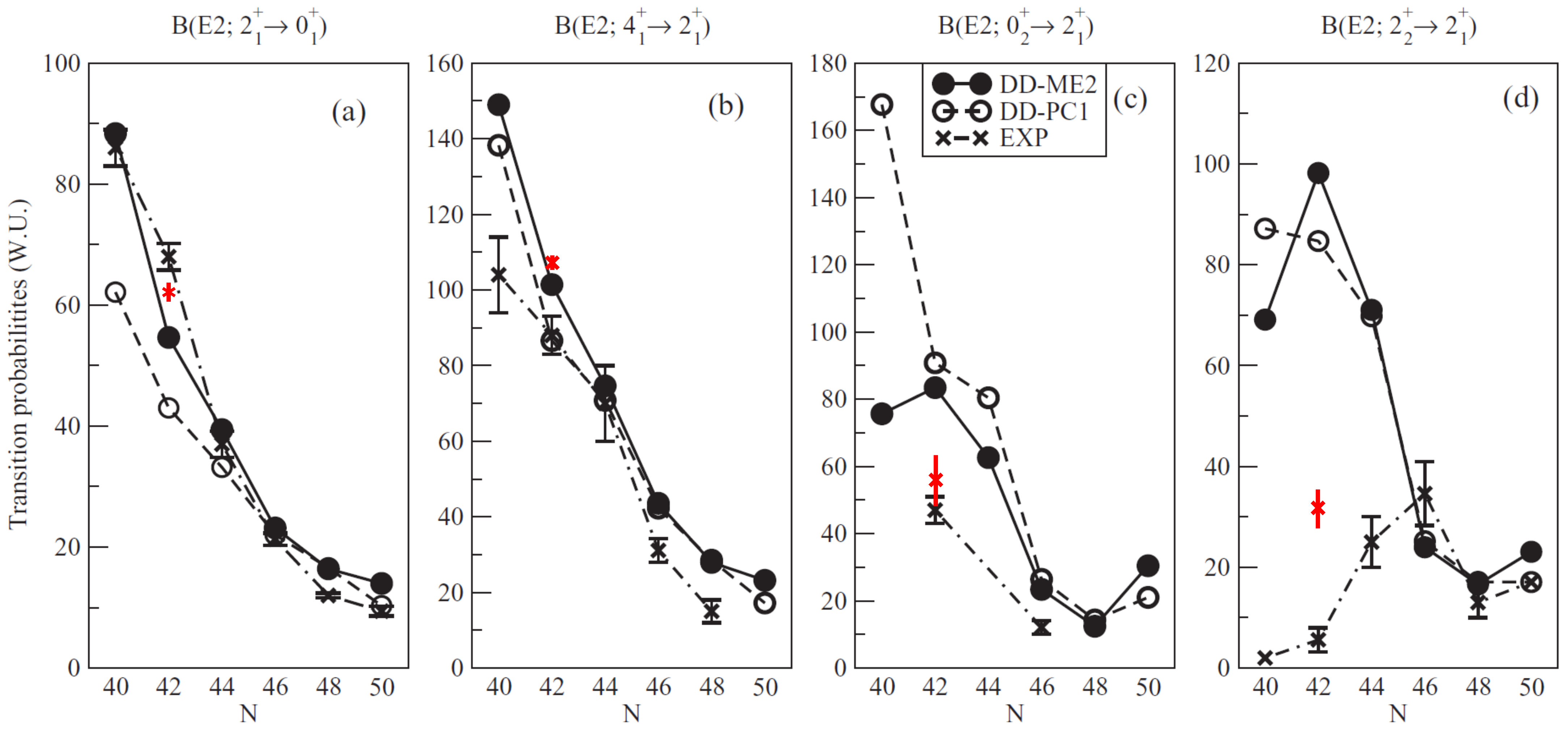
  - 2_2^+ lifetime agrees with adopted value
  - All branching ratios agree nicely with adopted values (decay data)
  - 2_2^+ mixing ratio highly discrepant
    - 0.45(10) vs 4_2^{30}



Results II



K. E. Karakatsanis and K. Nomura, Phys. Rev. C **105**, 064310 (2022)