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First Data on Dipole Excitations of ^{242}Pu from Nuclear Resonance Fluorescence

M. Beuschlein[1],
J. Birkhan[1], J. Kleemann[1], O. Papst[1], N. Pietralla[1], R. Schwengner[2], S. Weiß[2], V. Werner[1], U. Ahmed[1], T. Beck[1,3], I. Brandherm[1], A. Gupta[1], J. Hauf[1], K. E. Ide[1], P. Koseoglou[1], H. Mayr[1], C.M. Nickel[1], K. Prifti[1], D. Savran[4], M. Singer[1,] T. Stetz[1], and R. Zidarova[1]

[1] Institute for Nuclear Physics, TU Darmstadt, Germany [2] Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
[3] Facility for Rare Isotope Beams, MSU, East Lansing, MI, USA
[4] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

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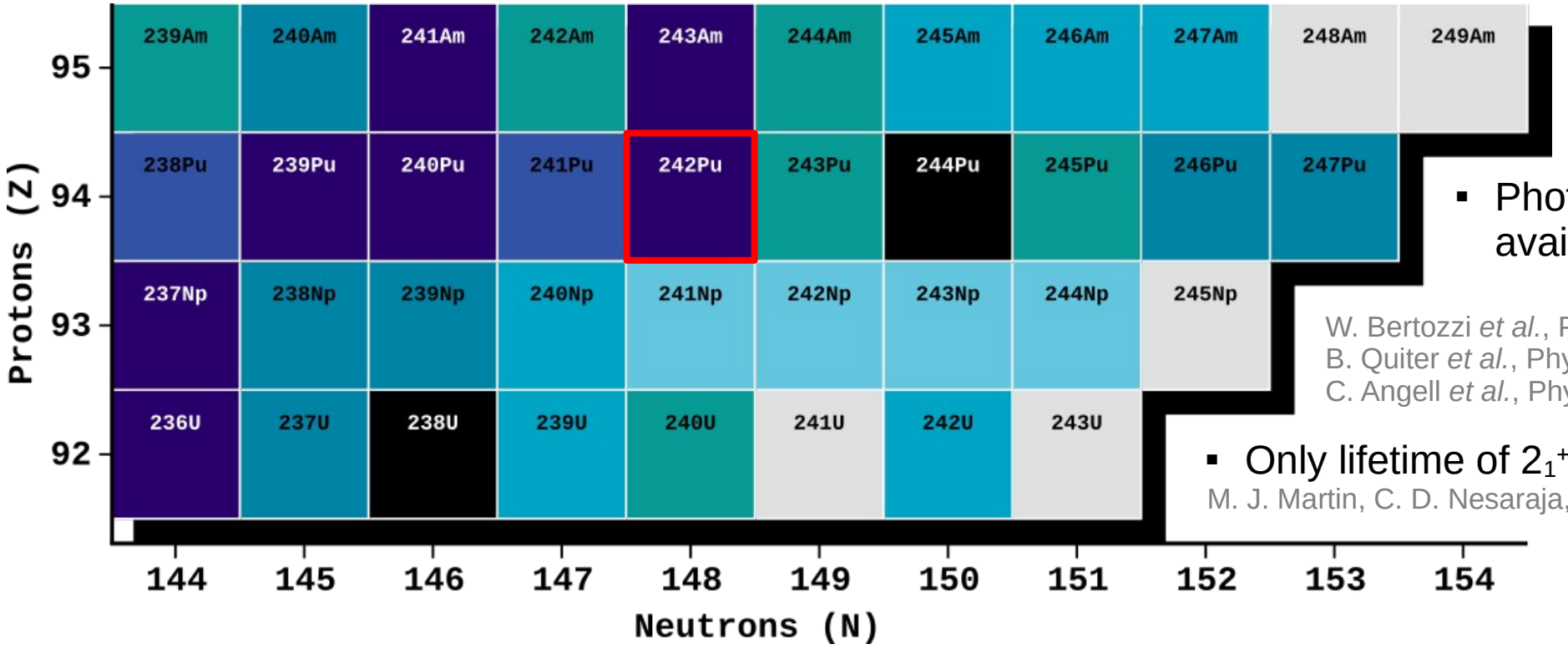
PLUTONIUM-242



- Transuranium actinide nucleus
- $T_{1/2} = 3.7 \cdot 10^5$ years
- Photonuclear reaction data available for **^{239,240}Pu, ^{237}Np**

W. Bertozzi *et al.*, Phys. Rev. C **78,** 041601 (2008)
B. Quiter *et al.*, Phys. Rev. C **78,** 034307 (2012)
C. Angell *et al.*, Phys. Rev. C **82,** 054310 (2010)

- Only lifetime of 2_1^+ state of ^{242}Pu known

M. J. Martin, C. D. Nesaraja, NDS **186,** 261 (2022)

National Nuclear Data Center, information extracted from the NuDat database, https://www.nndc.bnl.gov/nudat/

→ Expansion of photonuclear reaction data in transuranium actinide region with first nuclear resonance fluorescence experiment on ^{242}Pu

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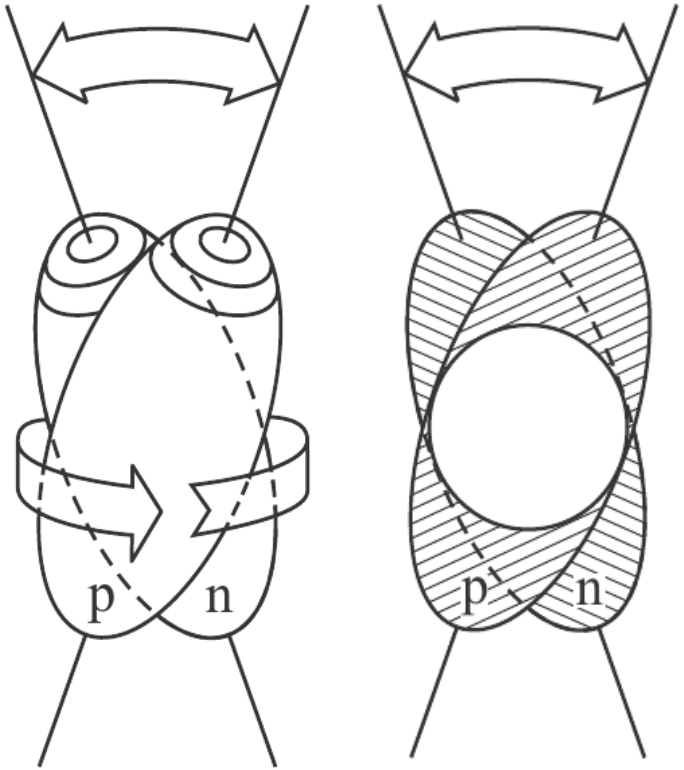
SCISSORS MODE

- **Two-rotor model:** *Rotational oscillation of the deformed proton against the deformed neutron body.*
  N. Lo Iudice and F. Palumbo, Phys. Rev. Lett. **41,** 1532 (1978)
  N. Lo Iudice and F. Palumbo, Nuc. Phys. A **326,** 193 (1979)
- **IBM-2:** Valence nucleons, 1^+ mixed-symmetry state
  F. Iachello, Nuc. Phys. A **358,** 89c (1981)
- Experimental discovery in ^{156}Gd
  D. Bohle et al., Phys. Lett. B 137, 27 (1984)
- Low-lying (~ 3 MeV) collective isovector *M1* excitation in deformed nuclei
  K. Heyde *et al.*, Rev. Mod. Phys. **82,** 2365 (2010)
- Fragmentation of strength with increasing deformation



K. Heyde *et al.*, Rev. Mod. Phys. **82** (2010) 2365

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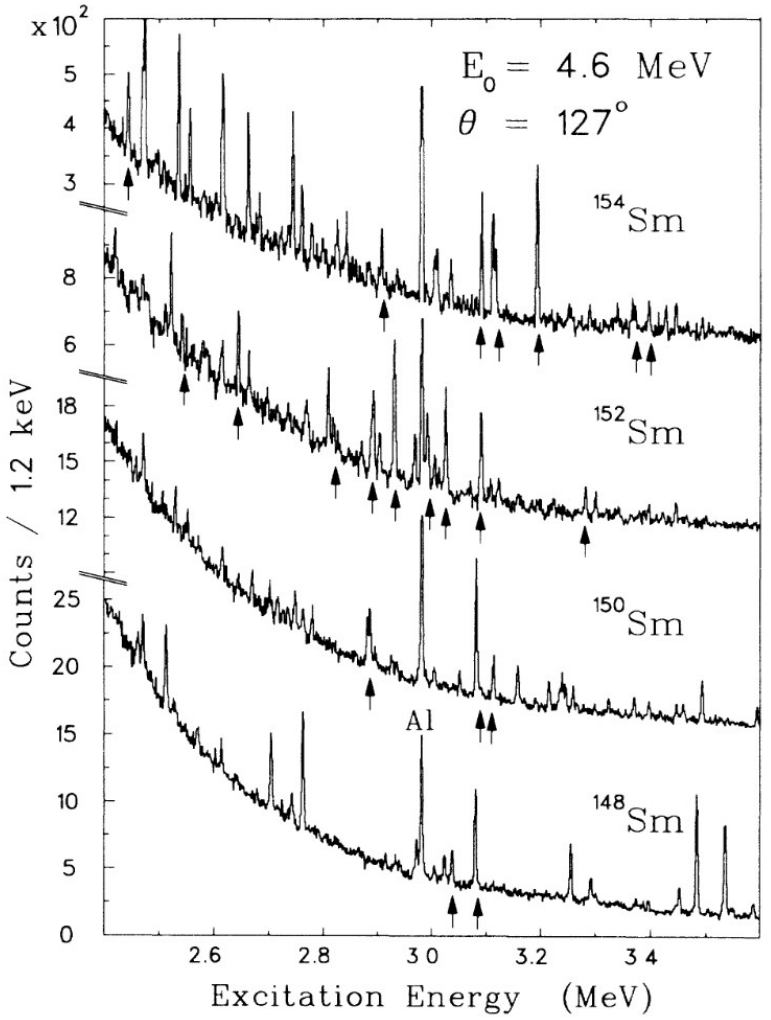

W. Ziegler *et al.*, Phys. Rev. Lett. **65,** 2515 (1990)

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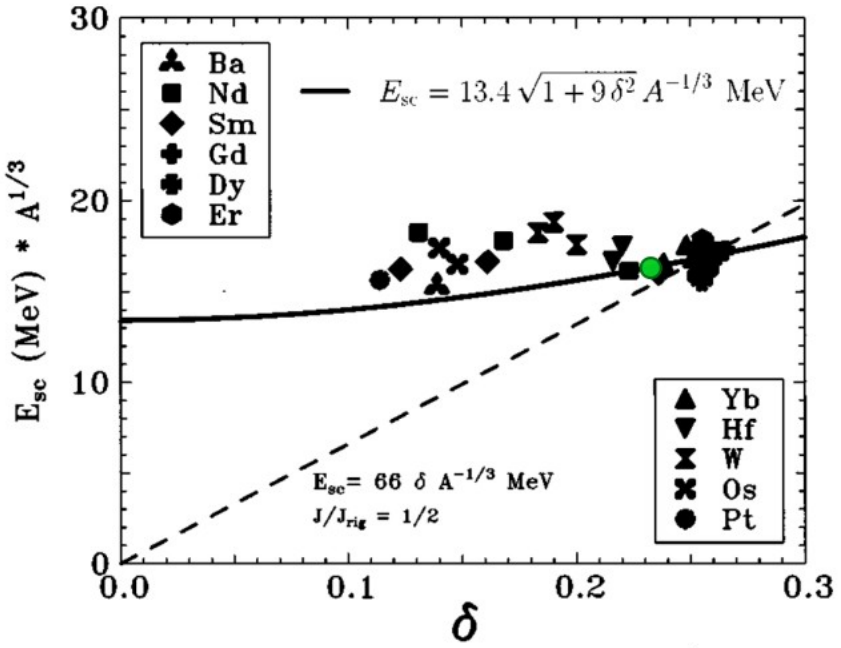
SCISSORS MODE IN ^{242}PU

- **Mean excitation energy:** $E_{sc} = 13.4\sqrt{1+(3\delta)^2}\,A^{-1/3}$ MeV



$\delta(^{242}\text{Pu}) = 0.23$ → $E_{sc} \approx 2.6$ MeV

B(E2) value from B. Pritychenko *et al.*, At. Data Nucl. Data Tables **107** (2016)

N. Pietralla *et al.*, Phys. Rev. C **58,** 184 (1998)

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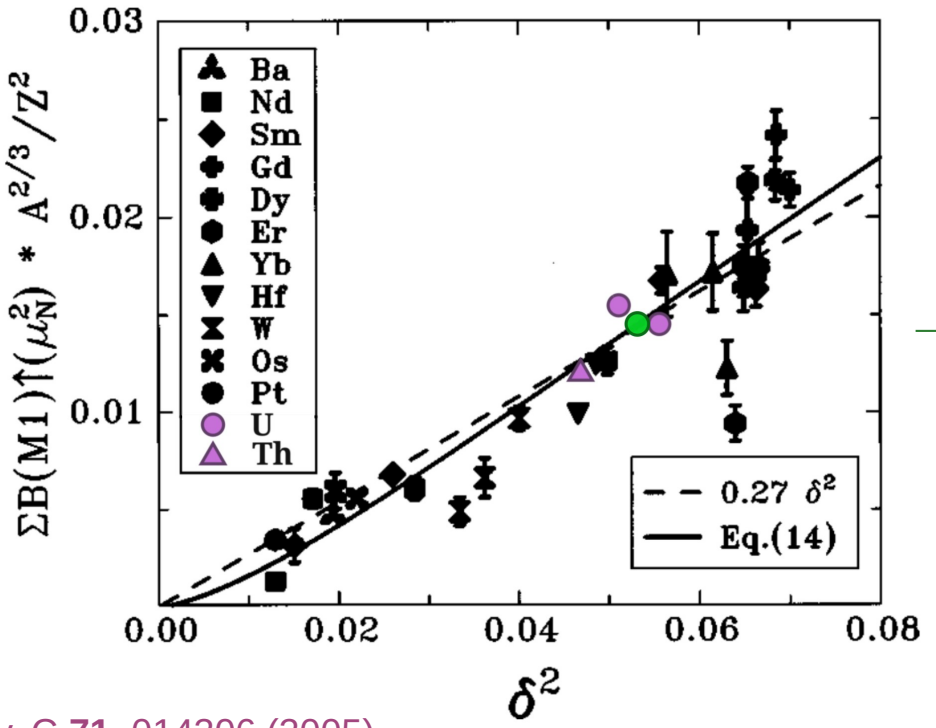
B(E2) value from B. Pritychenko *et al.*, At. Data Nucl. Data Tables **107** (2016)

- **Total excitation strength:**

$$B(M1;0_1^+ \rightarrow 1_{sc}^+) = 2.6 c_g^2 \frac{\delta^3}{1+(3\delta)^2} \frac{Z^2}{A^{2/3}} \mu_N^2$$



→ $B(M1)\uparrow \approx 3.2\ \mu_N^2$

N. Pietralla *et al.*, Phys. Rev. C **58,** 184 (1998)

Values for Th and U taken from Enders *et al*., Phys. Rev. C **71,** 014306 (2005)

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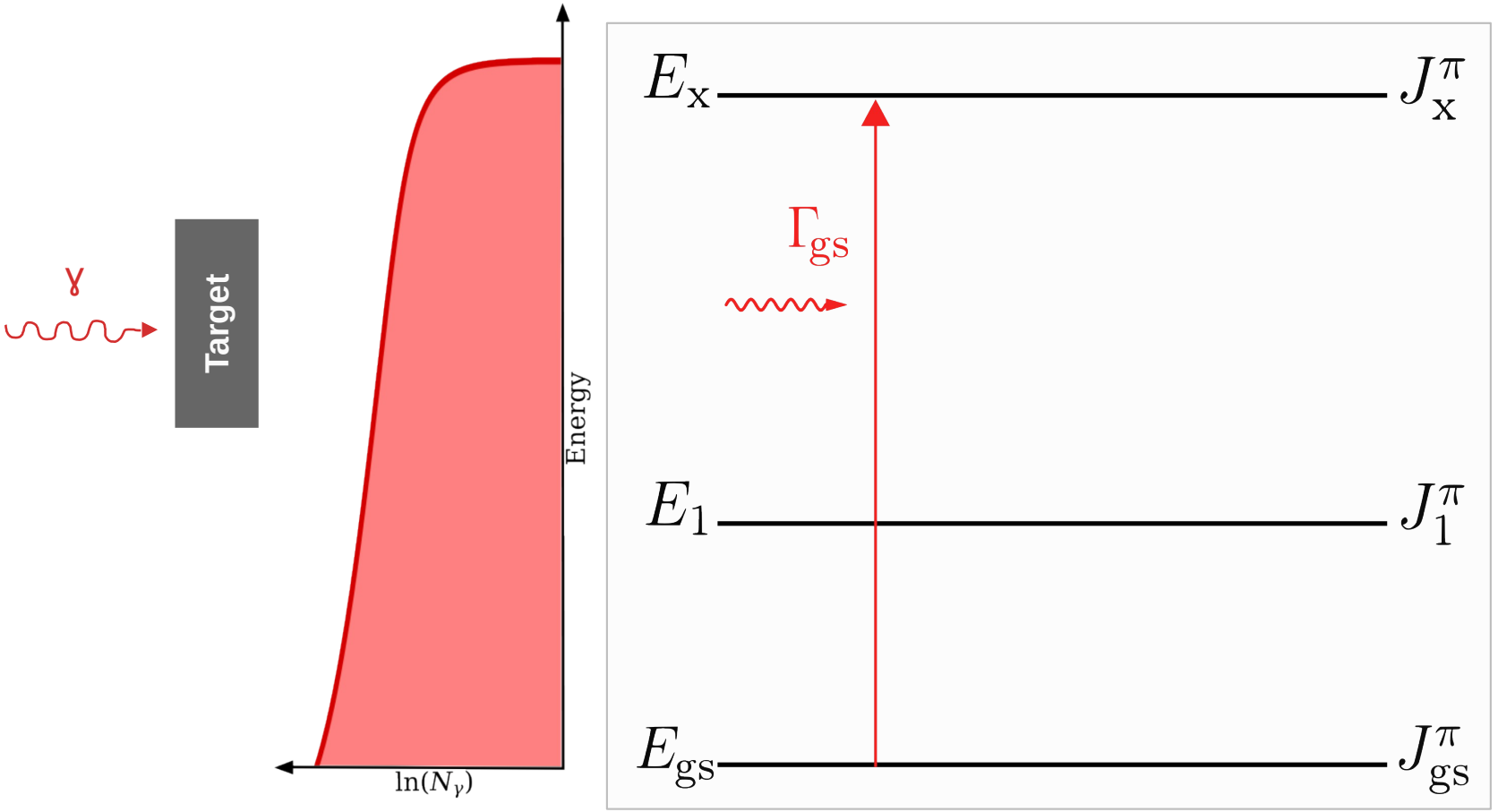
NUCLEAR RESONANCE FLUORESCENCE (NRF)



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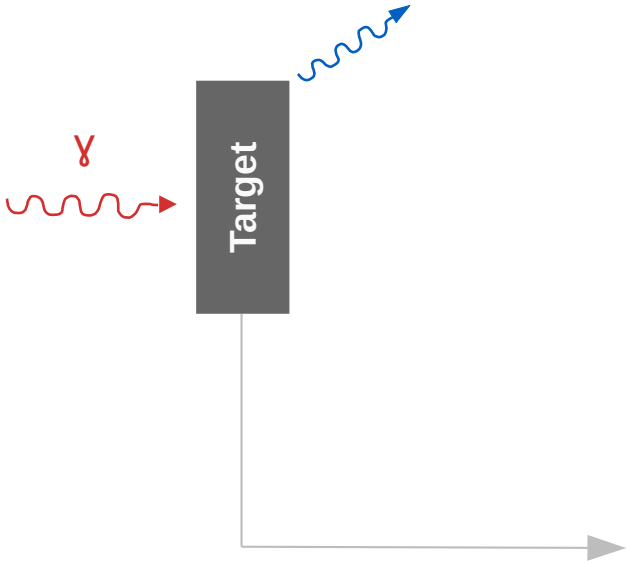

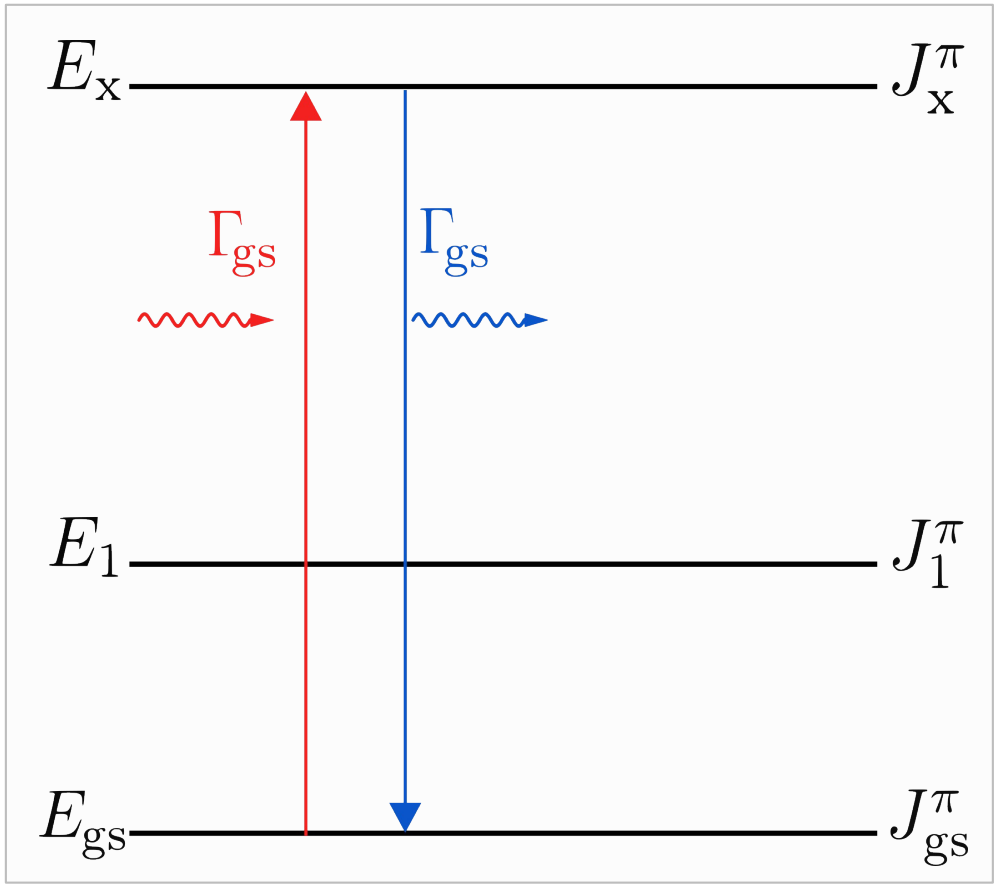

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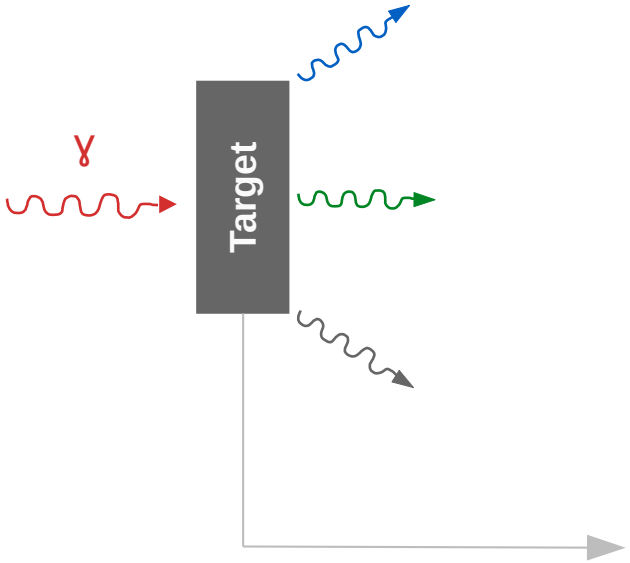

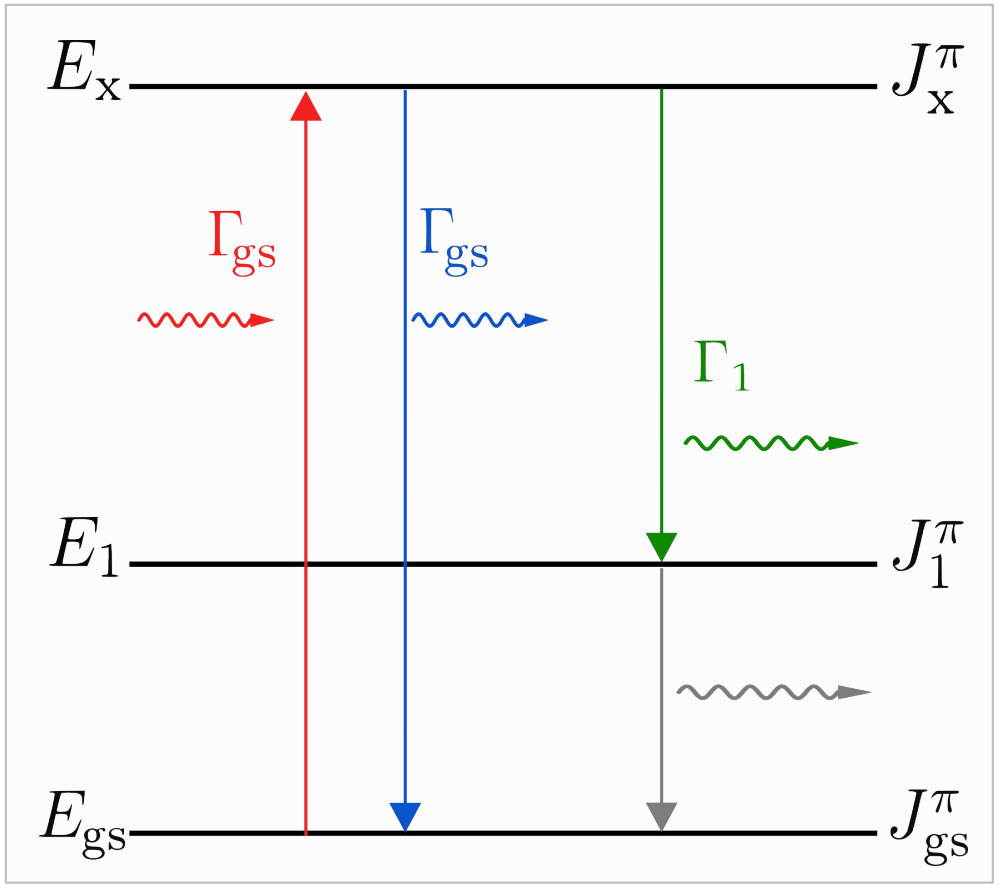

Spectroscopic quantities:

- Level energies E_x
- Spin quantum numbers J
- Transition strengths $B(\sigma L)$
- . . .

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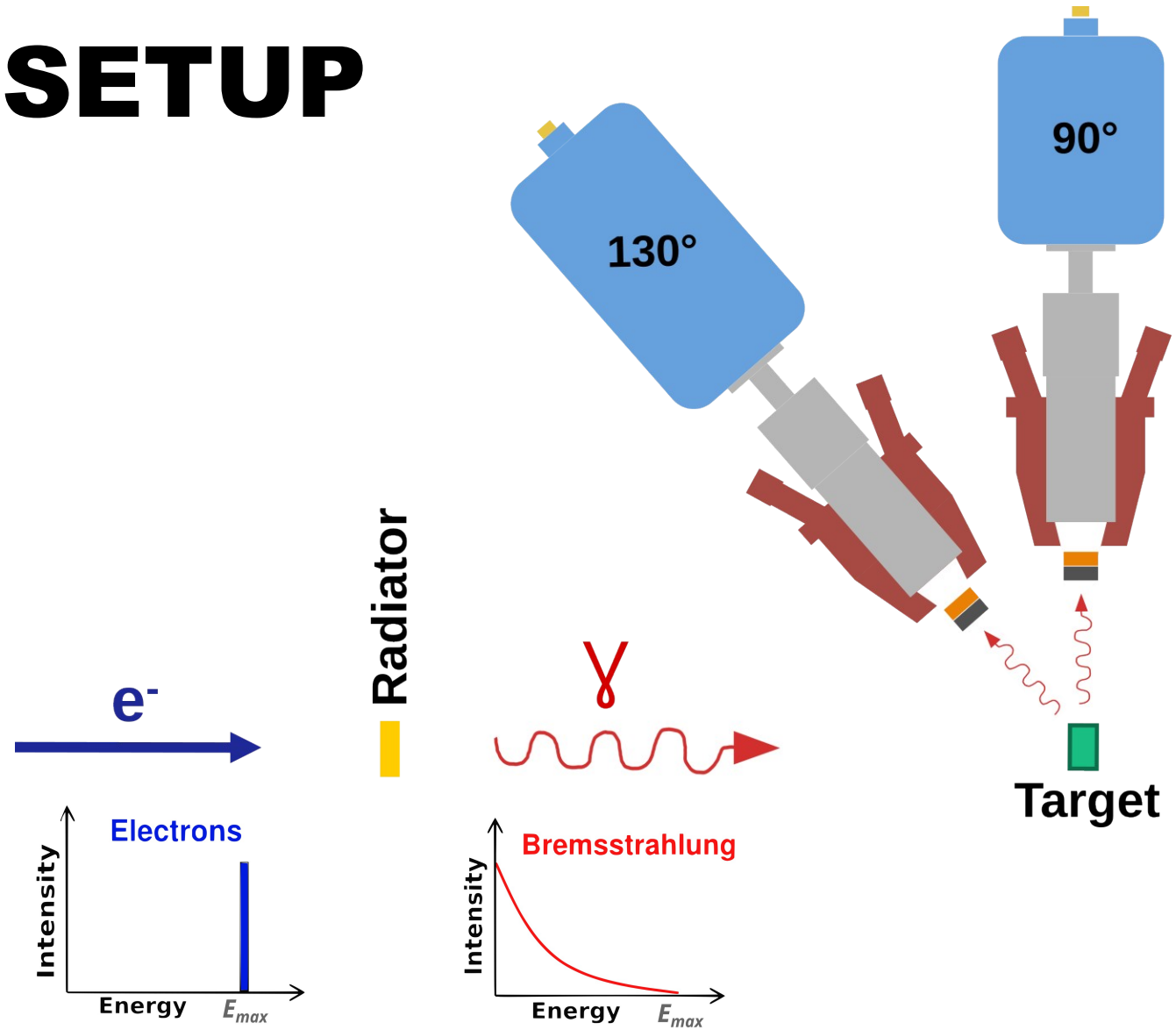
SETUP



- **D**armstadt **H**igh-**I**ntensity **P**hoton **S**etup (DHIPS) in 2022
- **S**uperconducting **Da**rmstadt **Lin**ear **Ac**celerator (S-DALINAC)
- E_{max} = 3.7 MeV
- Total measurement time = 320 h

Modified figure from C. Romig

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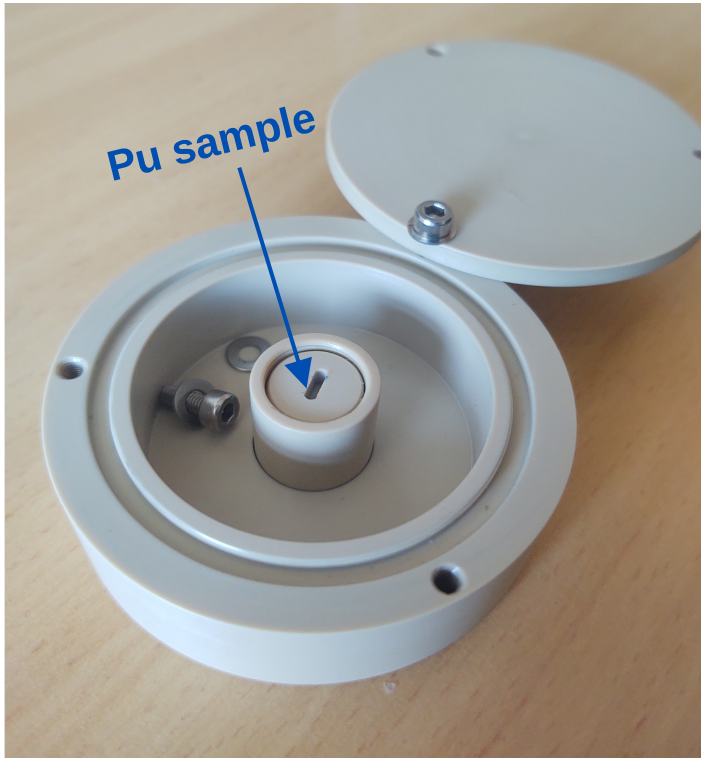
TARGET

- Provided by **H**elmholtz-**Z**entrum **D**resden-**R**ossendorf
- **1.1 g** PuO_2 highly-enriched in ^{242}Pu (~99.9 %)
- $^{238\text{-}241}$Pu, ^{241}Am
- Total activity ~ **370 MBq**
- **^{27}Al** reference target



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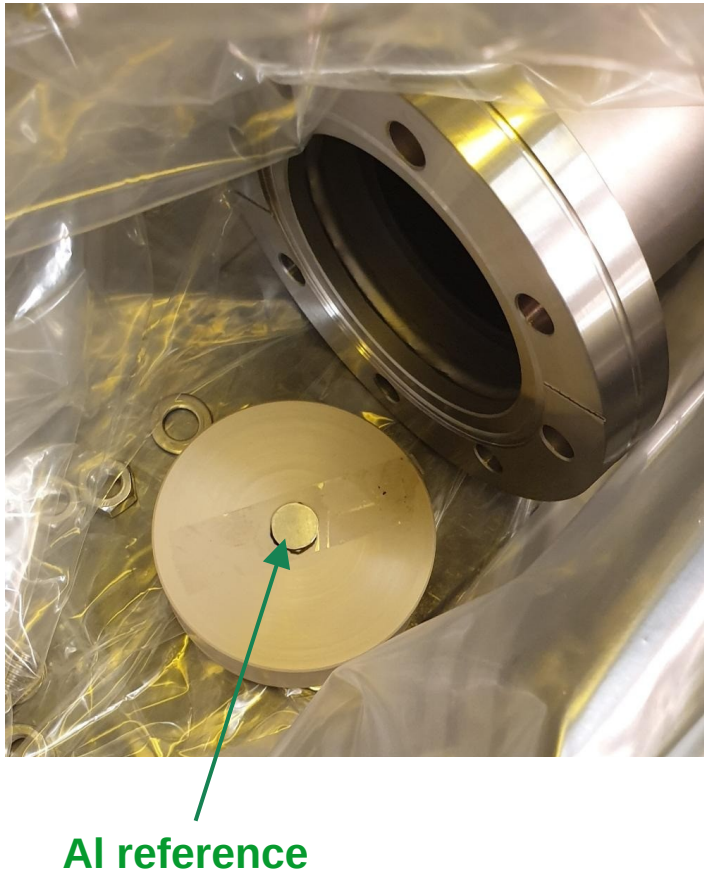

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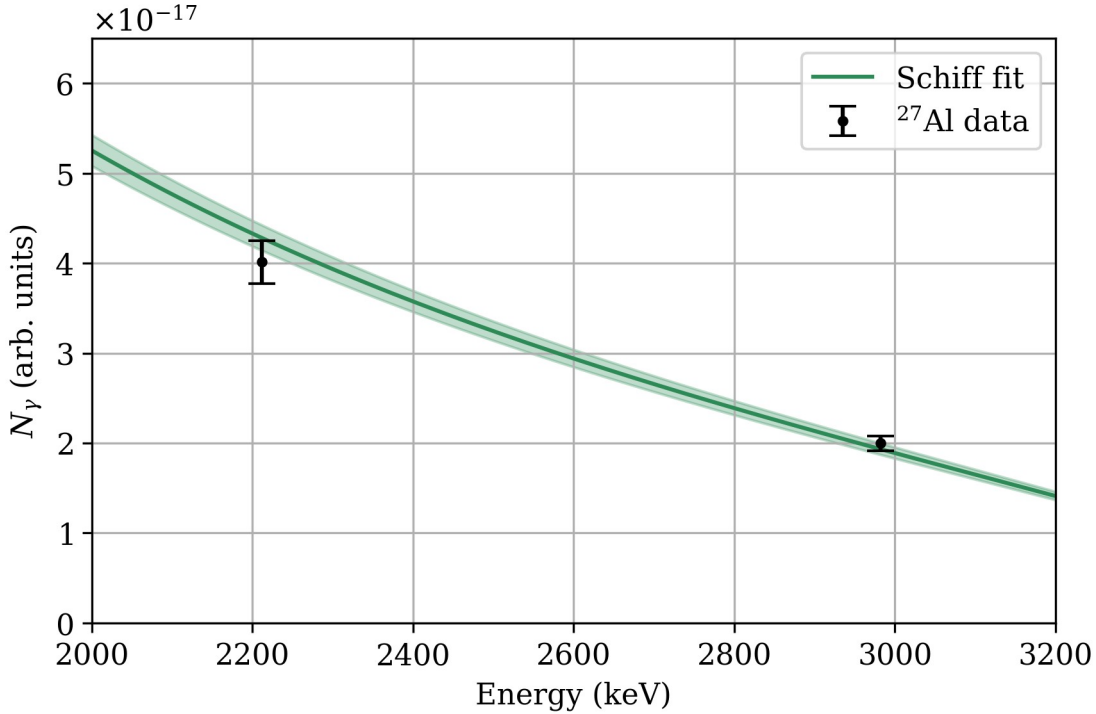
Photon flux calibration



Reference states at **2212 keV** and **2982 keV**

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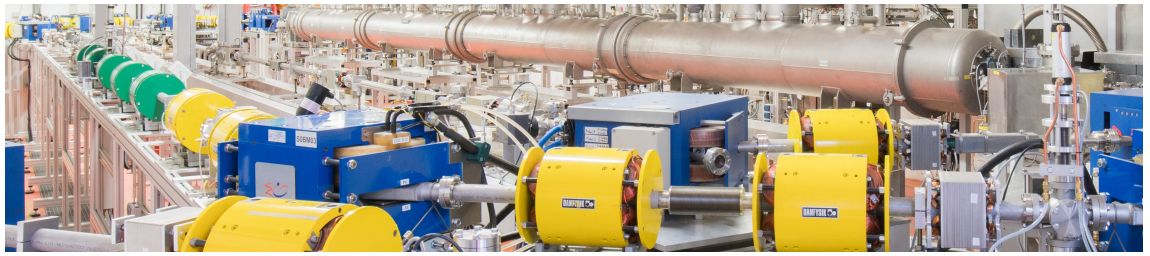
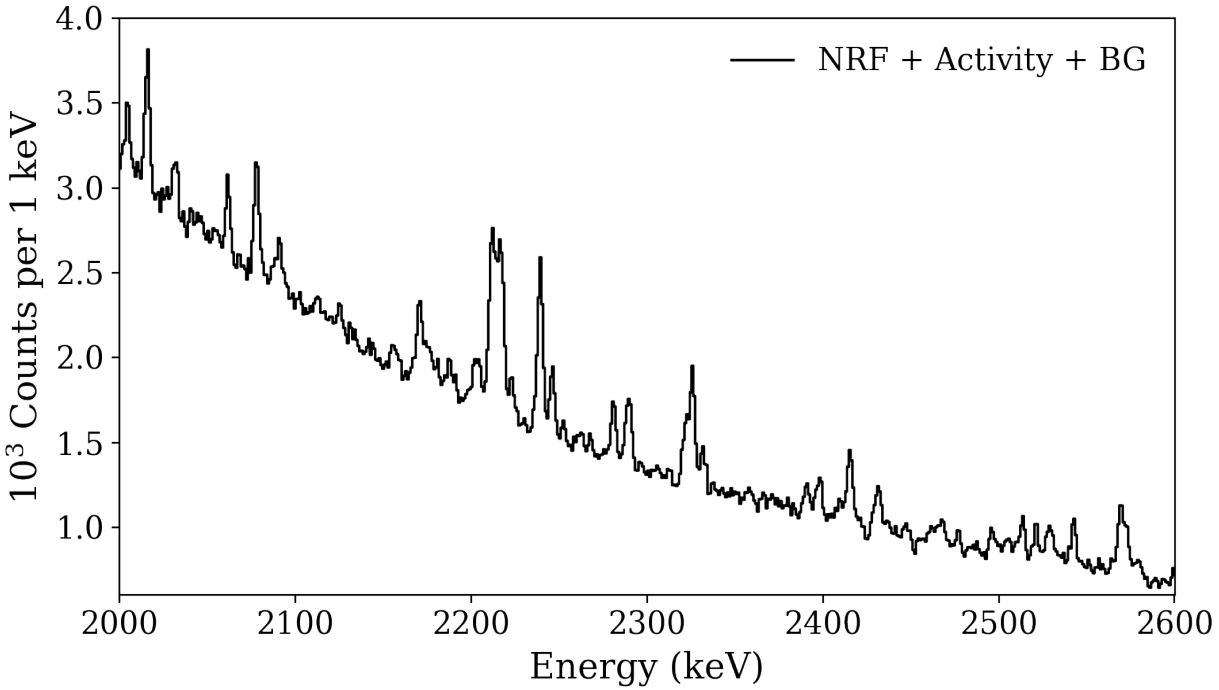
SPECTRA





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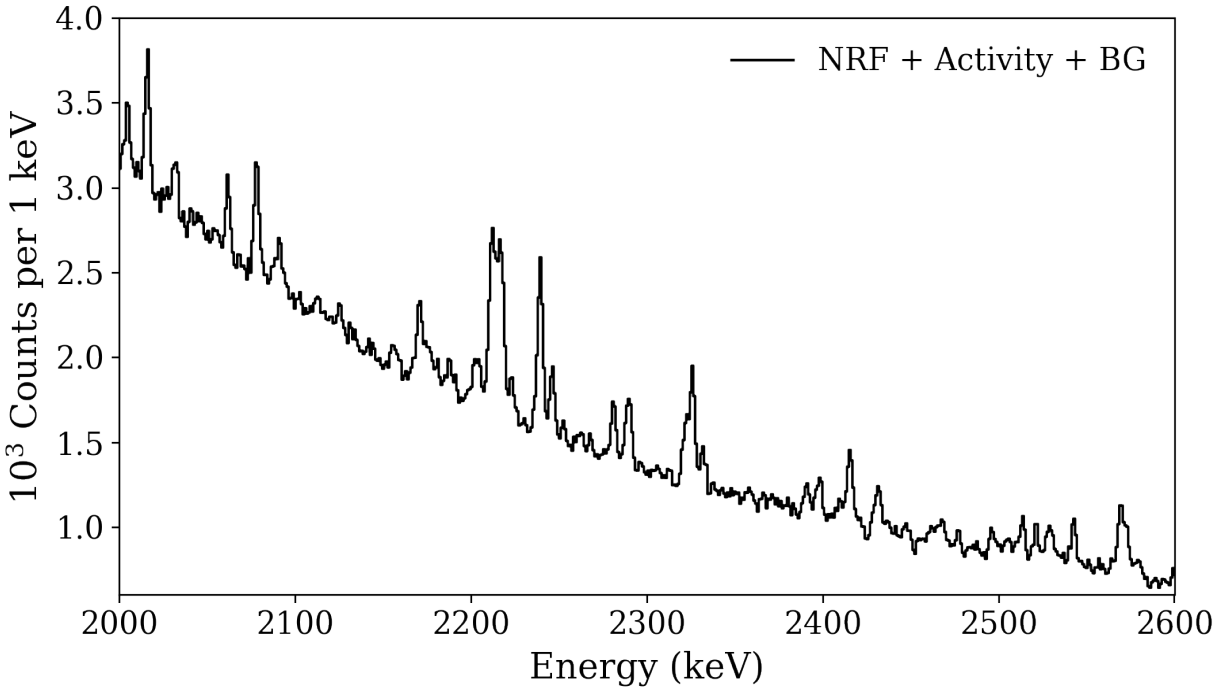

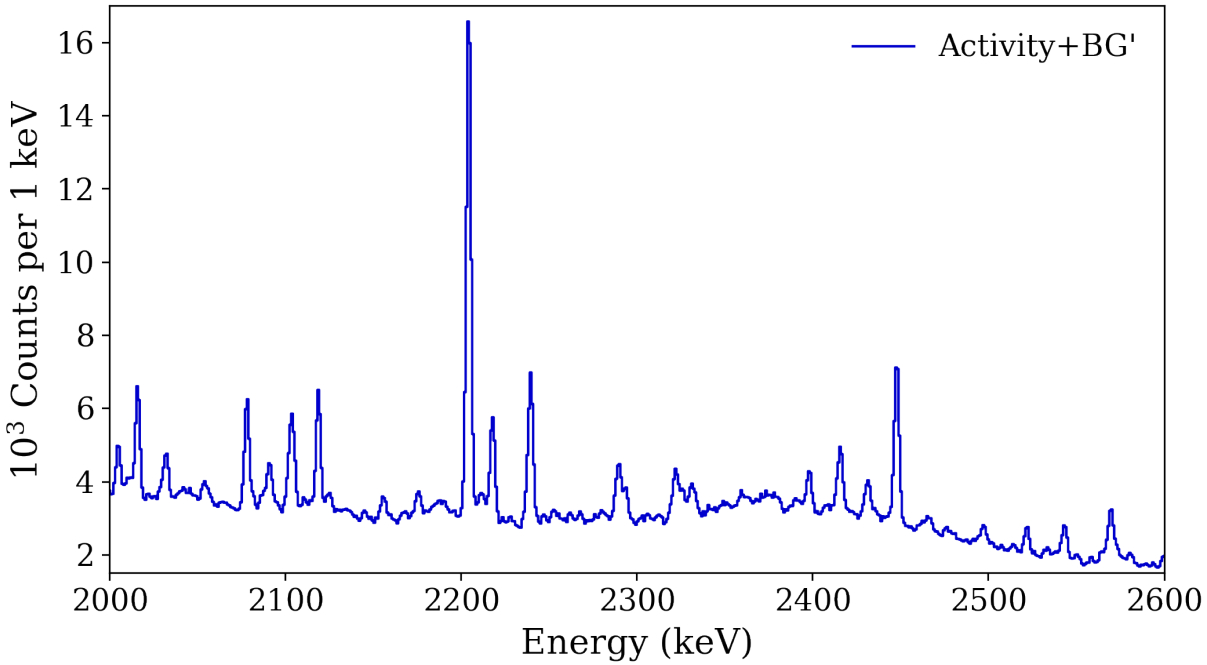

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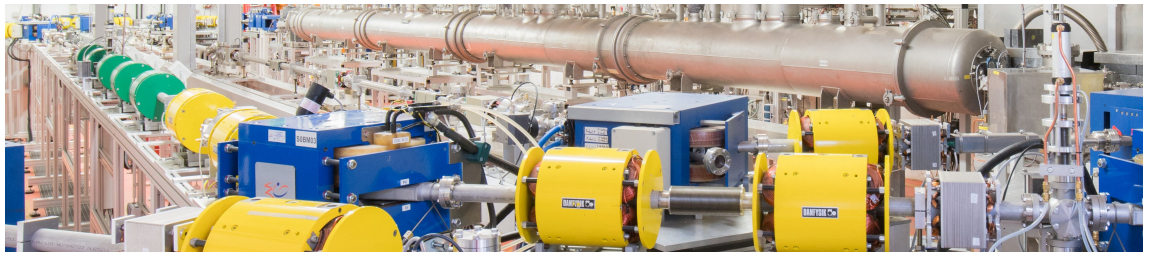

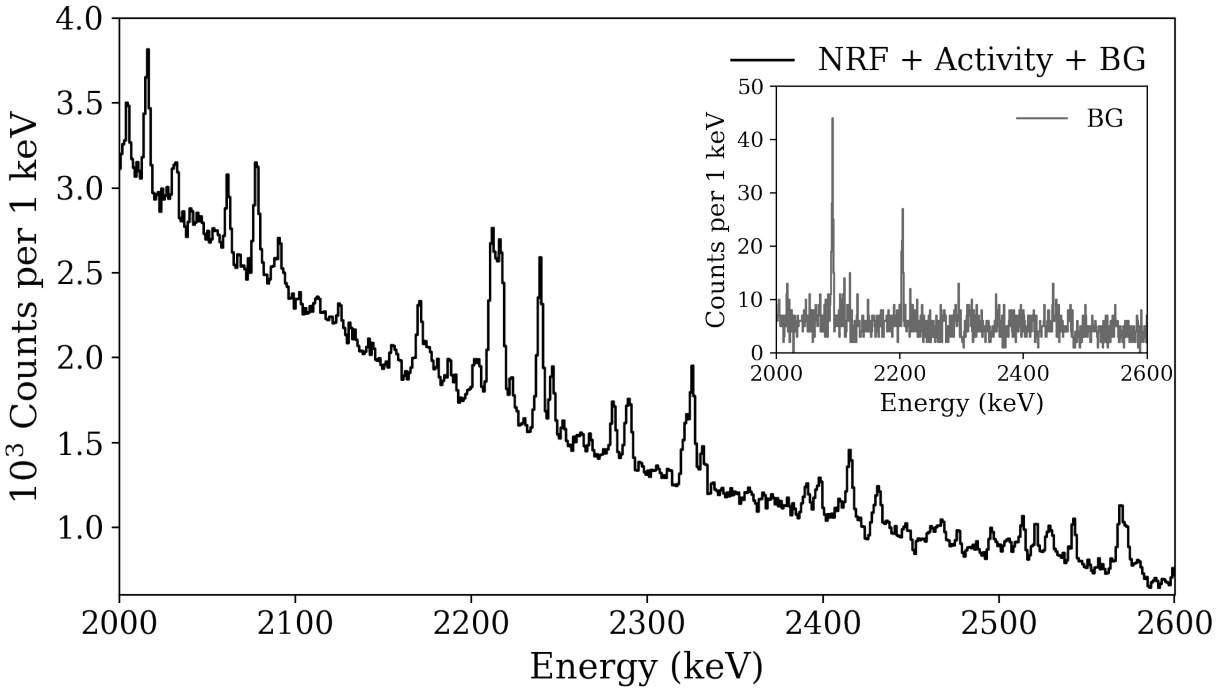

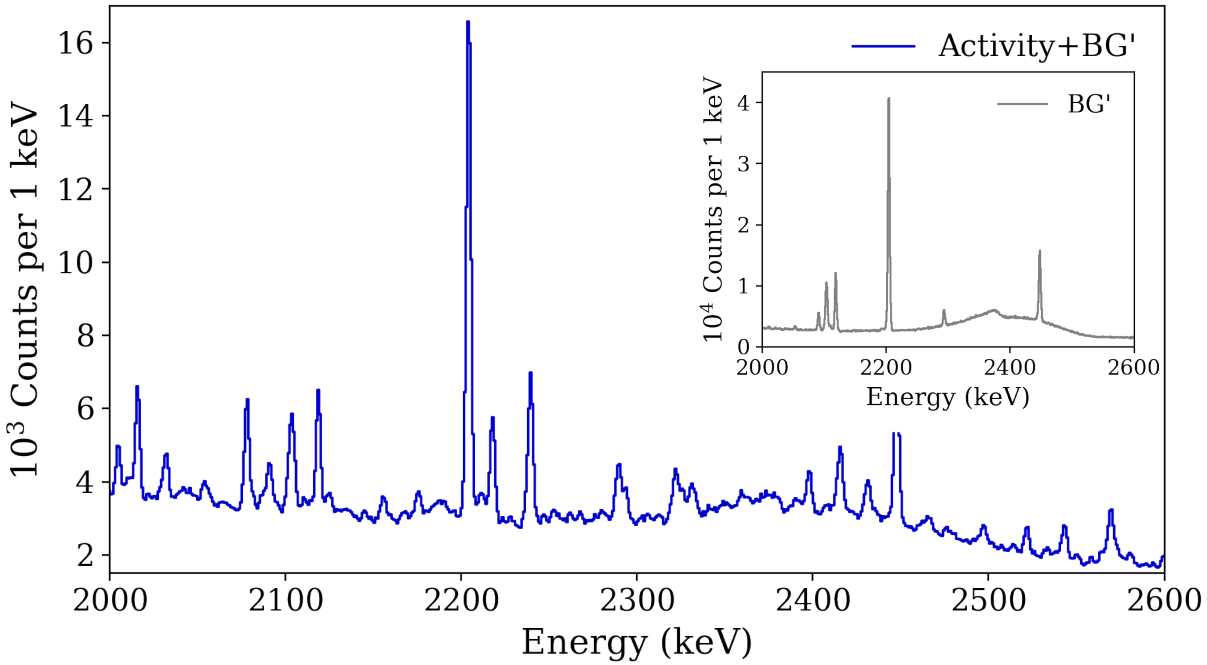

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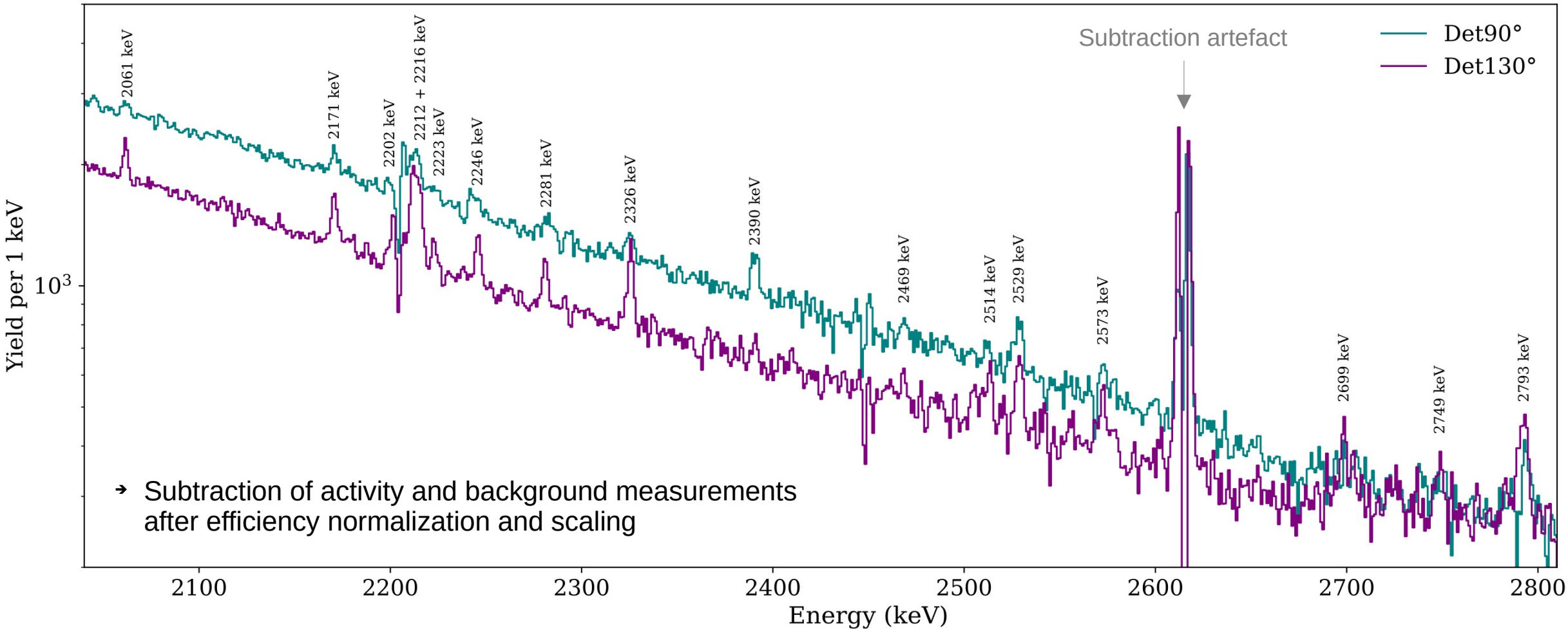
DIFFERENCE SPECTRA



- Subtraction of activity and background measurements after efficiency normalization and scaling

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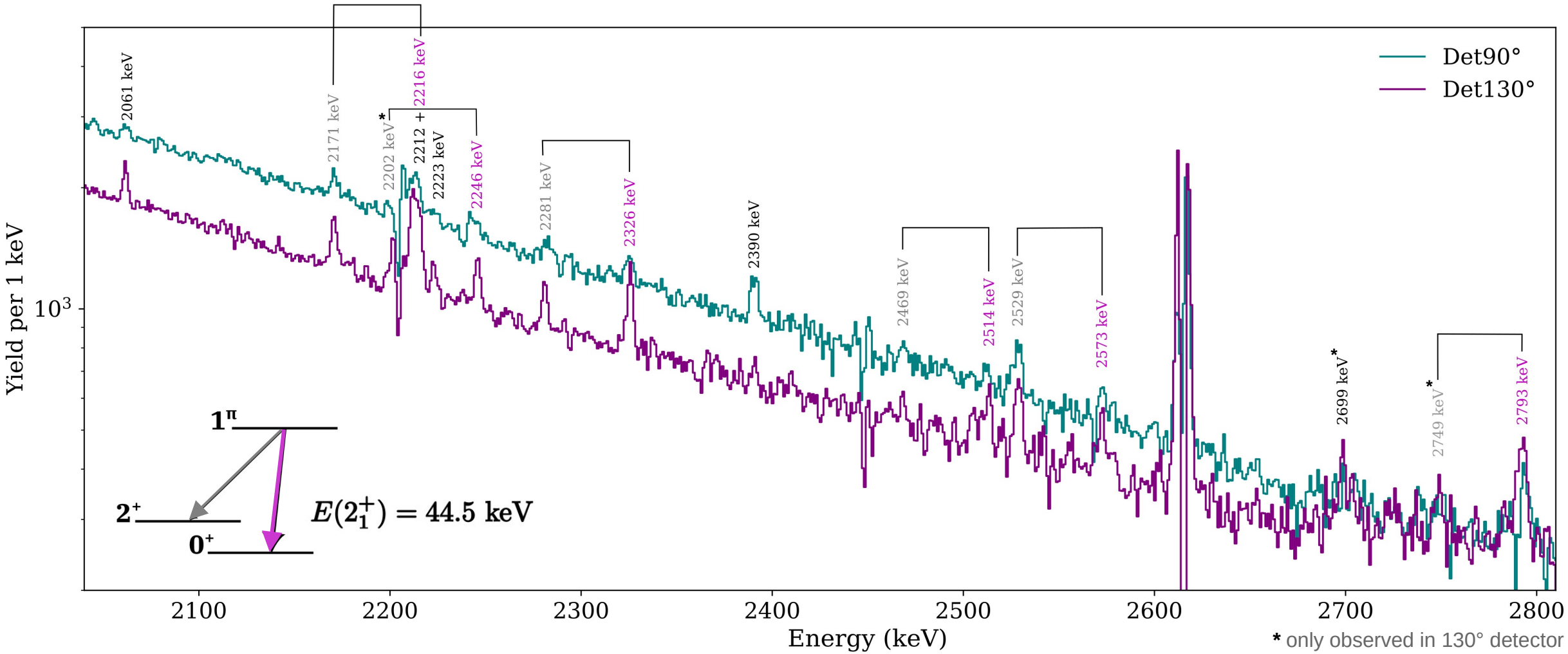
BRANCHING TRANSITIONS



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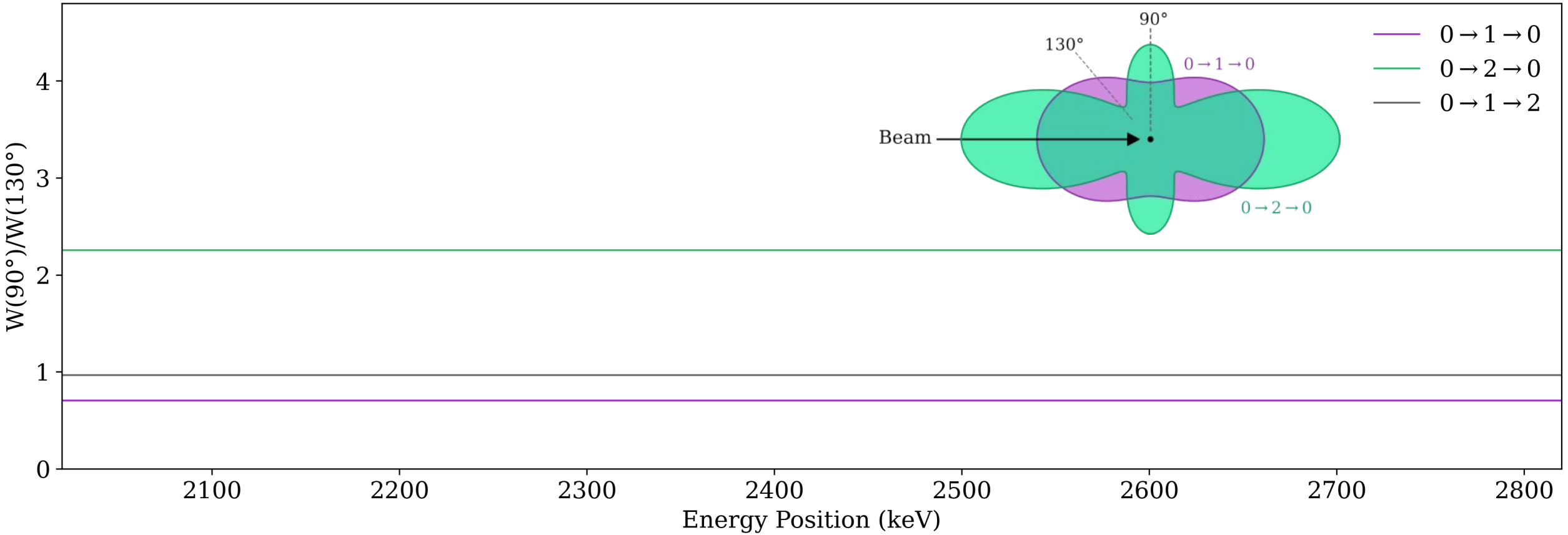
ANGULAR DISTRIBUTION



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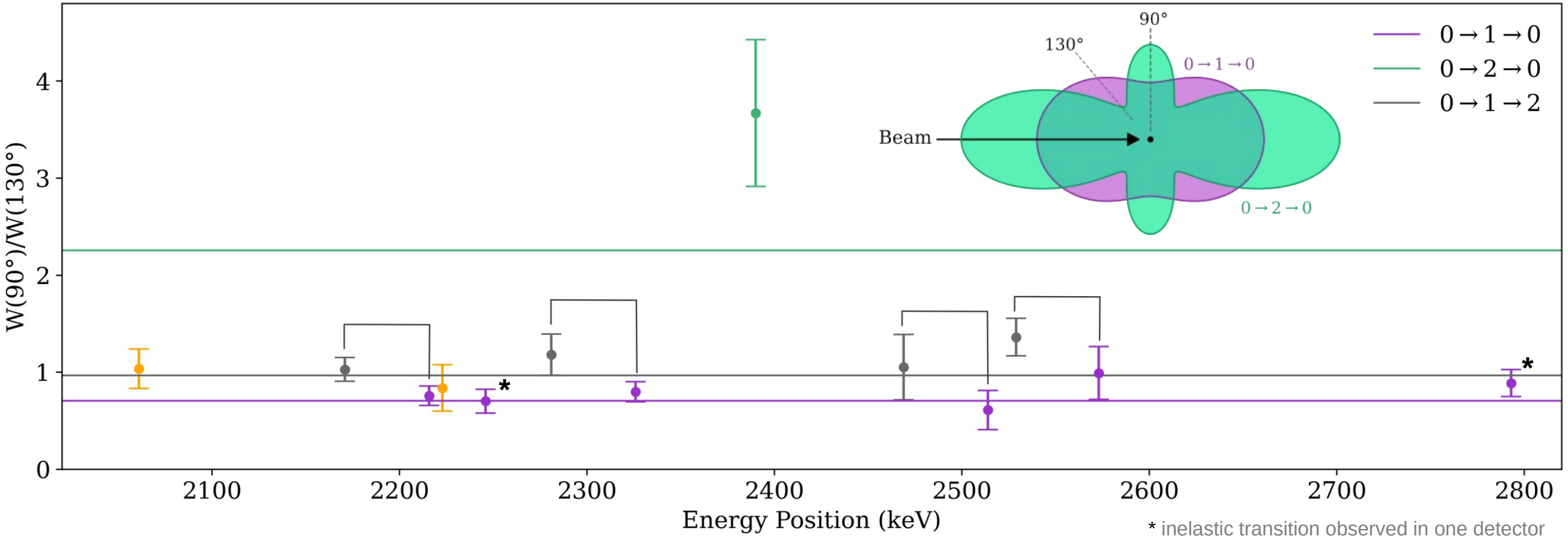

* inelastic transition observed in one detector

- Six **dipole** transitions ***E1*** **or** ***M1*** (incl. 780 keV) with **branchings** (incl. 2202, 2749 keV)
- One **quadrupole** transition ***E2***

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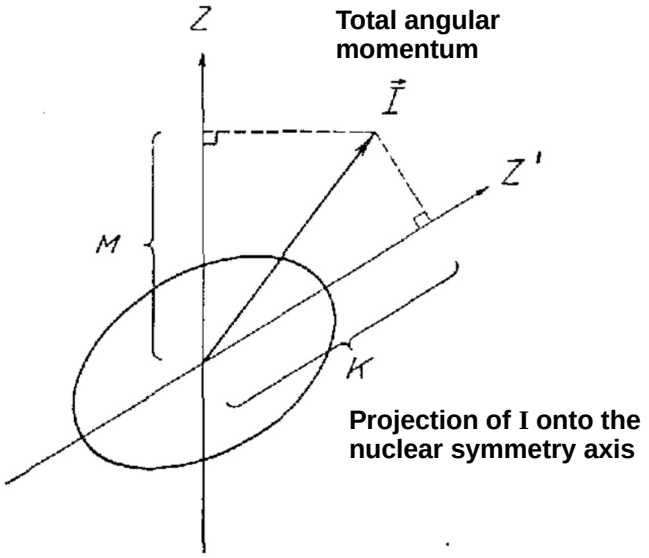
ALAGA RULES

- Relation for transition strength ratios of axially-deformed rotational nuclei
- Ratios depend only on Clebsch-Gordan coefficients (if no K mixing)

Even-even deformed nuclei

$$R_{\mathrm{Alaga}} = \frac{B(\Pi 1, 1^{\pi} \rightarrow 2_1^+)}{B(\Pi 1, 1^{\pi} \rightarrow 0_1^+)} = \begin{cases} 2, & K = 0 \\ 0.5, & K = 1 \end{cases}$$

- Scissors mode $K=1$



G. Alaga *et al.*, Dan. Mat. Fys. Medd. **29** (1955)

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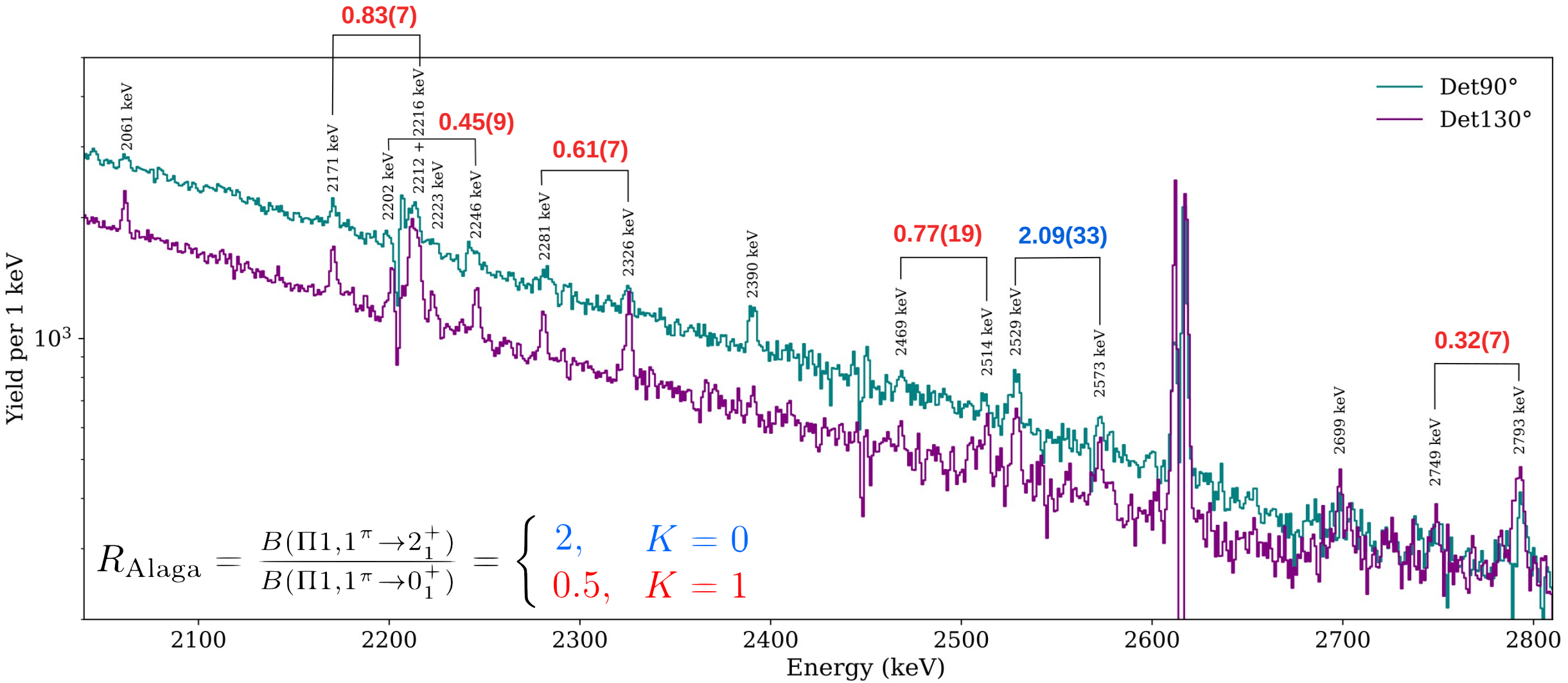
ALAGA RULES



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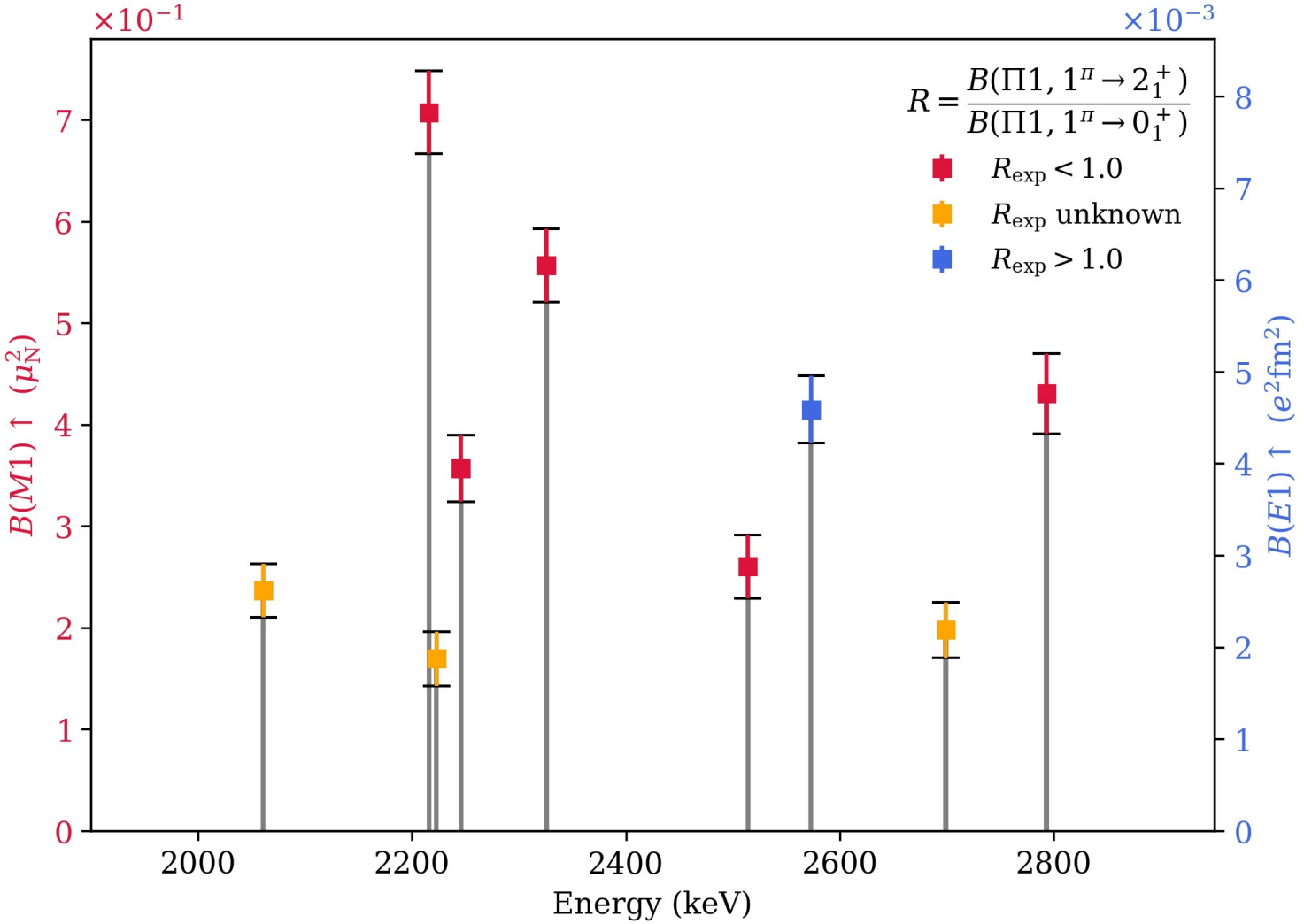
RESULTS



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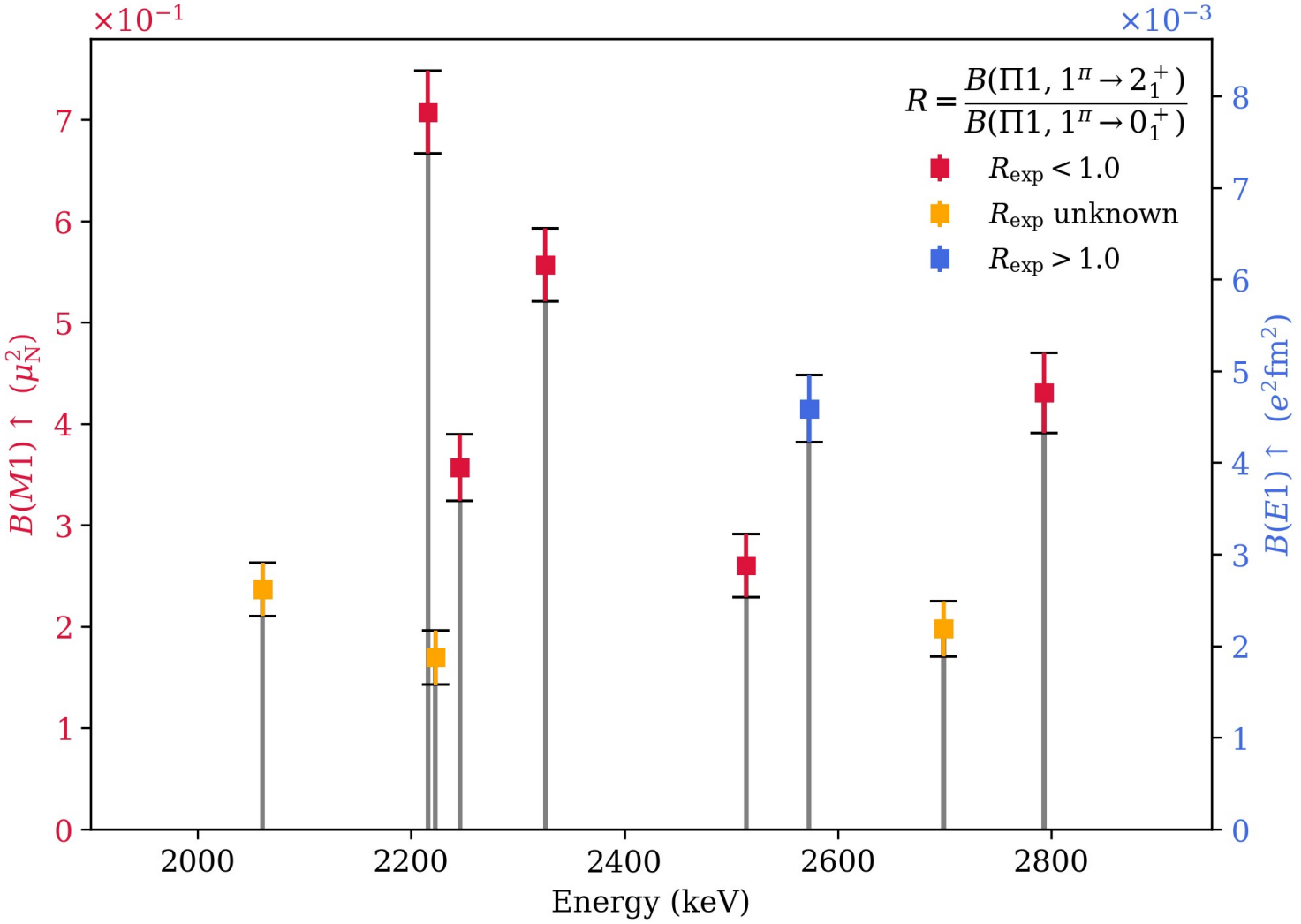
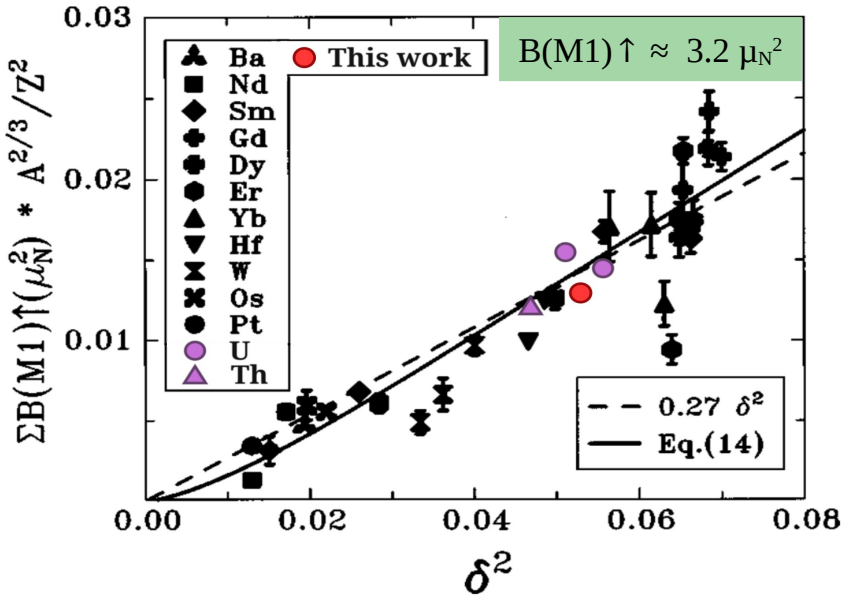


- Total M1 strength: **$\sum B(M1)\uparrow = 3.05(14)\ \mu_N^2$** *(incl. R_{exp} unknown)*



- Centroid energy: **$E_{sc} \approx 2.4$ MeV** $E_{sc} \approx 2.6$ MeV

Values for Th and U taken from Enders *et al.*, Phys. Rev. C **71,** 014306 (2005)

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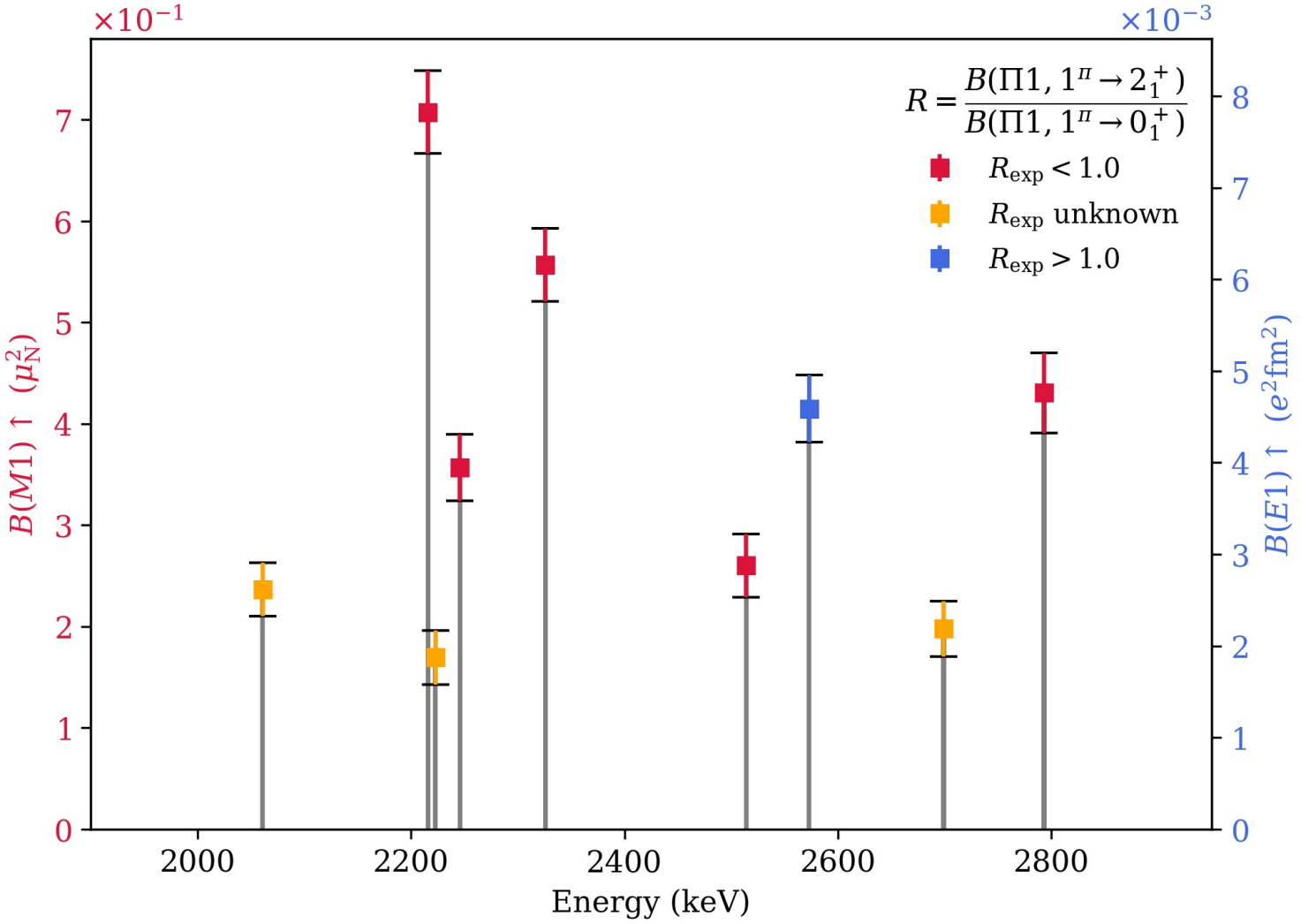
RESULTS



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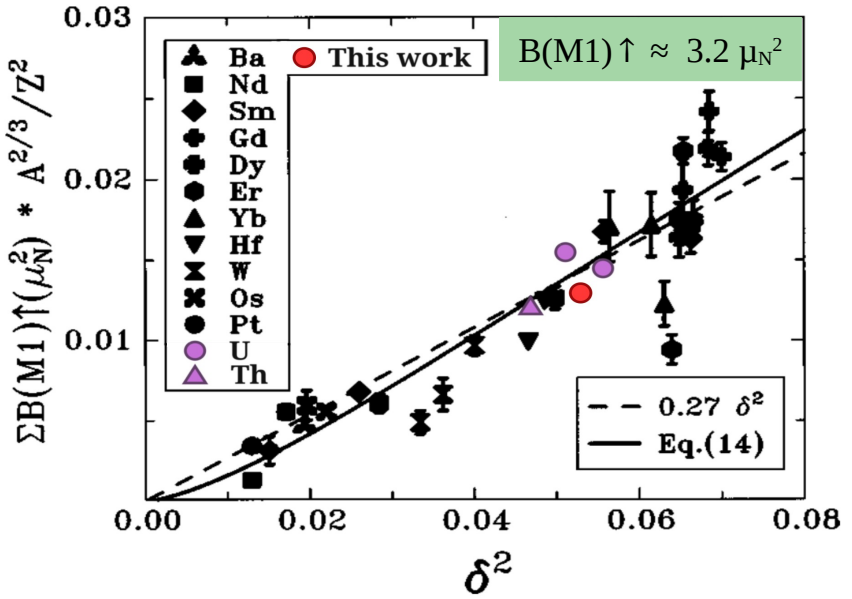

- Centroid energy: $E_{sc} \approx 2.4$ MeV $E_{sc} \approx 2.6$ MeV
- **2390 keV**: $B(E2)\uparrow = 557(62)\ e^2fm^4$

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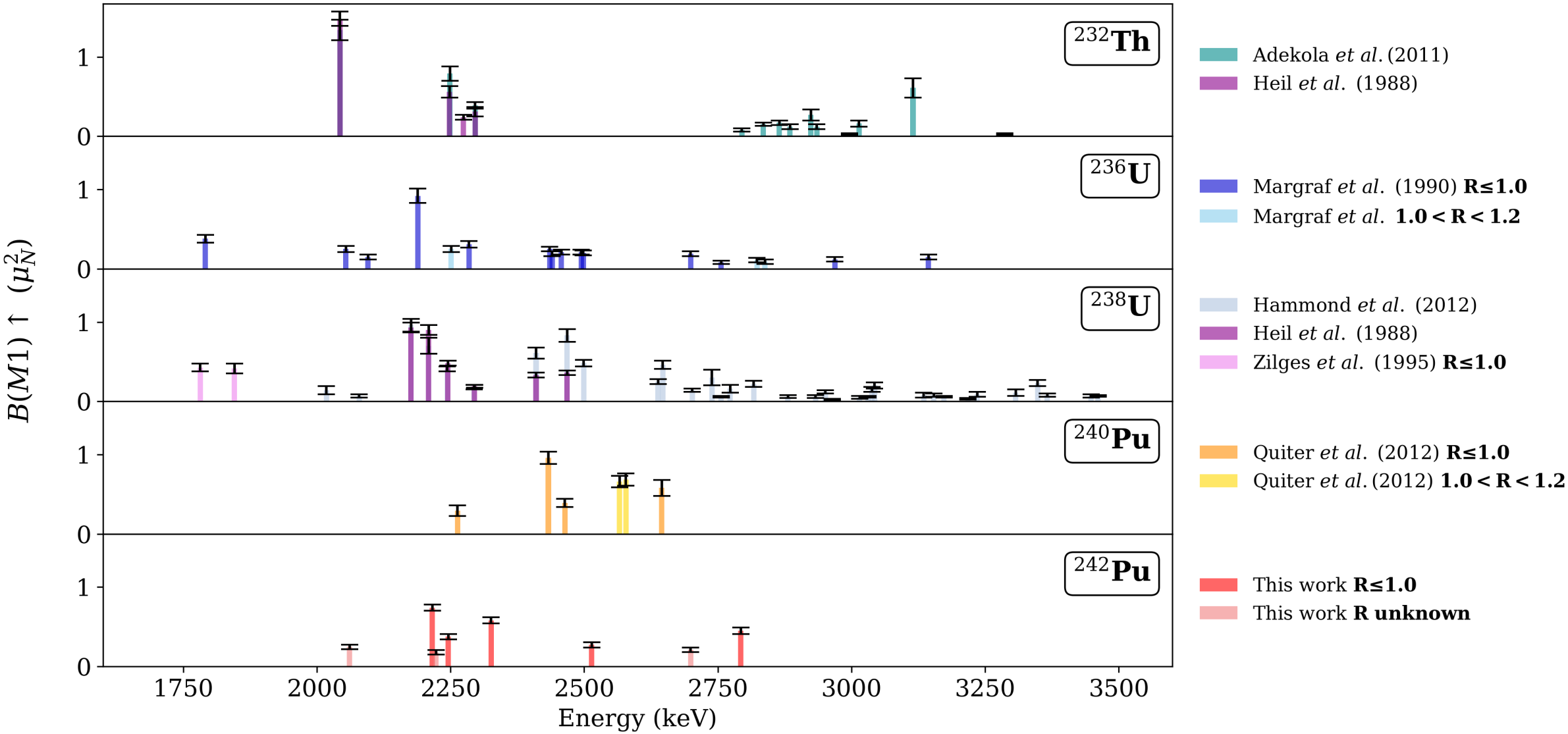
RESULTS



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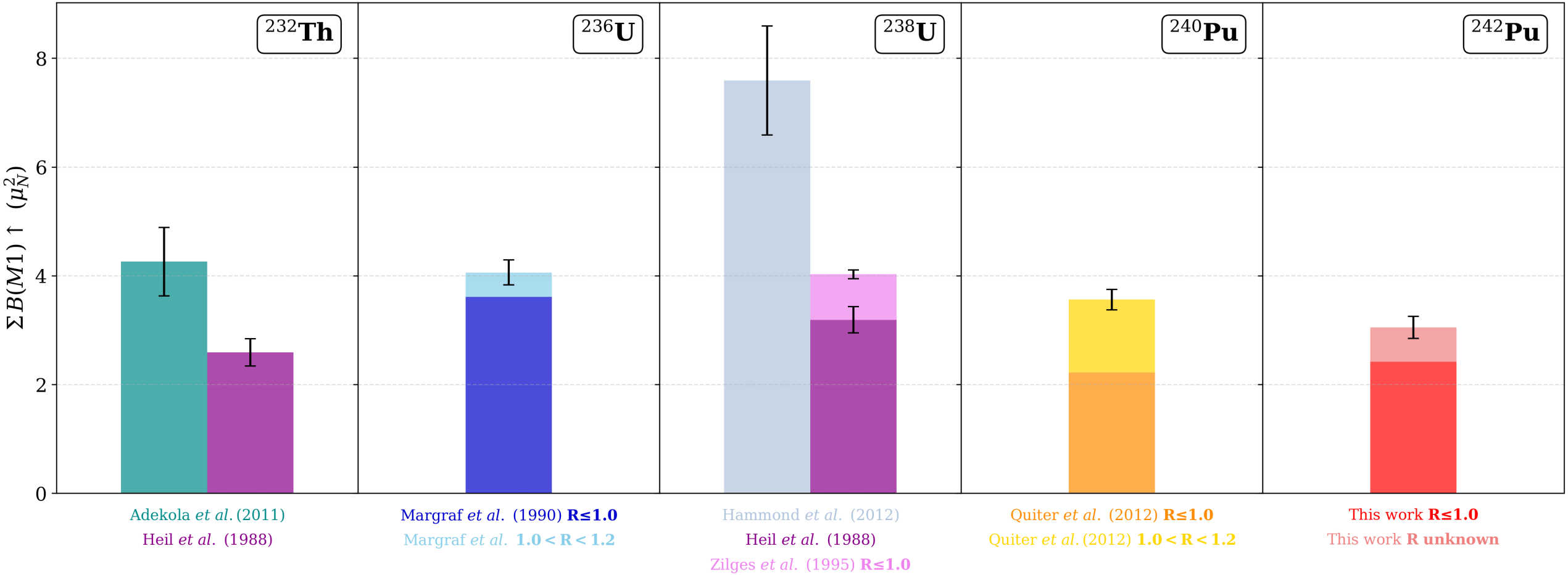

A. S. Adekola *et al.*, Phys. Rev. C **83** (2011) 034615
R.D. Heil *et al.*, Nuc. Phys. A **476** (1988) 39-47
J. Margraf *et al.*, Phys. Rev. C **42.2** (1990) 771
S. L. Hammond *et al.*, Phys. Rev. C **85** (2012) 044302
A. Zilges *et al.*, Phys. Rev. C **52.2** (1995) R468
B. J. Quiter *et al.*, Phys. Rev. C **86** (2012) 034307

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SUMMARY

- First NRF experiment on ^{242}Pu at the S-DALINAC 2022 to study dipole response
- Eighteen transitions from NRF on ^{242}Pu observed
- Seven dipole transitions with branching to first 2^+ state and one quadrupole transition at 2.39 MeV
- Total observed M1 strength of **3.05(14) μ_N^2** with centroid energy ~ **2.4 MeV**

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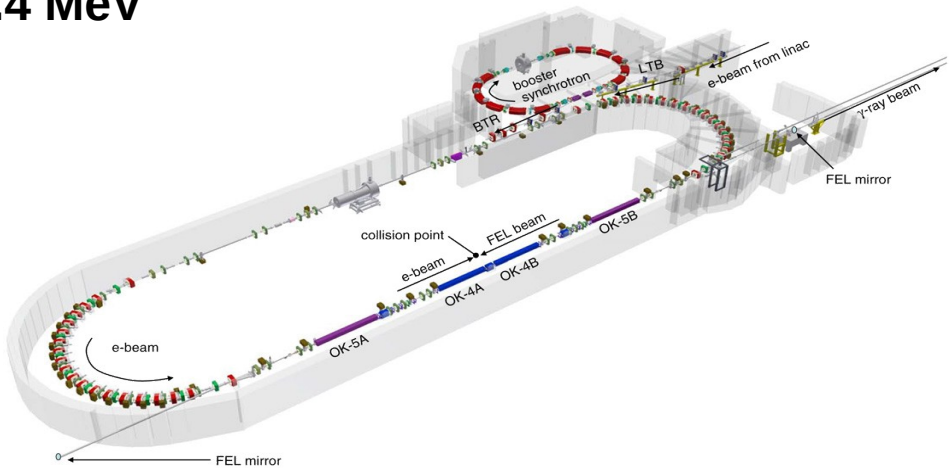
OUTLOOK

- Approved proposal for NRF on ^{242}Pu at HIγS
  → Monoenergetic polarized photon beam
  → Higher sensitivity and determination of parity quantum numbers
- Scissors mode in ^{244}Pu



H. R. Weller *et al.*, Prog. Part. Nucl. Phys. **62** (2009) 257

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Thanks for your attention!

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[1] Institute for Nuclear Physics, TU Darmstadt, Germany [2] HZDR, Dresden, Germany [3] FRIB, MSU, East Lansing, MI, USA
[4] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

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