Shape Coexistence in A=96 nuclei: new results on the 2_3^+ state in ^{96}Zr

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Istituto Nazionale di Fisica Nucleare

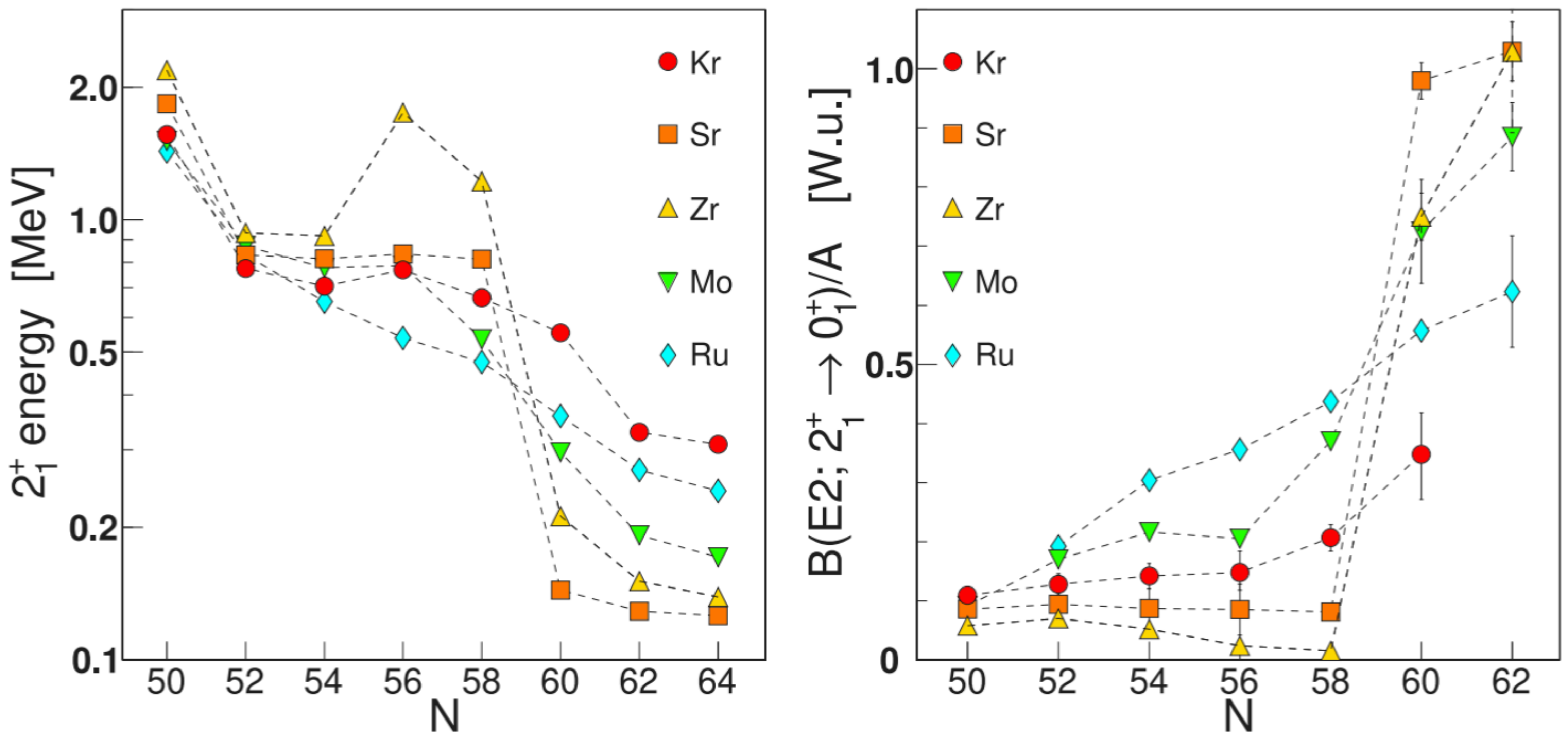
Shape Transition around N=60

- The region with $A \approx 100$ of the nuclide chart is of high interest for various reasons

- Abrupt changes in 2_1^+ state energy and $B(E2; 2_1^+ \rightarrow 0_1^+)$ values for Sr (Z=38) and Zr (Z=40) isotopes between N=58 and N=60

- Evidence of a transition from spherical to deformed ground state configurations

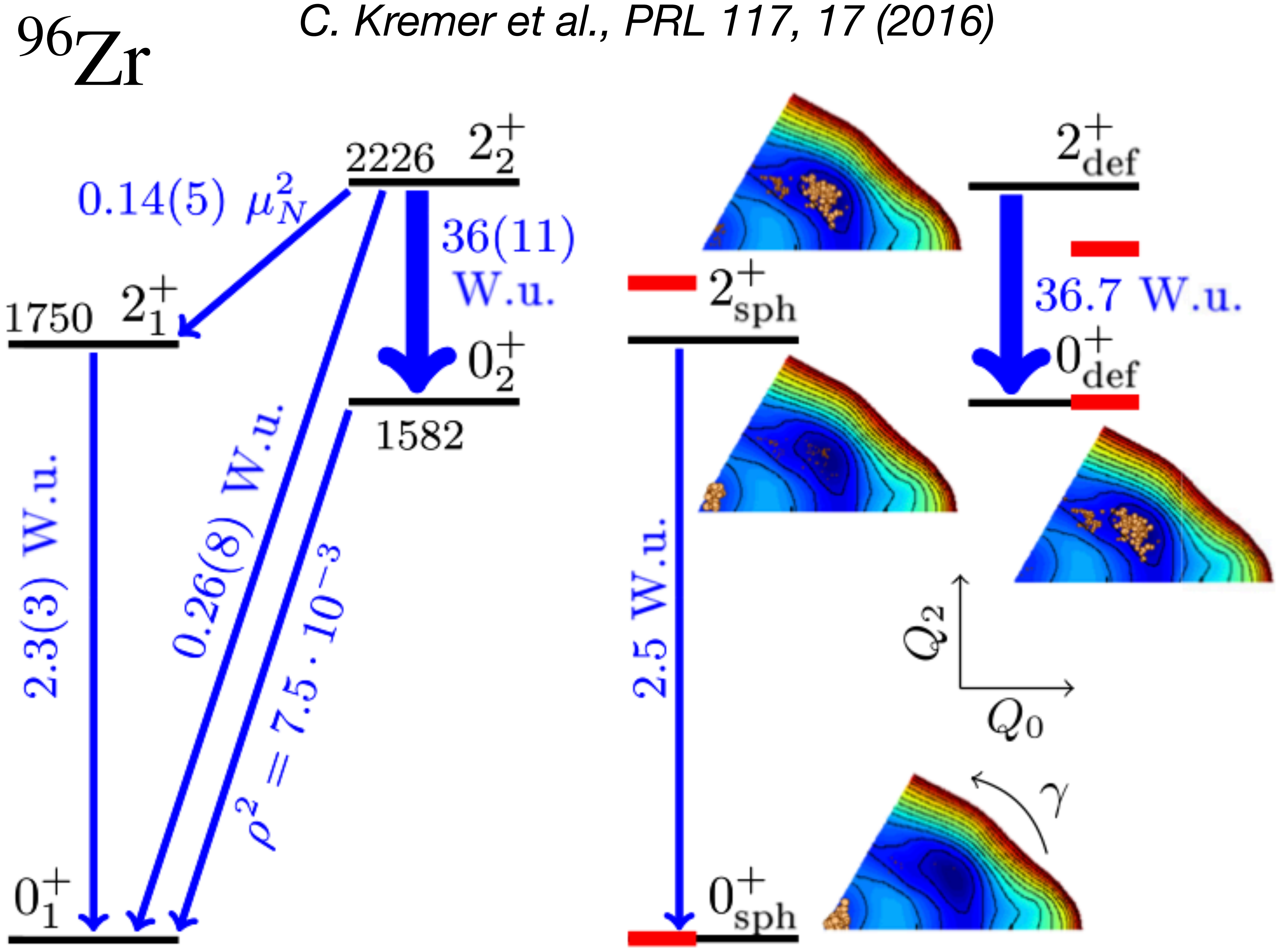
P. E. Garrett, M. Zielińska, E. Clément, Progress in Particle and Nuclear Physics 124 (2022)



Shape Coexistence in Sr and Zr isotopes

- Shape coexistence is a widespread phenomenon
- Clues of shape coexistence can be found in monopole and quadrupole transition strengths
- High B(E2) values are indicative of collective behaviour
- Low B(E2) values may indicate their belonging to two separate configurations
- Shape coexistence has been proposed in both ^{96}Sr and ^{96}Zr

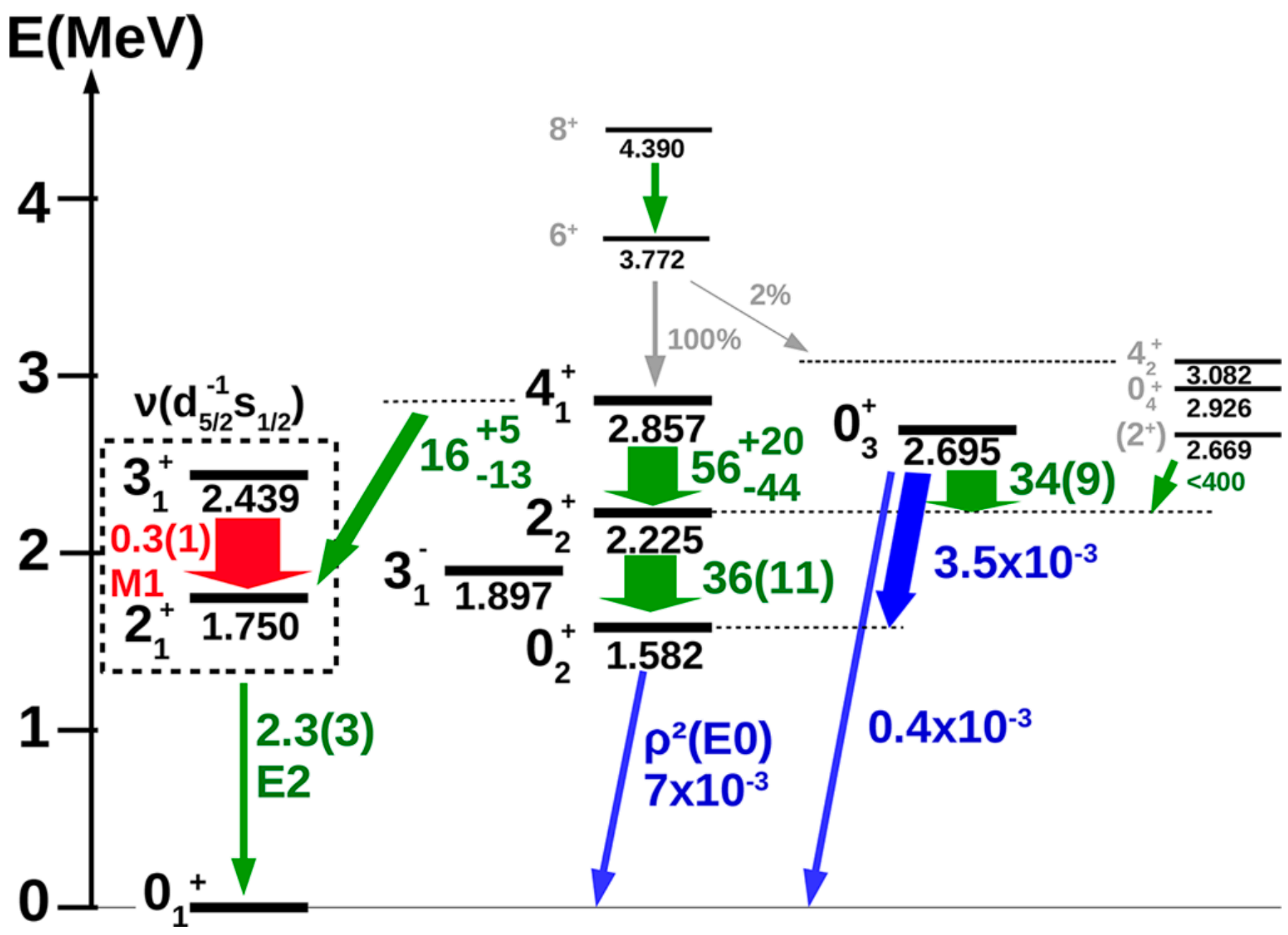
C. Kremer et al., PRL 117, 17 (2016)



The ^{96}Zr puzzle

- Recently, a review of the available spectroscopic data for ^{96}Zr was made
- Large $B(E2;4_1^+ \to 2_2^+)$, $B(E2;2_2^+ \to 0_2^+)$ and $B(E2;0_3^+ \to 2_2^+)$ values indicate a collective nature of the structure built on top of the 0_2^+ state
- $\rho^2(0_3^+ \to 0_2^+)$ and $\rho^2(0_3^+ \to 0_1^+)$ have only been roughly estimated
- $\rho^2(0_2^+ \to 0_1^+)$ is well known and equal to $7.53(14) \times 10^{-3}$
- The precise interpretation is still debated

W. Witt et al., EPJA 55, 79 (2019)



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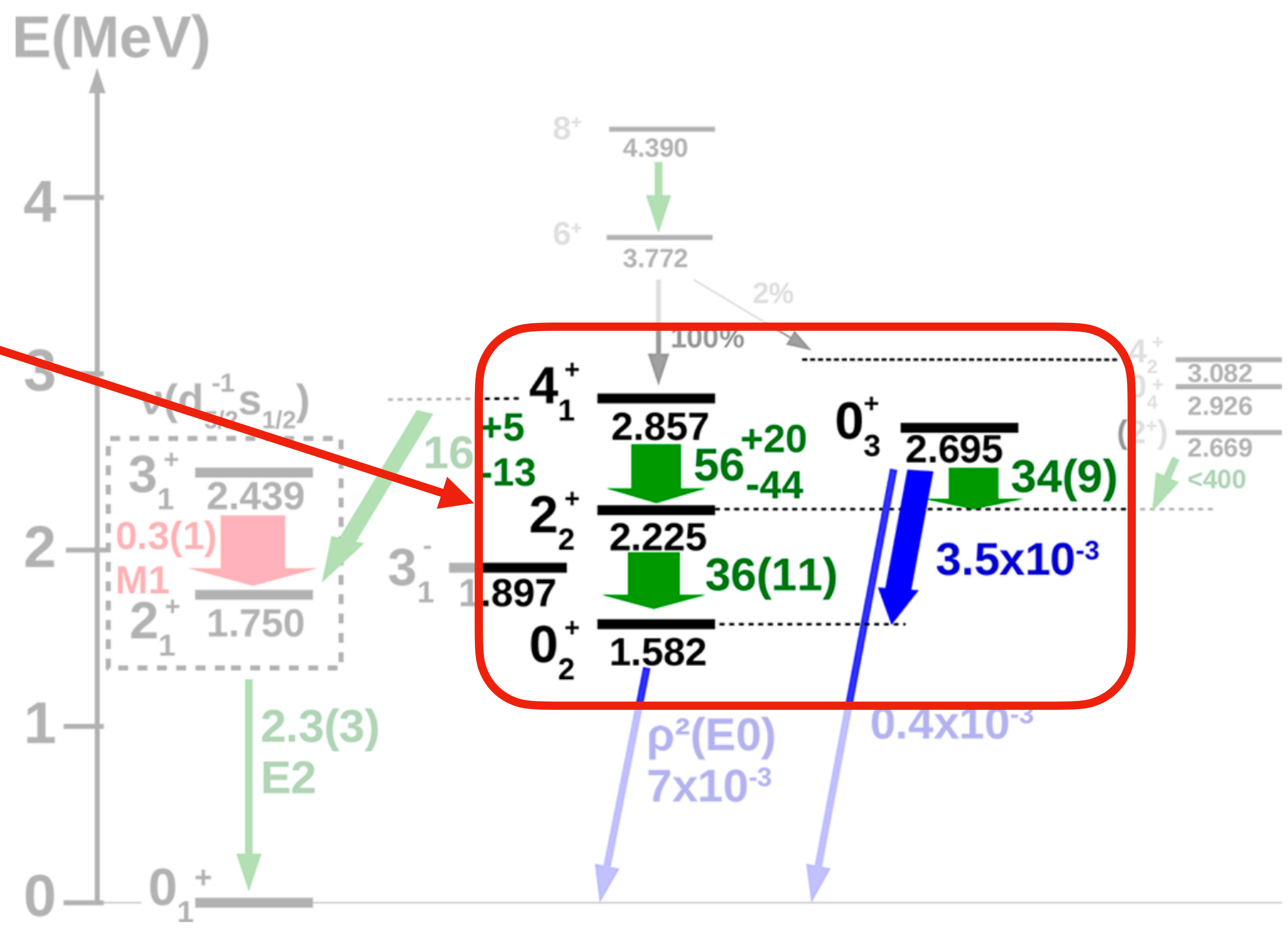

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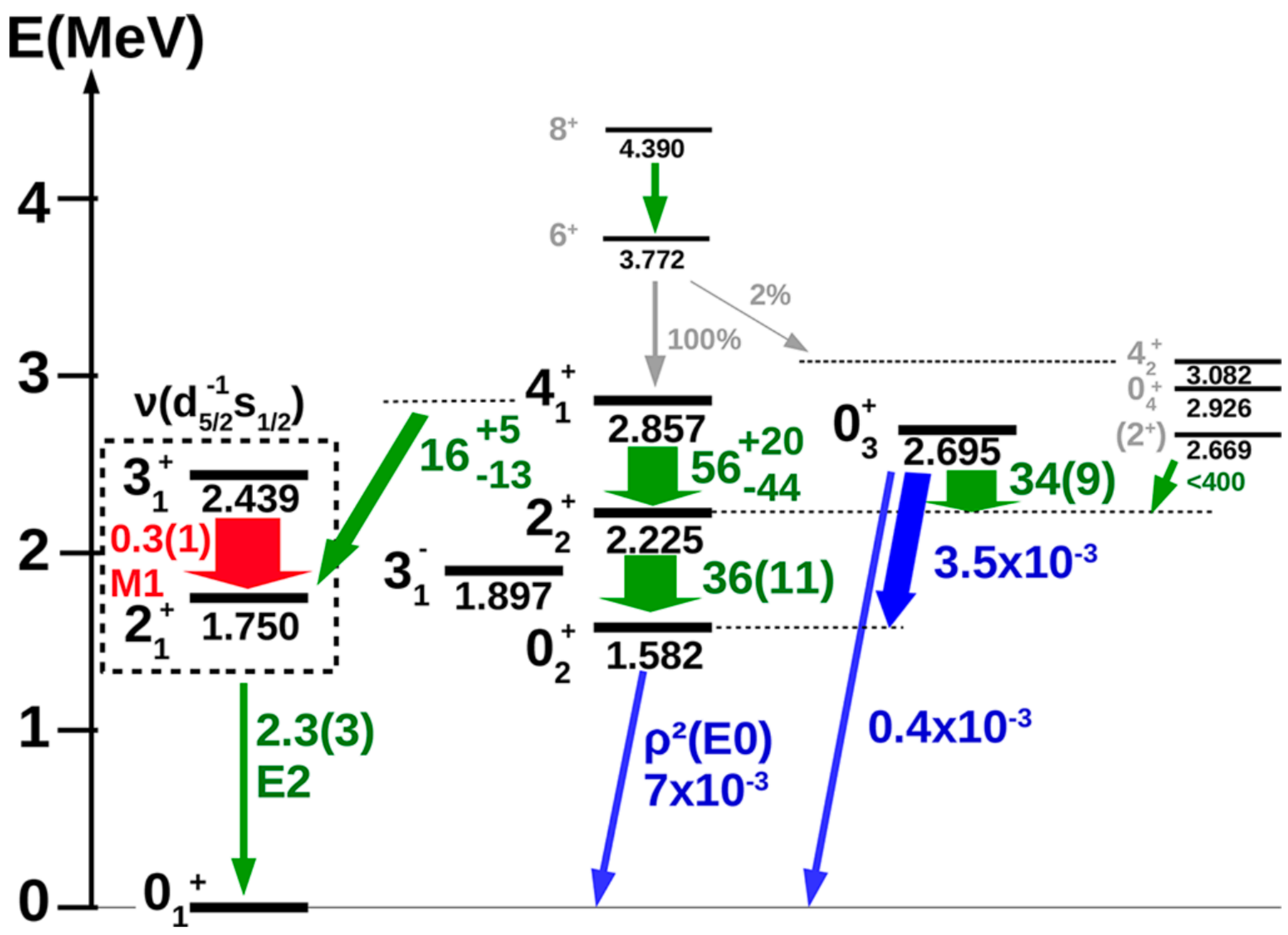

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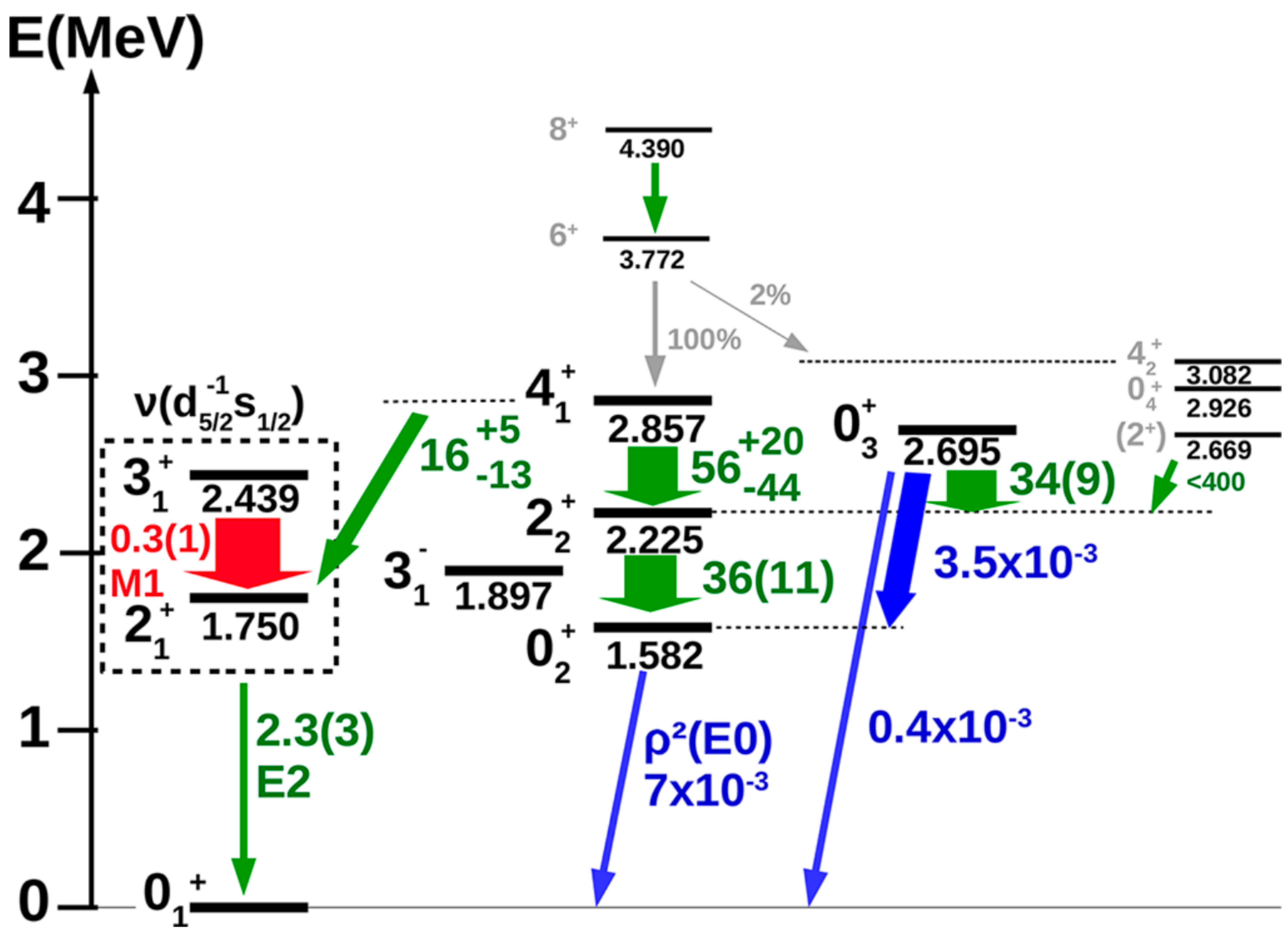
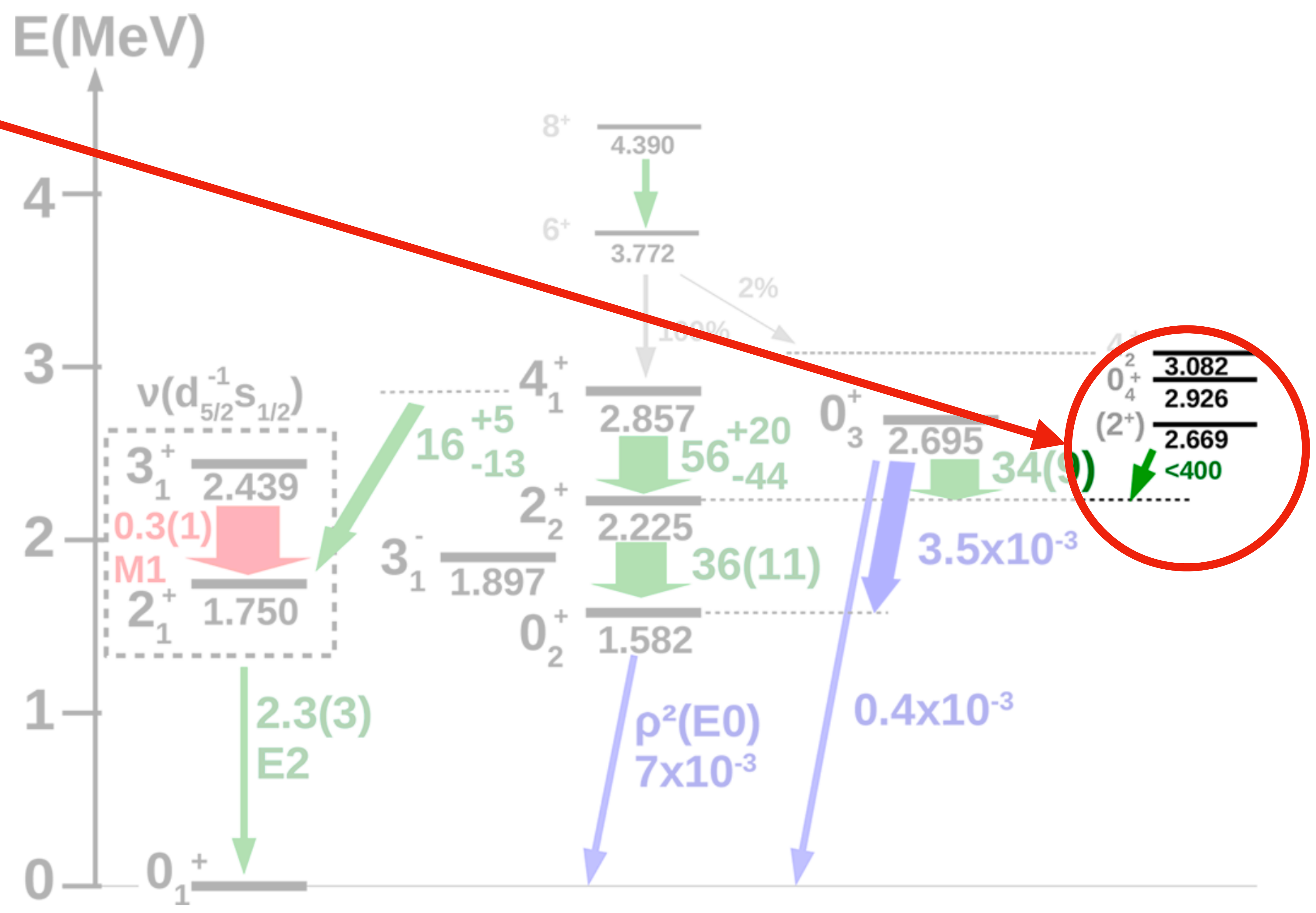


The ^{96}Zr puzzle

- Of particular interest is also the state at 2669keV, with the tentative assignment of $J^{\pi} = 2^{+}$
- It could be part of a quadrupole vibrational structure based on the 0_2^+ state
- With known data, an upper limit of 400 W.u. on the $B(E2; (2^+) \rightarrow 2_2^+)$ value was deduced, assuming a pure E2 transition because the mixing ratio was unknown
- No transitions to lower energy 0^+ states were observed for this state, questioning the (2^+) assignment

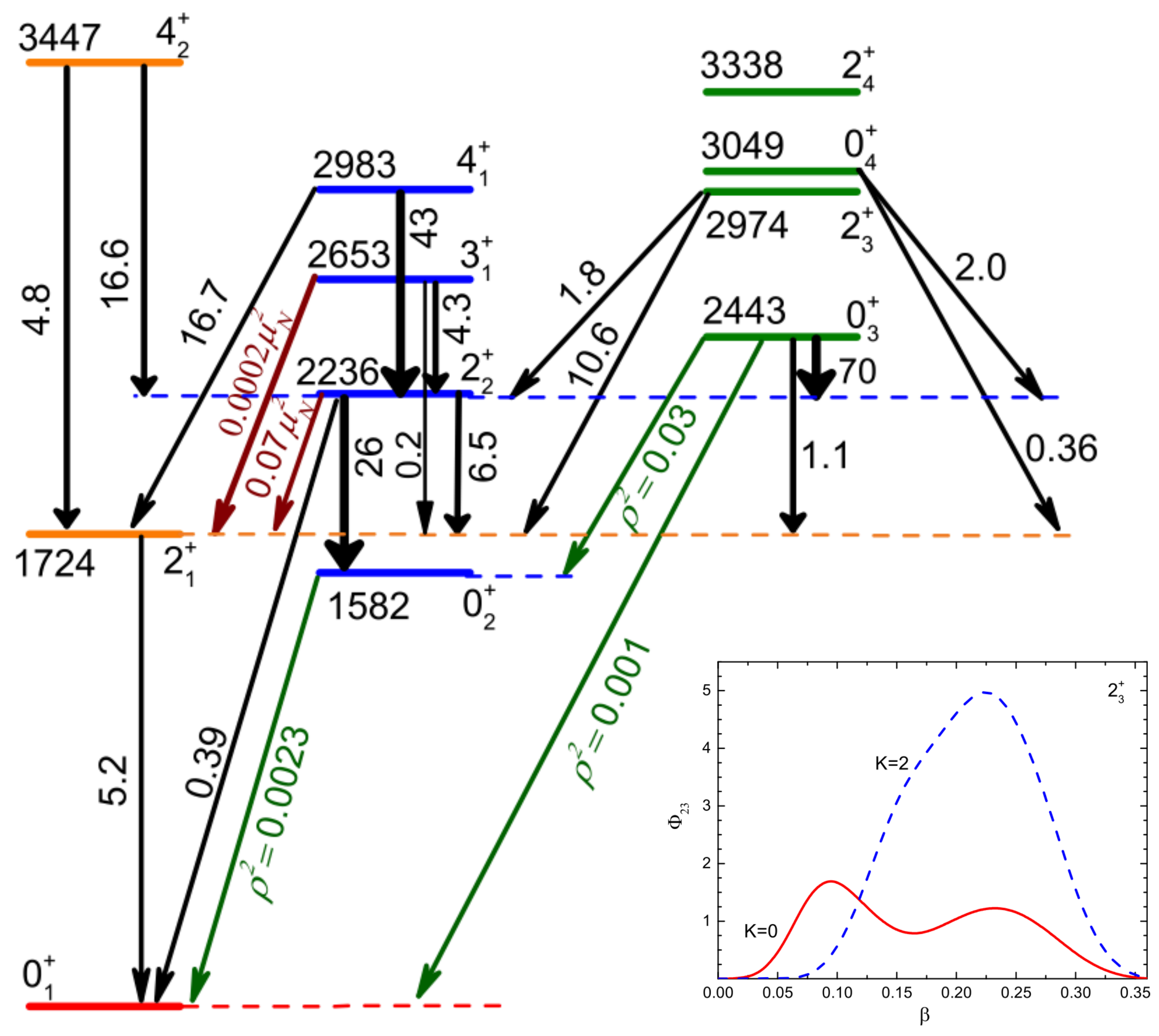
W. Witt et al., EPJA 55, 79 (2019)



The ^{96}Zr puzzle

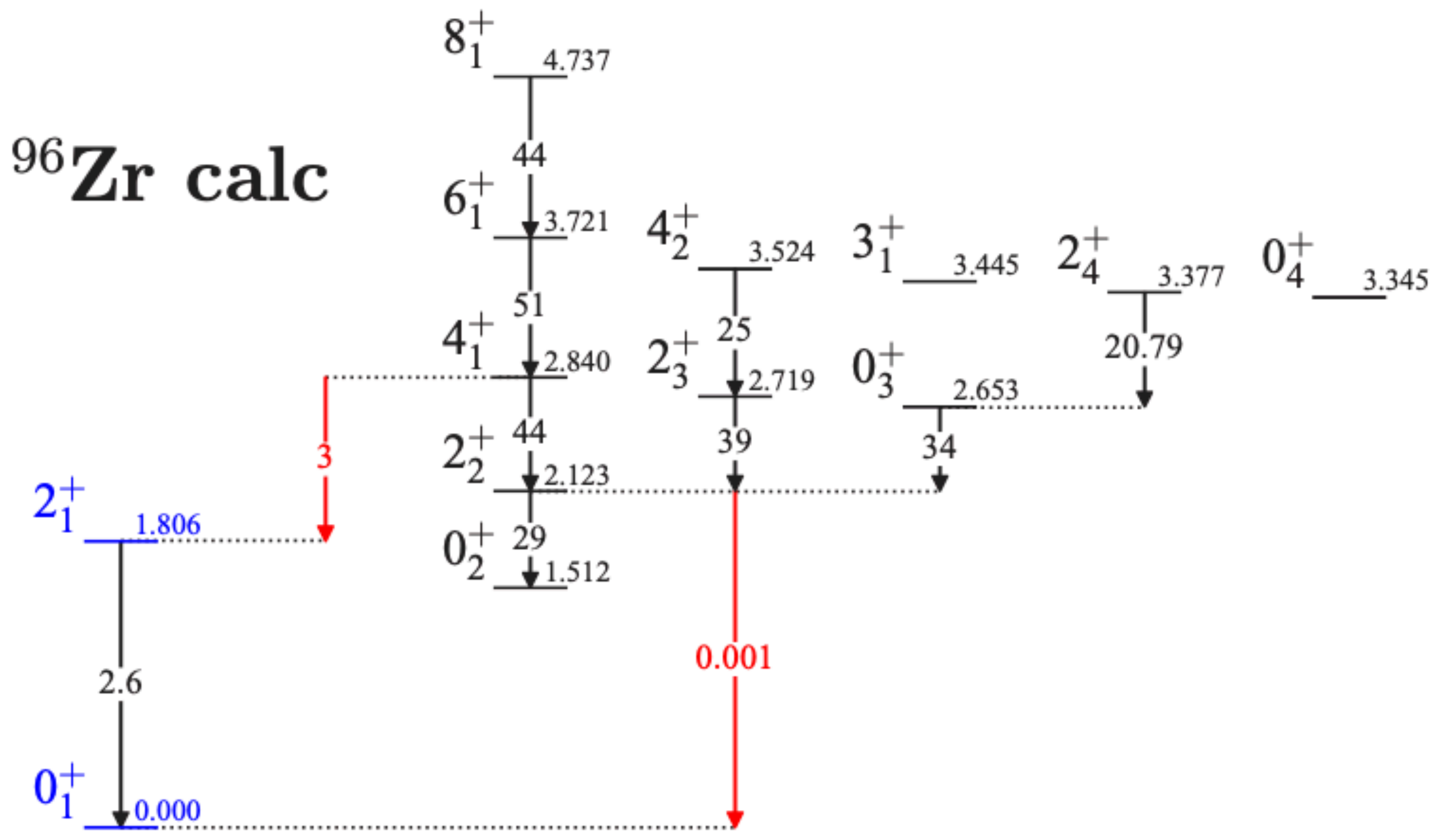
Rotational-like

E. V. Mardyban et al., PRC 102, 034308 (2020)

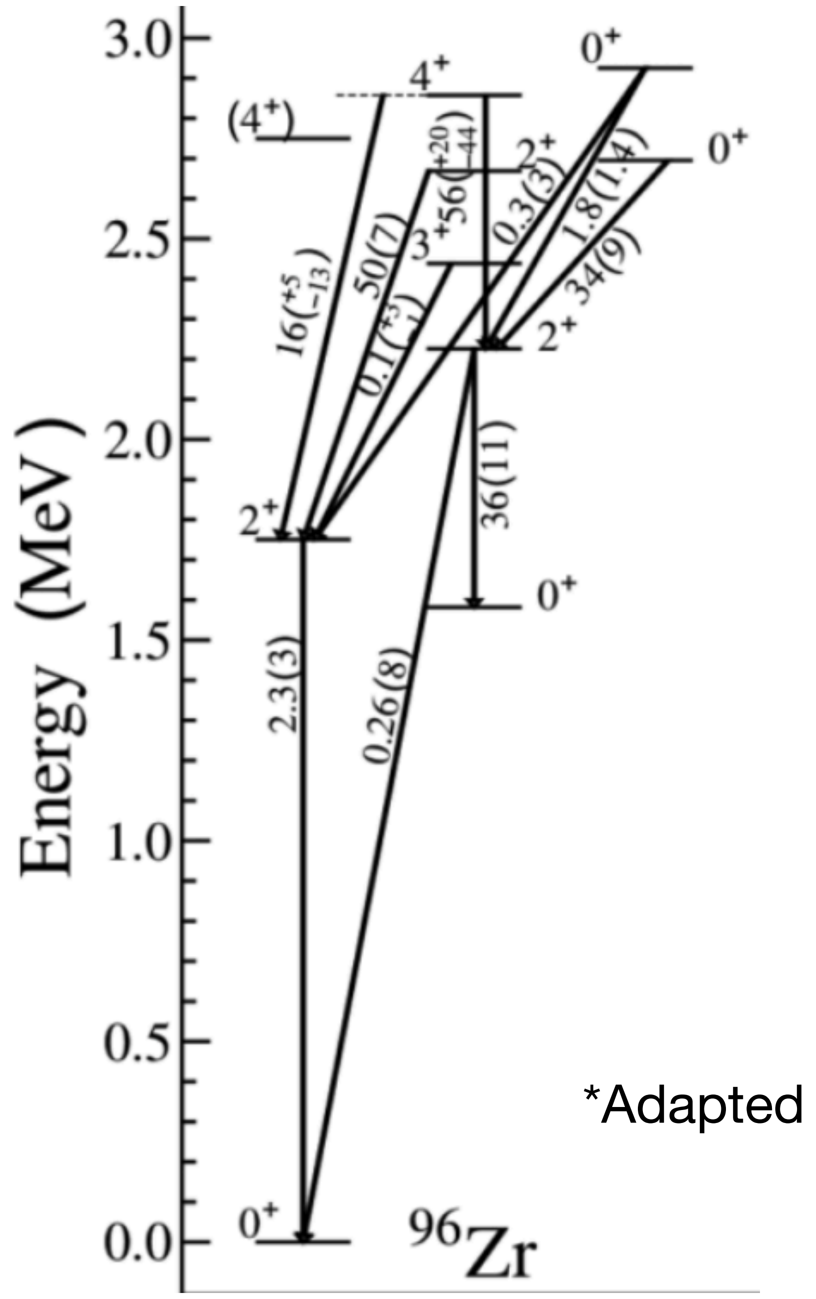


Vibrational-like

N. Gavrielov et al., PRC 105, 014305 (2022)



J. E. García-Ramos and K. Heyde, PRC 100, 044315 (2019)



*Adapted

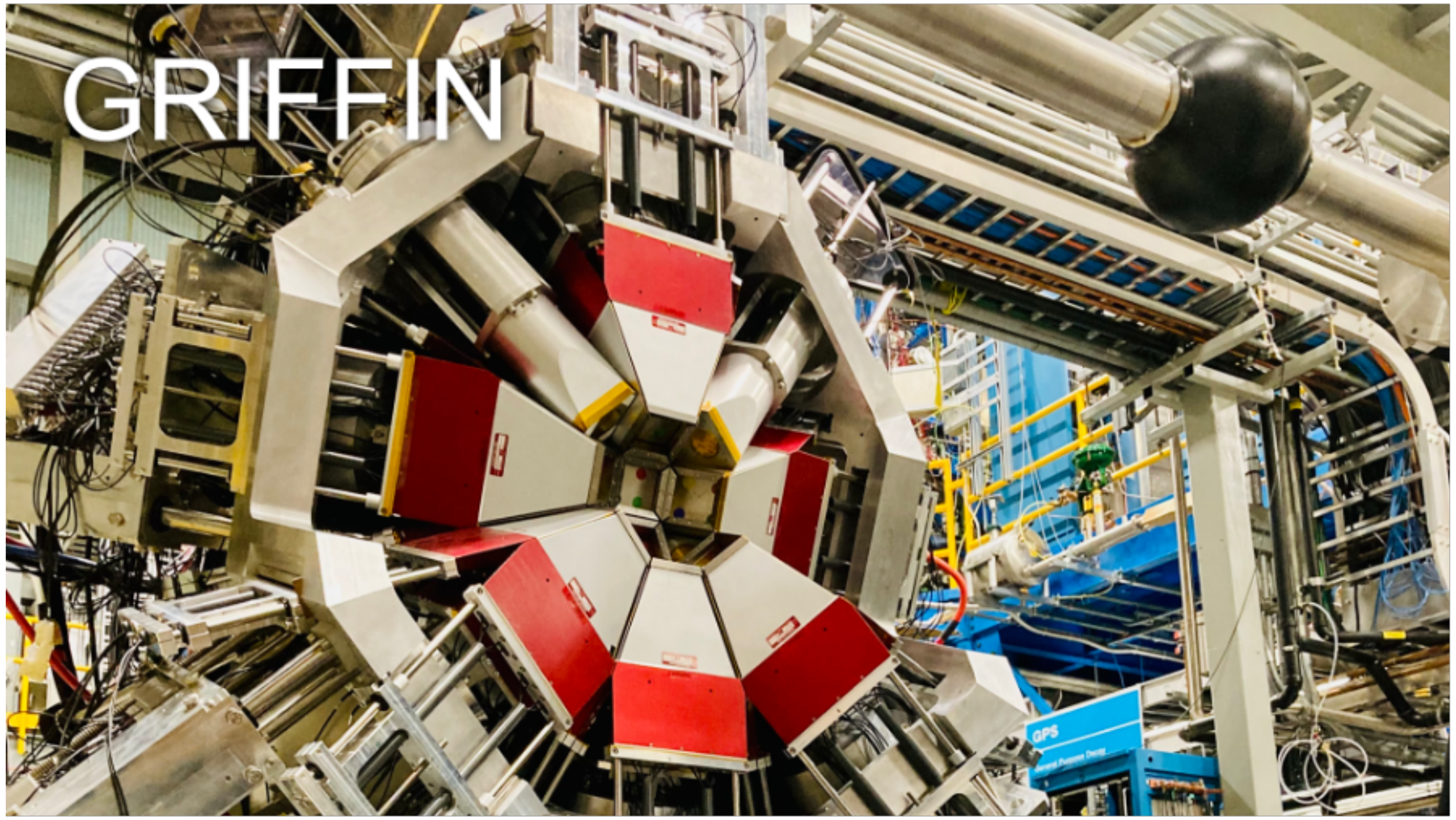
Experiment

Study of ^{96}Zr and ^{96}Sr with β-decay @ TRIUMF Laboratories

- β-decay cascade to populate nuclei of interest

$$^{96}\mathrm{Rb} \xrightarrow{\beta^-} {}^{96}\mathrm{Sr} \xrightarrow{\beta^-} {}^{96}\mathrm{Y} \xrightarrow{\beta^-} {}^{96}\mathrm{Zr}$$

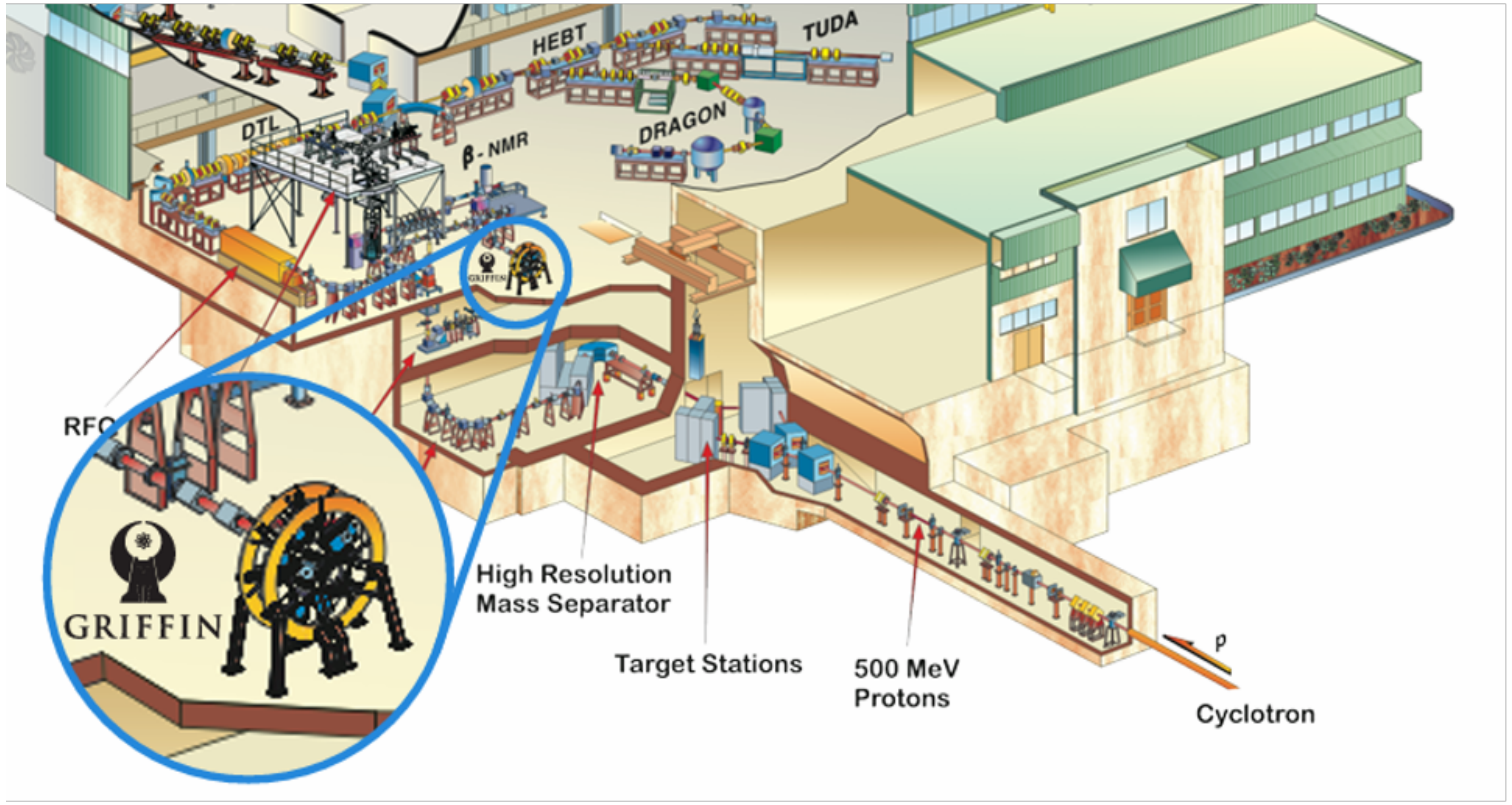
- High resolution γ-ray spectroscopy
- High resolution Internal Conversion Electrons spectroscopy
- Angular Correlations between cascades of γ-rays
- Lifetime measurements



Experiment

TRIUMF ISAC-I: A Radioactive Ion Beam production facility

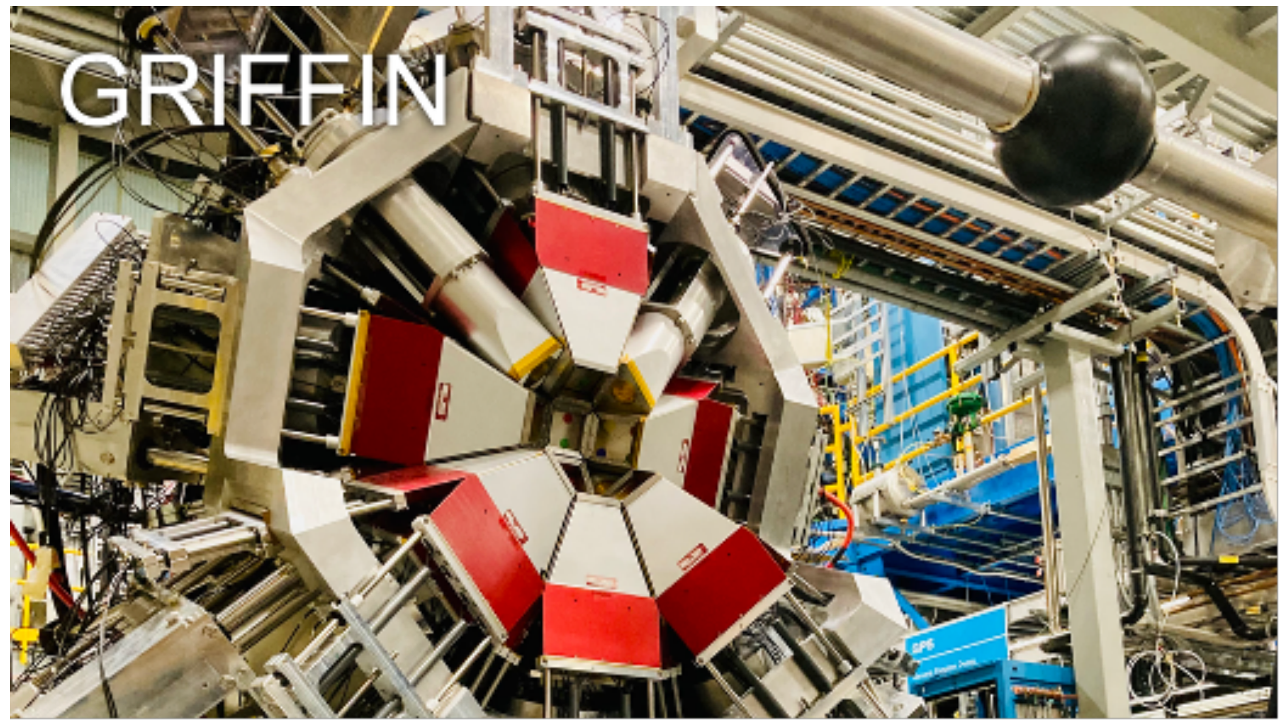
- Isotope Separation OnLine Facility
- 500 MeV protons on primary target
- Neutron-rich fission fragments are ionised
- Magnetic separation and transport
- Implantation at GRIFFIN measurement station



Experimental Setup

GRIFFIN Spectrometer and Ancillary Detectors

Gamma Ray Infrastructure For Fundamental Investigation of Nuclei (GRIFFIN)

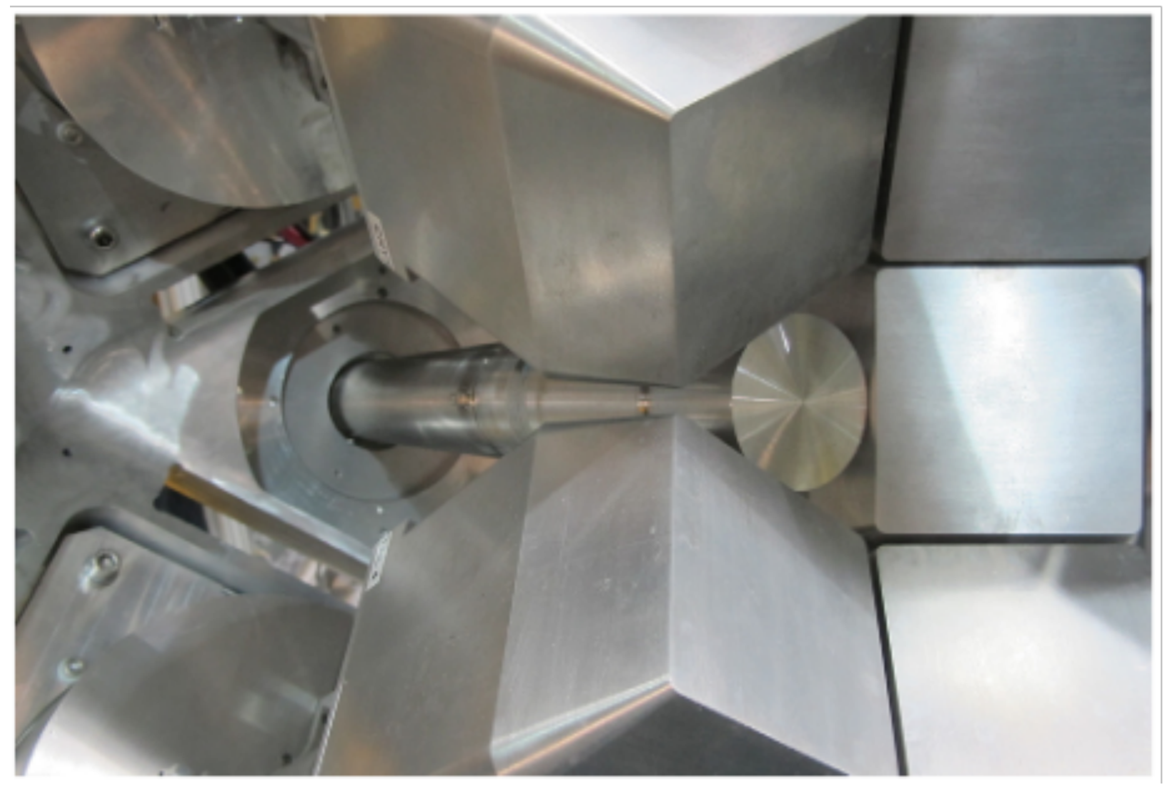


- Up to 16 Compton suppressed HPGe clovers
- γ-ray intensities
- Branching Ratios
- Angular Correlations

Pentagonal Array for Conversion Electron Spectroscopy (PACES)

- 5 cooled Si(Li) detectors
- Internal Conversion Electron intensities
- Internal Conversion coefficients

$LaBr_3(Ce)$ scintillators



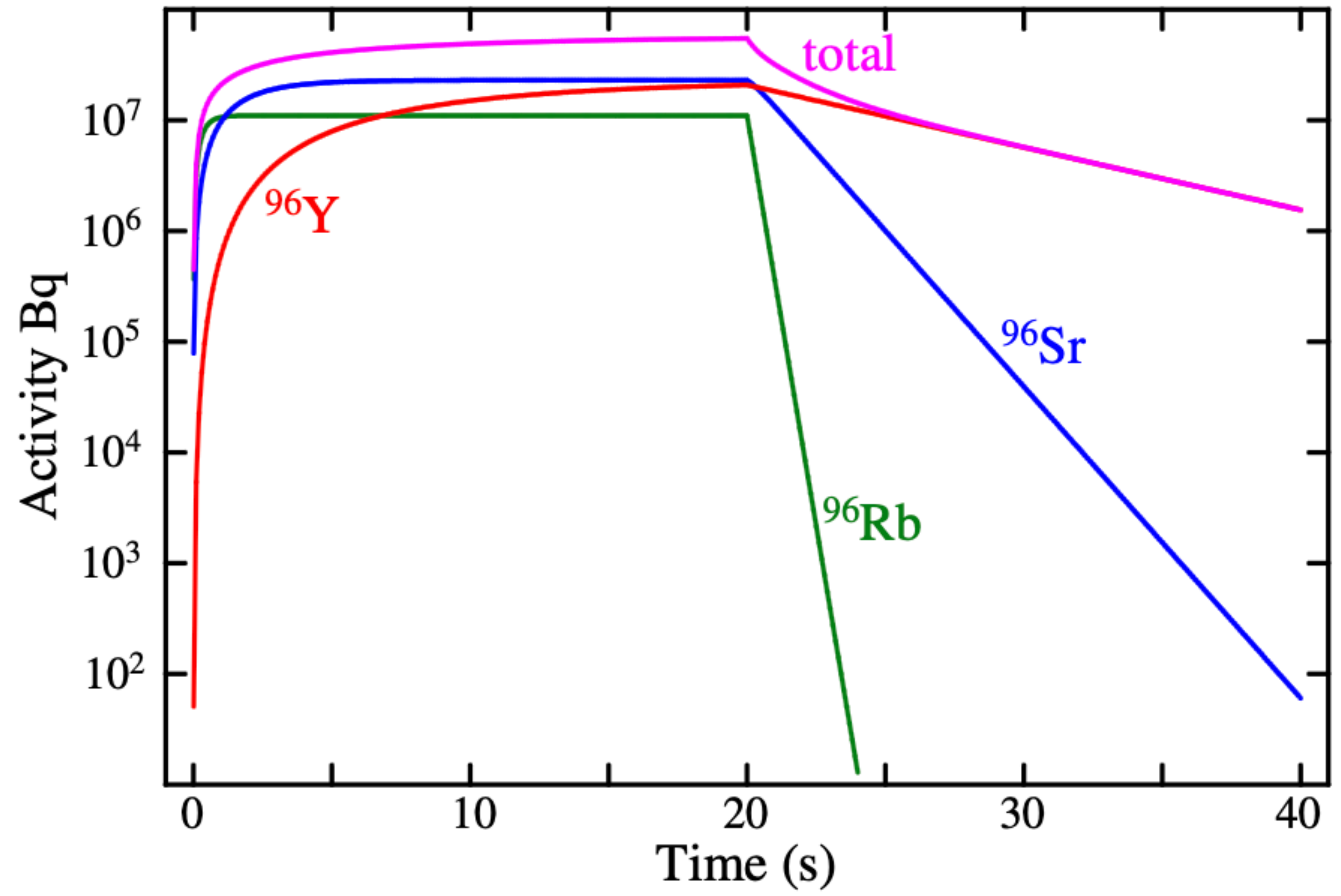
- 8 $LaBr_3(Ce)$ detectors
- Lifetime measurements with Fast Electronic Timing technique

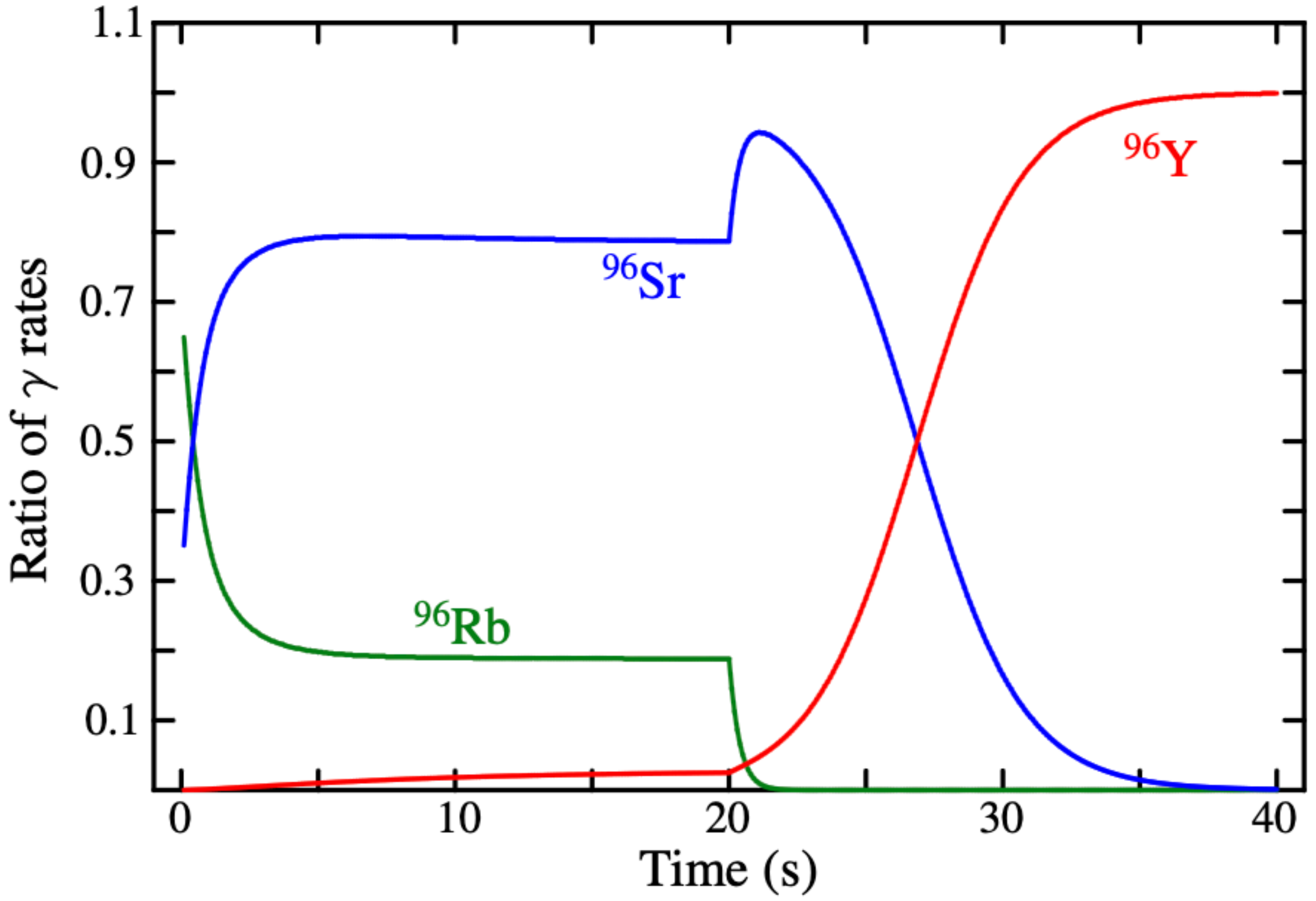
Experiment

Moving Tape Collector (MTC)

- Beam (A=96 isobars, mainly ^{96}Rb and ^{96}Sr, both decaying to ^{96}Y) implanted on the MTC at the center of GRIFFIN
- Measurements performed in cycles
- Increased sensitivity to decays of interest

$$^{96}\mathrm{Rb} \xrightarrow{\beta^-} {}^{96}\mathrm{Sr} \xrightarrow{\beta^-} {}^{96}\mathrm{Y} \xrightarrow{\beta^-} {}^{96}\mathrm{Zr}$$





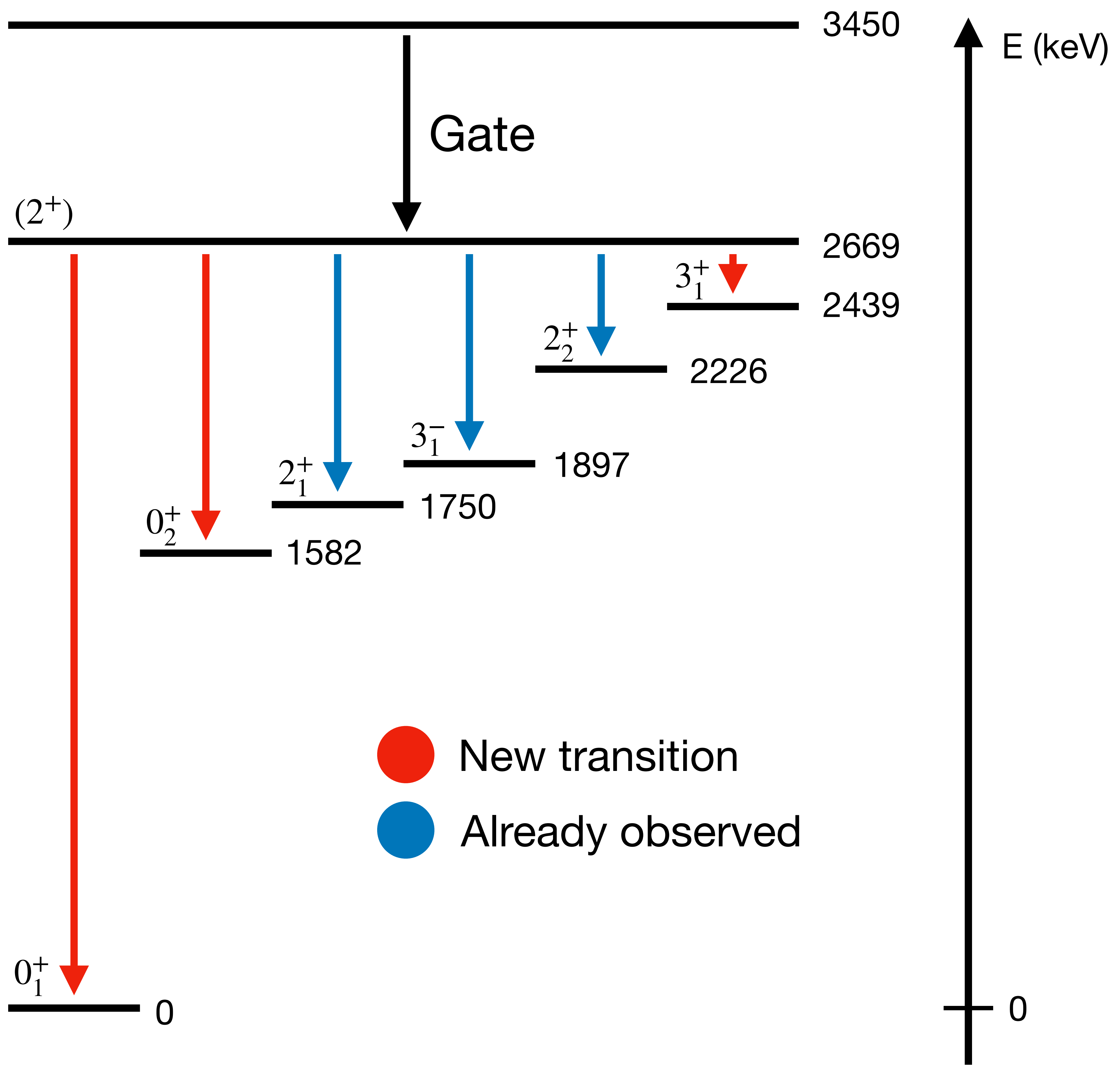
Preliminary Results

Branching Ratios

- Gating from above, all the transitions concerning the de-excitation of the (2^+) state were found, some for the first time

Transition	Energy (keV)	I_γ	$I_\gamma^{(a)}$	$I_\gamma^{(b)}$
$2_3^+ \rightarrow 3_1^+$	230.07	0.32(10)		
$2_3^+ \rightarrow 2_2^+$	442.9	3.4(2)	4.0(13)	
$2_3^+ \rightarrow 3_1^-$	771.6	23.0(10)	28(4)	20(3)
$2_3^+ \rightarrow 2_1^+$	918.6	100(4)	100(4)	100(6)
$2_3^+ \rightarrow 0_2^+$	1087.73	1.42(15)		
$2_3^+ \rightarrow 0_1^+$	2669.07	1.24(15)		

(a) G. Molnàr et al., Nuclear Physics A 500 (1989)
(b) H. Mach et al., PRC 41, 226 (1990)



Preliminary Results

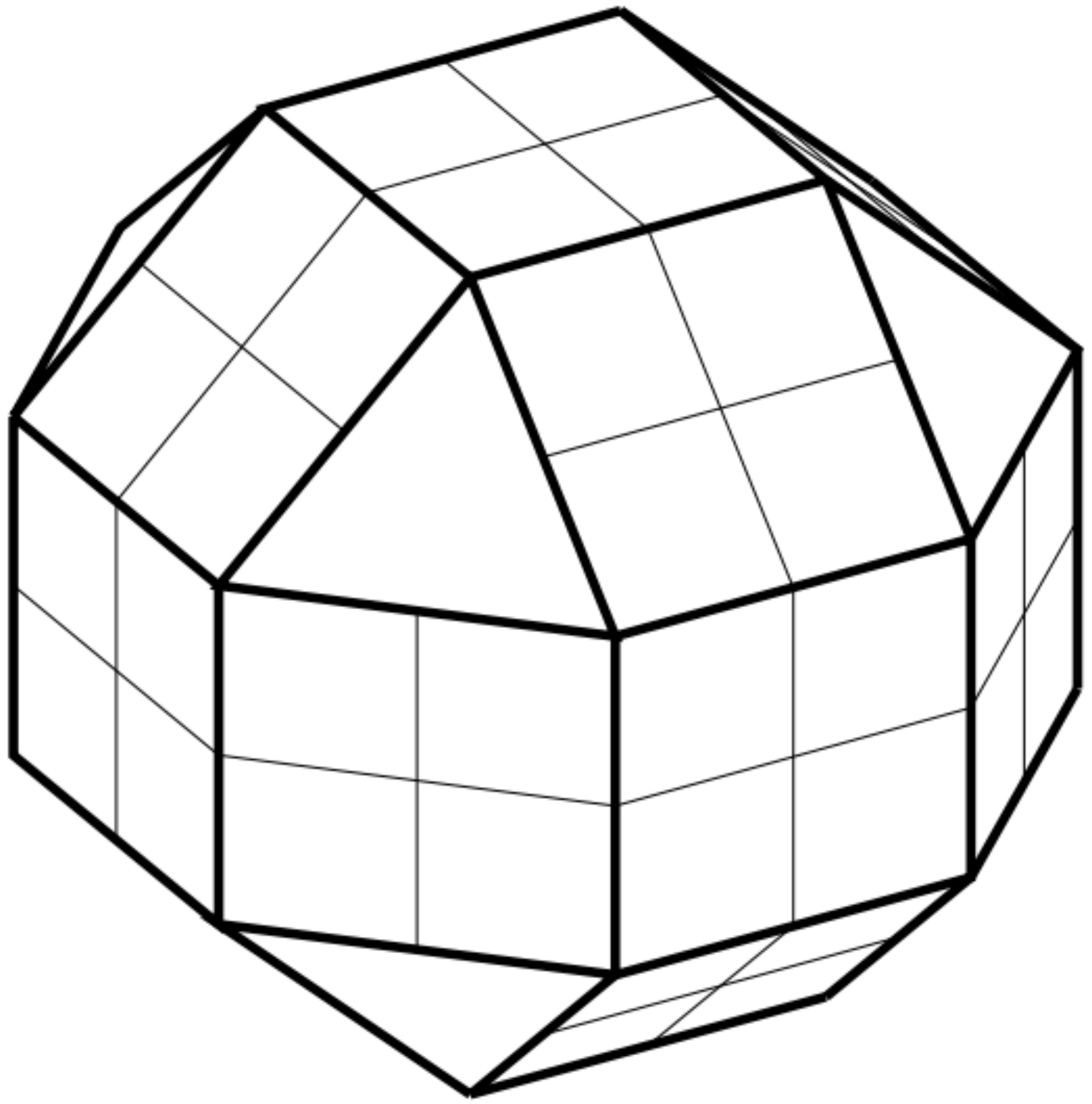
$\gamma - \gamma$ Angular Correlation with GRIFFIN

- Up to 52 unique angular openings (with 16 active clovers)
- Event mixing technique: normalisation of A.C. spectra over uncorrelated coincidence events

$\downarrow$

No need to know # of pairs for each opening angle or detectors efficiency

- GEANT4 simulations to account for finite sizes of the detectors
- Spin assignment at 99% Confidence Level



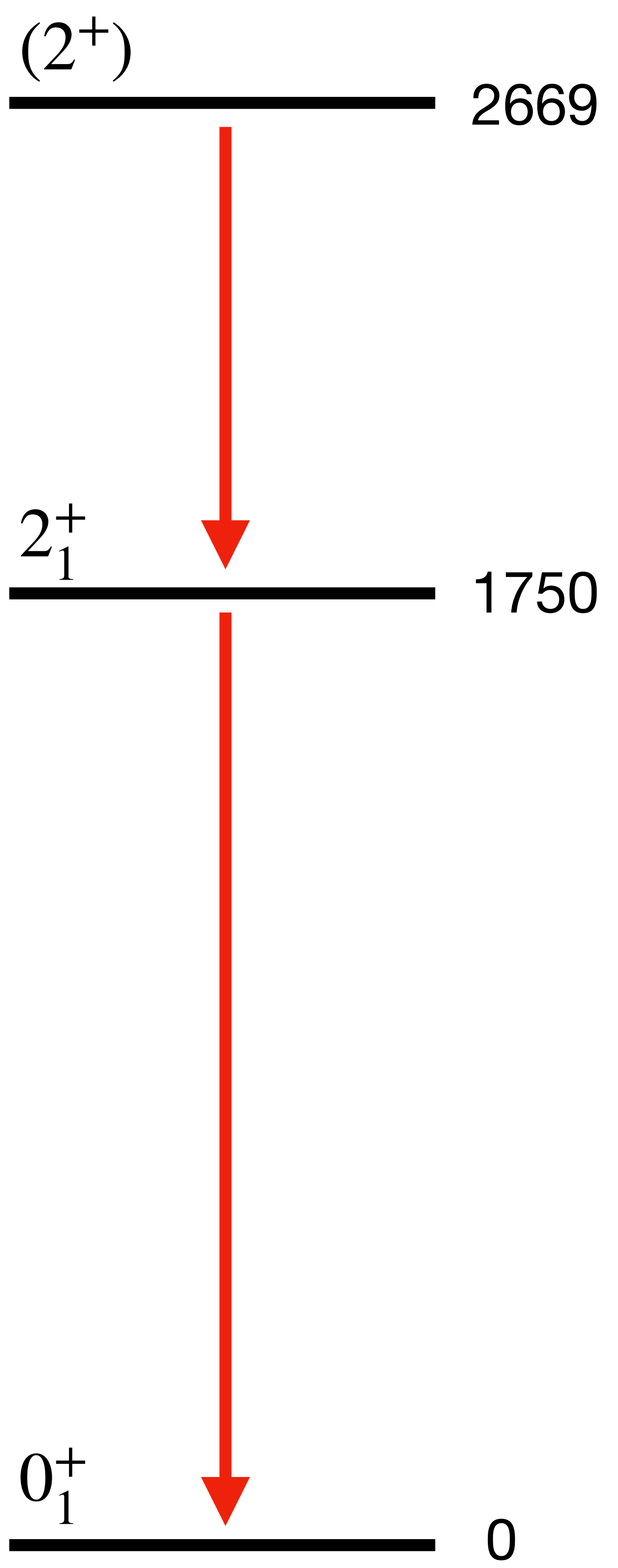
J.K. Smith et al., NIMA 922, 47 (2019)

Preliminary Results

J^π assignment and mixing ratio measurement

- To determine the J of the 2669 keV state, the angular correlations of the γ-ray cascade on the right was considered

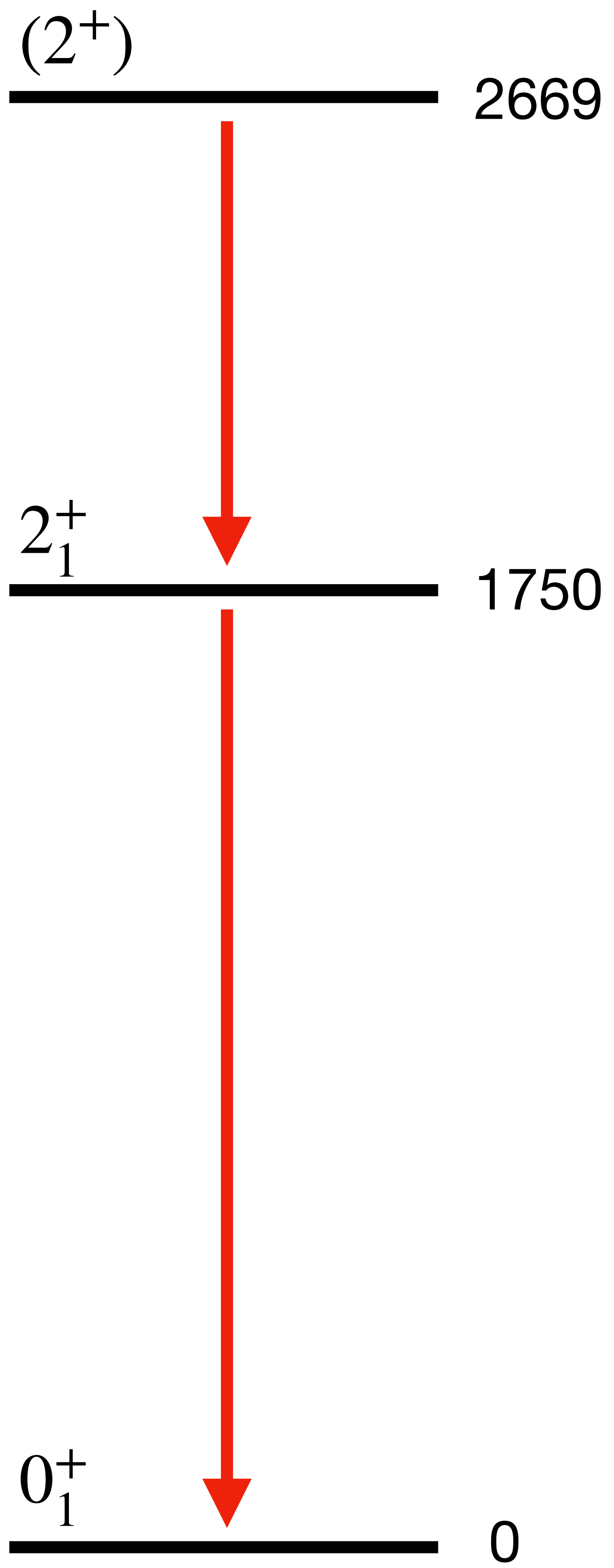
- The χ^2 minimisation procedure allowed for the determination of the angular correlation coefficients and mixing ratio of the upper transition

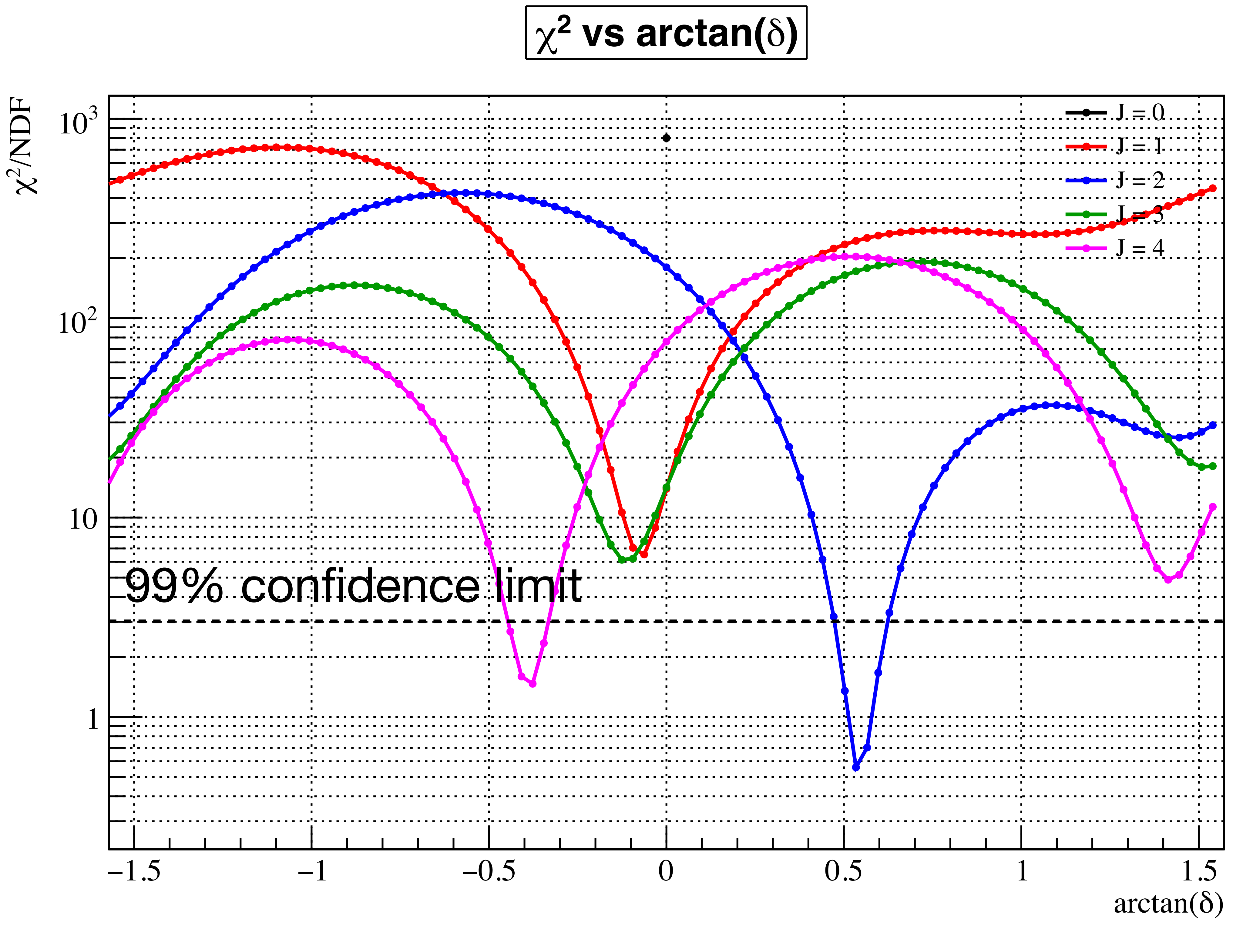


Preliminary Results

J^{π} assignment and mixing ratio measurement

- The minimum of the χ^2 function is reached for $J = 2$ and $\delta = 0.61(3)$
- All the assignments below the 99% confidence limit may be accepted in principle
- The unrealistic value of $\delta(M3/E2)$ for a $4^+ \rightarrow 2^+_1$ transition, combined with the observation of transitions to the lower energy 0^+ states rules out the $J = 4$ assignment

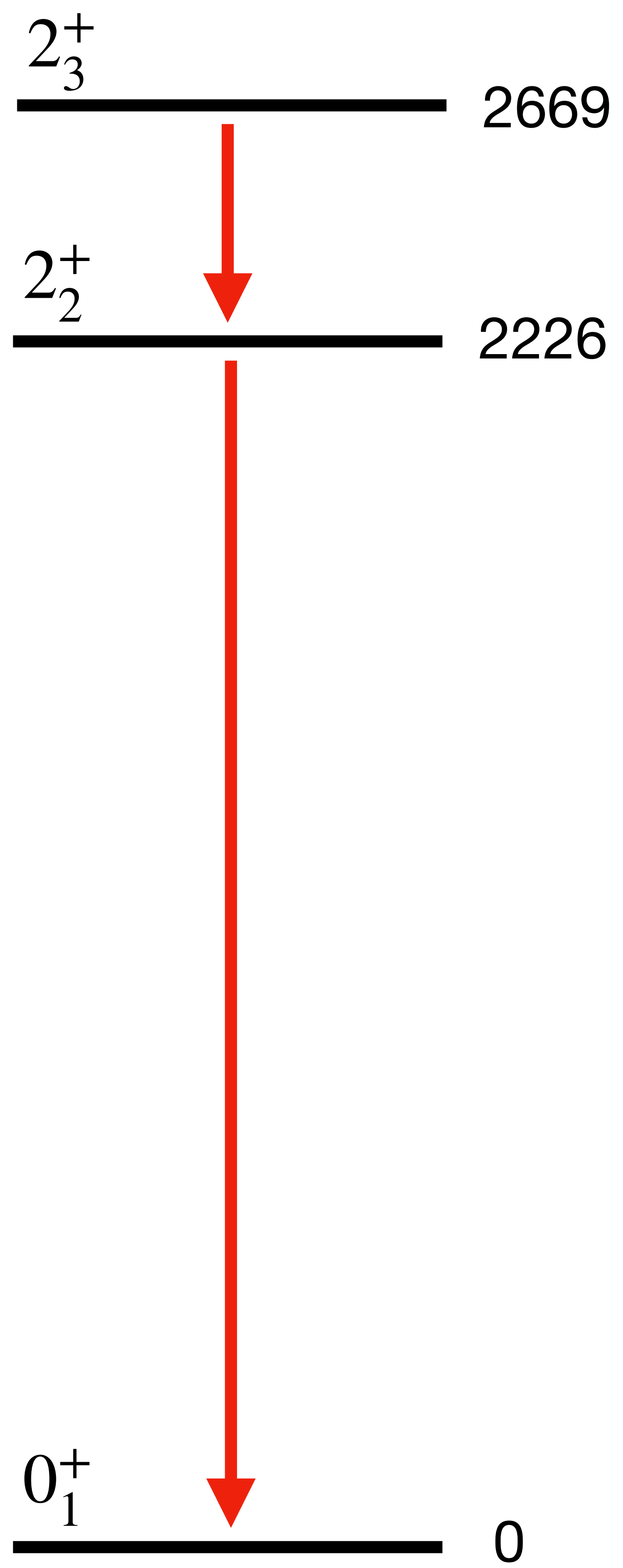


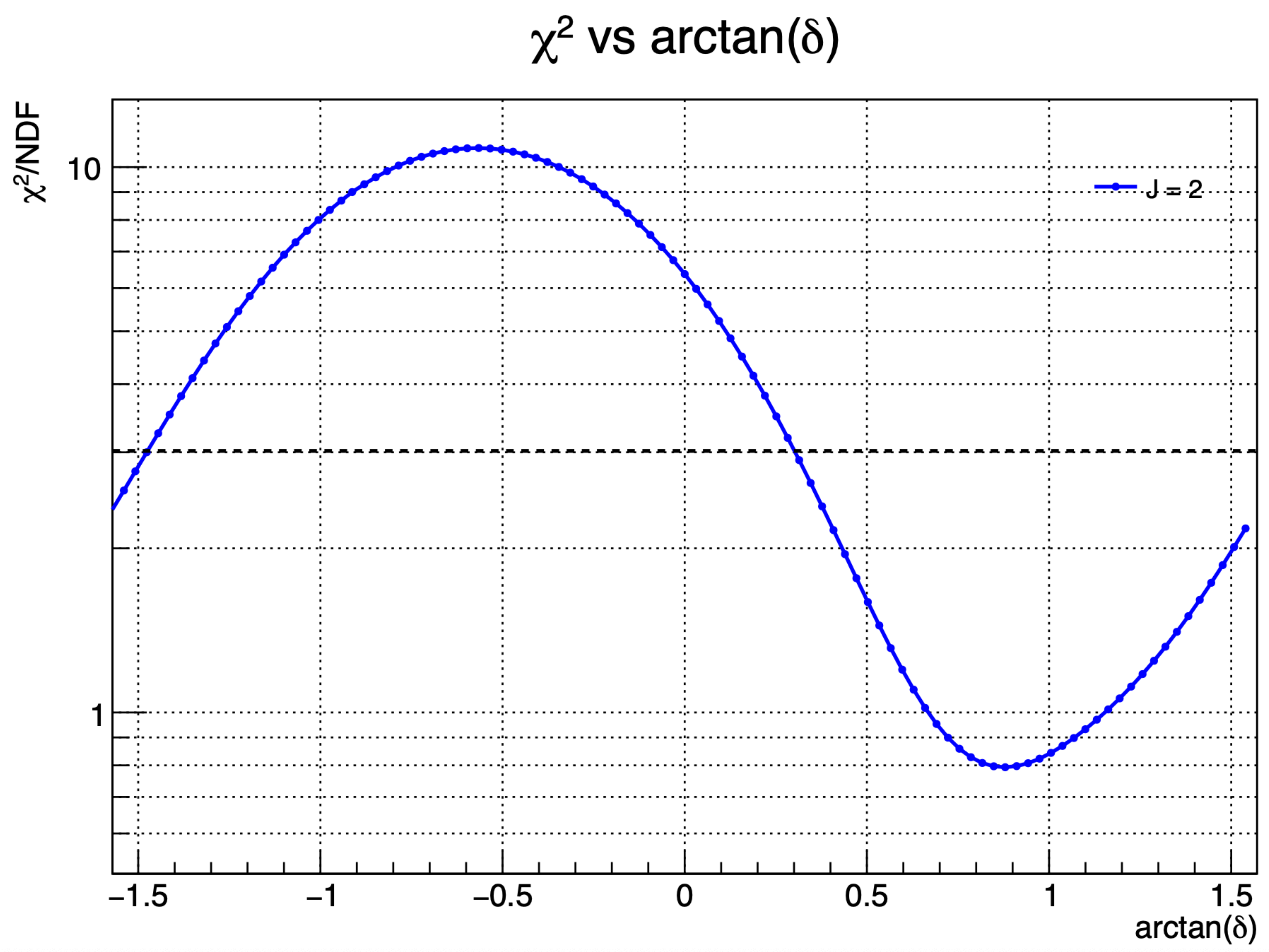


Preliminary Results

J^π assignment and mixing ratio measurement

- We can repeat the analysis for the $2_3^+ \rightarrow 2_2^+$ transition
- The minimum of the χ^2 function is reached for $\delta = 1.2^{+1.0}_{-0.4}$

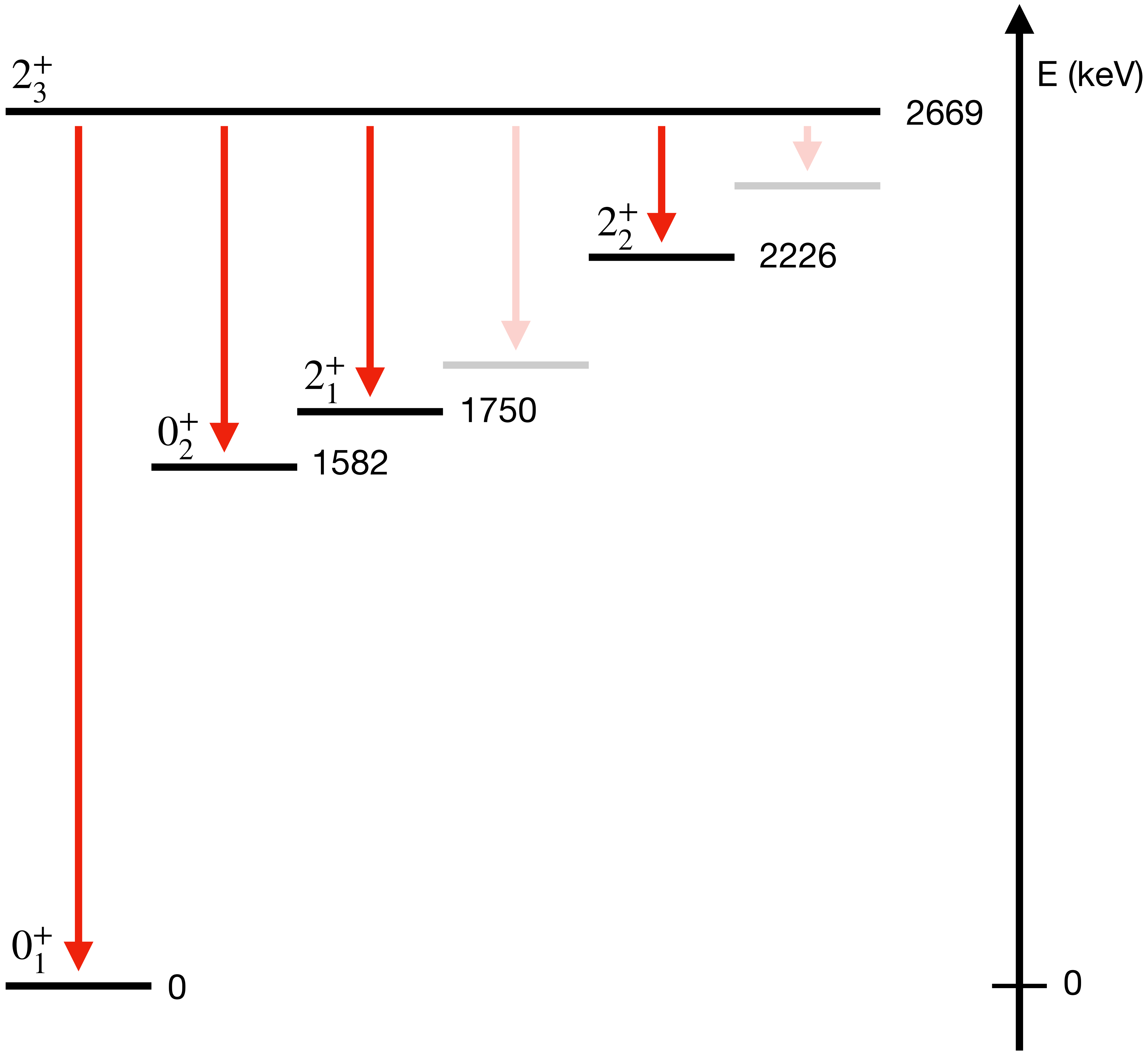




Preliminary Results

B(E2) Values

Transition	Energy (keV)	$\mathrm{B}(E2; 2_3^+ \to X)/\mathrm{B}(E2; 2_3^+ \to 2_1^+)$
$2_3^+ \to 2_2^+$	442.9	> 1
$2_3^+ \to 2_1^+$	918.6	1
$2_3^+ \to 0_2^+$	1087.73	0.023(3)
$2_3^+ \to 0_1^+$	2669.07	0.00022(3)



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Absolute B(E2) values (W.u.)

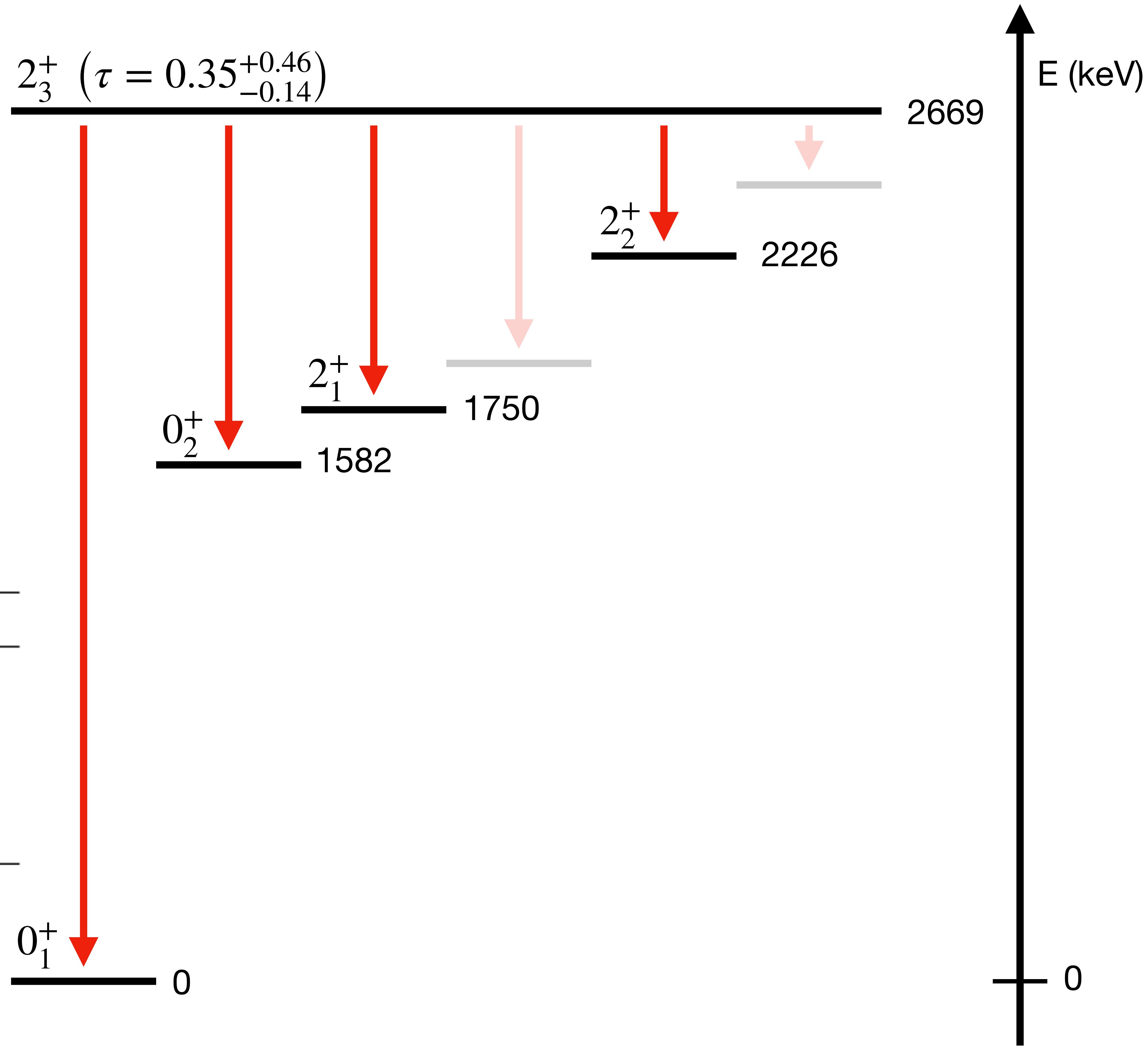
Transition	Energy	This work*	Previous data	Ref. 1	Ref. 2	Ref. 3
$2_3^+ \to 2_2^+$	442.9	> 20	< 400	1.85		39
$2_3^+ \to 2_1^+$	918.6	28^{+24}_{-17}	50(70)	10.6	46	
$2_3^+ \to 0_2^+$	1087.73	$0.6^{+0.5}_{-0.4}$				
$2_3^+ \to 0_1^+$	2669.07	$0.006^{+0.005}_{-0.004}$				

*Large uncertainties due to poorly known lifetime of 2_3^+ state

Ref. 1) E. V. Mardyban et al., PRC 102, 034308 (2020)

Ref. 2) J. E. García-Ramos and K. Heyde, PRC 100, 044315 (2019)

Ref.3) N. Gavrielov et al., PRC 105, 014305 (2022)



Summary

- A β-decay experiment aimed at measuring crucial observables in $^{96}\mathrm{Sr}$ and $^{96}\mathrm{Zr}$ was performed at TRIUMF laboratories
- The high statistics allowed for two rich datasets to be obtained
- Preliminary values of mixing ratios, branching ratios and transition strength concerning the 2_3^+ state of $^{96}\mathrm{Zr}$ have been measured, of particular interest for better understanding the structure based on the 0_2^+ state

Thank you for your attention!

Tommaso La Marca[1], Zarin Ahmed[2], Corina Andreoiu[3], Dominic Annen[3], Heinz Asch[3], Abraham A. Avaa[4], Gordon Ball[4], Giovanna Benzoni[5], Soumendu Bhattacharjee[6], Harris Bidaman[2], Vinzenz Bildstein[2], Samantha Buck[2], Robin Coleman[2], Ethan D. Geerlof[4], Sophia Devinyak[4], Iris Dillman[4], Jackson Dowie[7], Roger Caballero Folch[4], Eric Gyabeng Fuakye[8], Fatima Garcia[9], Adam Garnsworthy[4], Paul Garrett[2], Beau Greaves[10], Chris Griffin[4], Annabelle Lee Grimes[4], Gwen Grinyer[8], Gregory Hackman[4], Sally Hicks[7], Devin Hymers[2], Desislava Kalaydjieva[2], Ritu Kanungo[4], Kushal Kapoor[8], Vasil Karayonchev[11], Eva Kasanda[2], Wolfram Korten[12], Samantha Lange[2], Brian Lenardo[13], Lwazikazi Maqungo[14], Naomi Marchini[15], Ben Marlow[4], Matthew Martin[3], Konstantin Mashtakov[2], Javier R. Murias[4], Sivlia Murillo-Morales[4], Adriana Nannini[15], Connor Natzke[4], Bruno Olaizola[16], Kevin Ortner[3], Erin Peters[7], Costel Petrarche[17], Marta Polettini[5], Carlotta Porzio[9], Allison Radich[2], Glenn Richardson[18], Marco Rocchini[19], Nastaran Saei[8], Magda Satrazani[20], Marcus Scheck[21], Marco Siciliano[10], Mukhwinder Singh[22], Pietro Spagnoletti[3], Carl Svensson[2], Emily Taddei[3], Guillem Tocabens[12], Diego Torres[23], Smarajit Triambak[24], Rashmi Umashankar[25], Sally Valbuena[2], Victoria Vedia[4], Frank Wu[3], Tammy Zidar[2], Magda Zielinska[12!]

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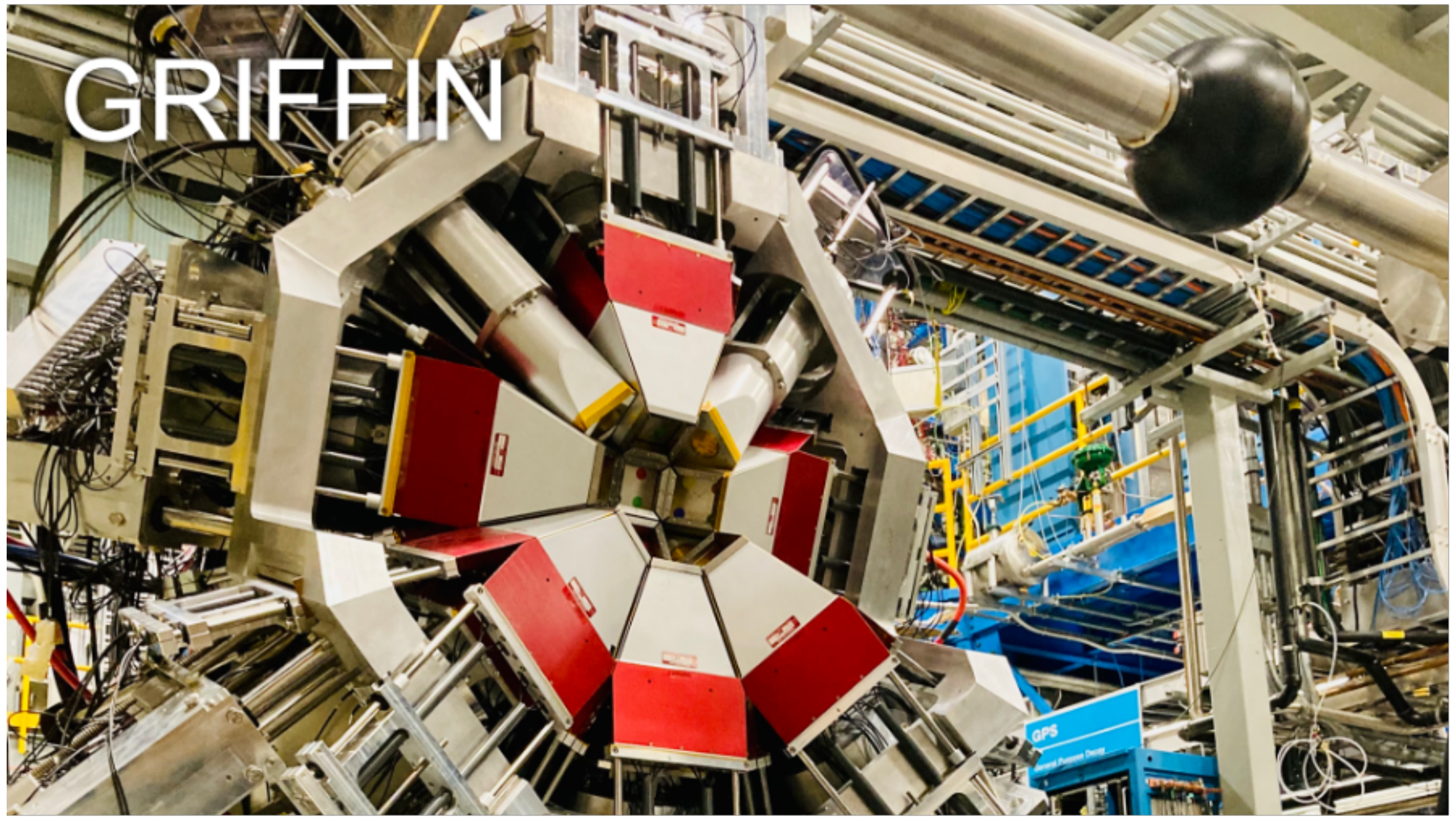
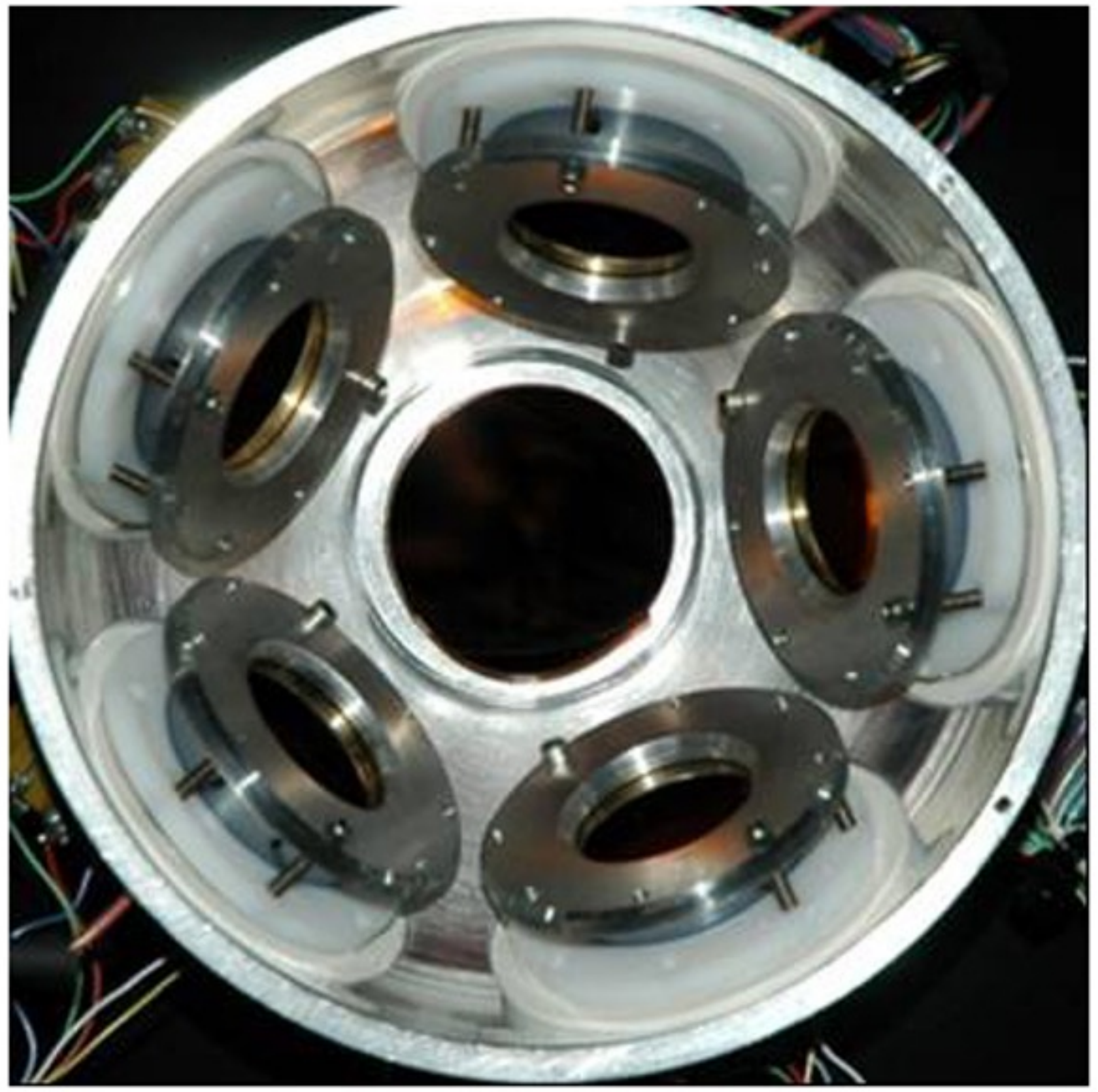
GRIFFIN

- Array of 64 HPGe crystals with Compton shields
- Angular coverage: 4π sr
- Energy resolution: 1.89 keV at 1.3 MeV
- Efficiency: ~12% at 1.3 MeV



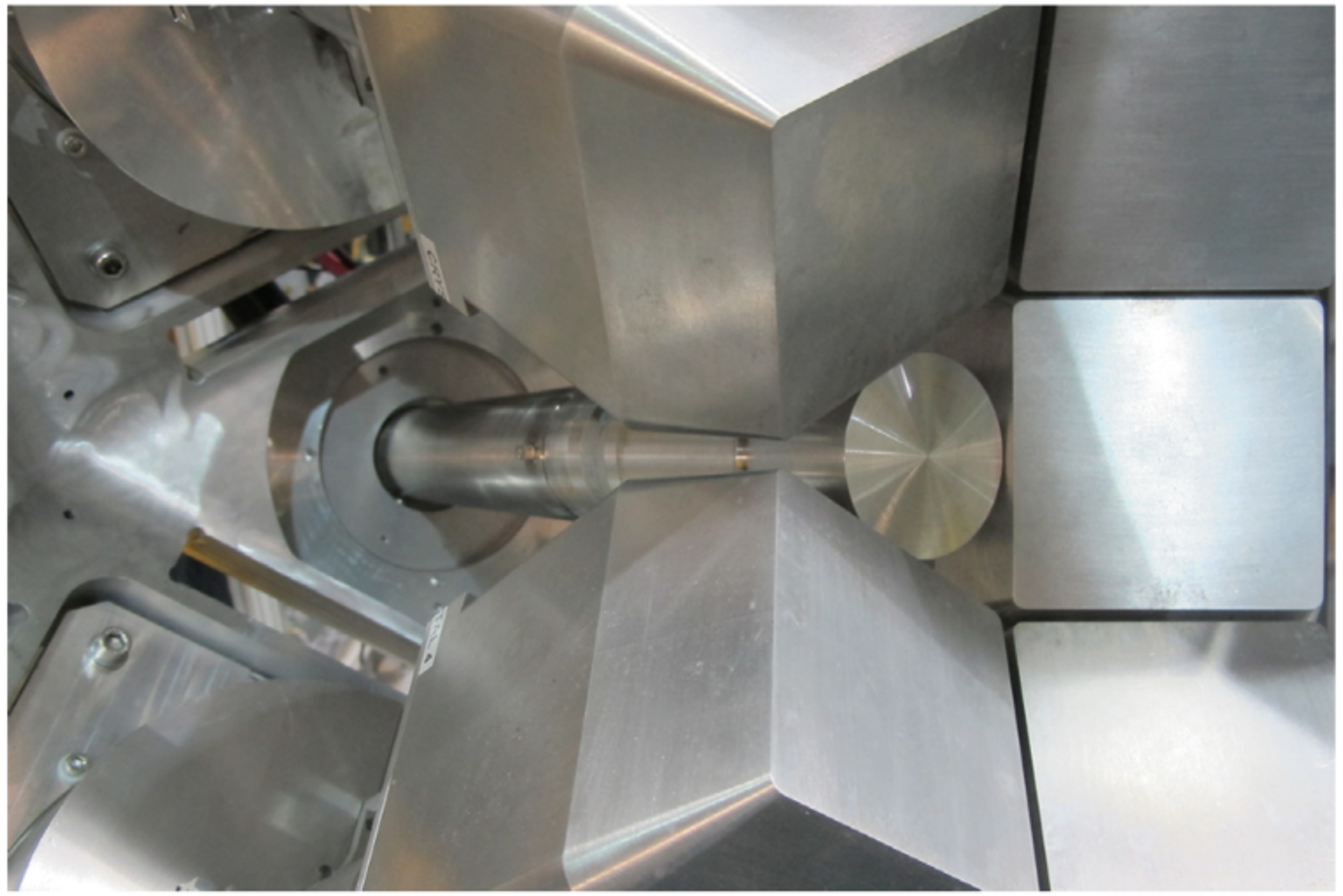
PACES

- Array of 5 Si(Li) detectors
- Angular coverage: 7.4% of 4π
- Energy resolution: 2.5 keV at 1 MeV
- Absolute efficiency: 4% at 1 MeV
- Punchthrough: 2 MeV



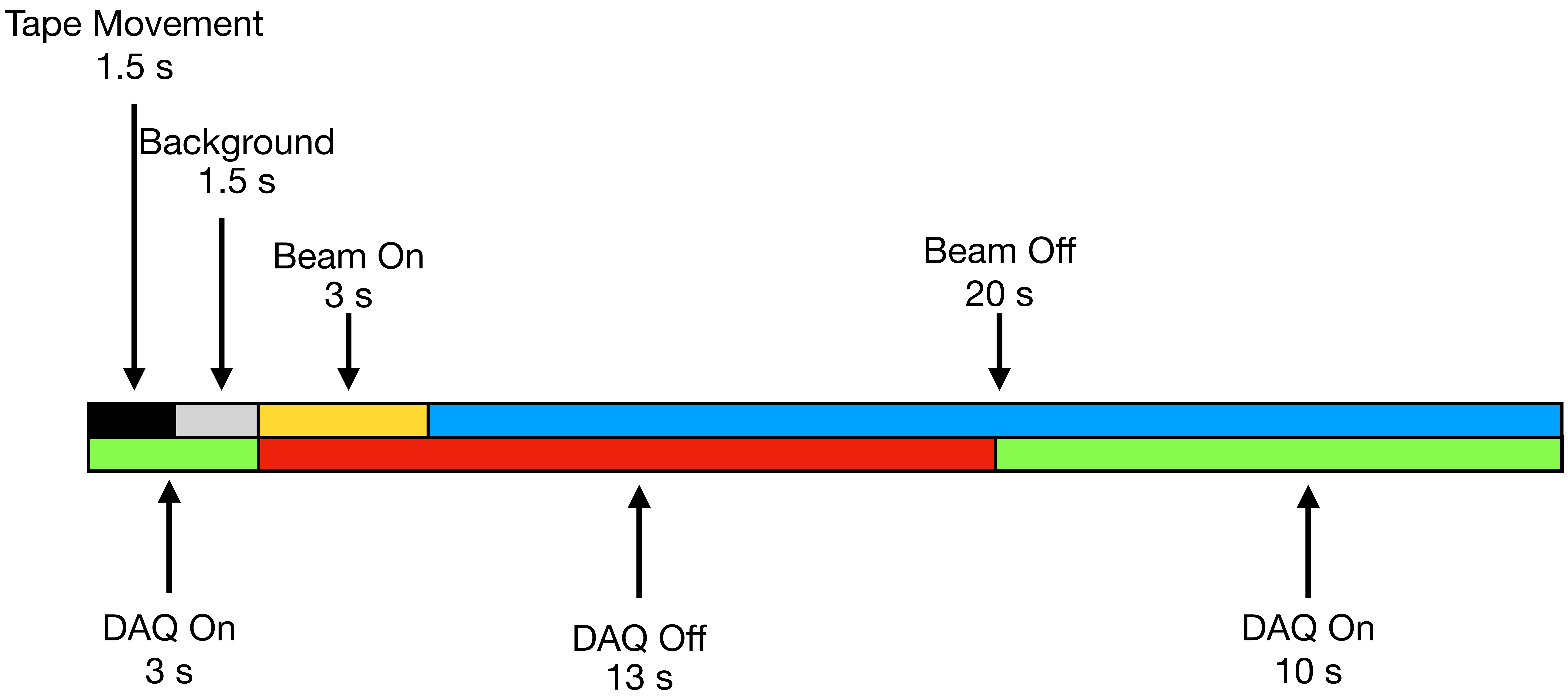
LaBr3(Ce)

- Array of 8 $LaBr_3(Ce)$ scintillators
- Dimensions of crystals: 5.1cm diameter and 5.1 cm length
- Energy resolution: ~20 keV at 662 keV
- Time resolution: ~330 ps



Experiment Description

Tape Cycle and Data Acquisition



Preliminary Results