

Connecting experimental observables in low-energy nuclear physics to the strong interaction

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Heavy Ion Accelerators



National Research
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National
University**

Fundamental Problems in Subatomic Physics

Sep 23 – 27, 2026
Novotel Cairns Oasis Resort
Australia/Brisbane timezone

Enter your search term 

Overview

Important dates

Scientific Program

Call for Abstracts

Timetable

Registration information

Registration

Visa information

Accommodation

Social events

Contribution List

Scientific Program

The aim of this workshop is to bring together people working on challenges at the frontier of subatomic physics from a variety of different directions. Over the past 30 years, the CSSM has held more than 40 workshops and conferences, and the cross-fertilisation of ideas in a collegial environment has often led to unexpected advances.

In this workshop the topics covered will range from lattice QCD to perturbative QCD, from models of the QCD vacuum to QCD phenomenology and experiments, from effective theories to physics beyond the Standard Model, especially the nature of dark matter and its detection. The scope of the conference also includes the interface between QCD, nuclear physics and astrophysics, **nuclear structure** and reactions, hadron structure and spectroscopy (including DIS, GPDs and TMDs), as well as the application of new tools, such as AI, across these fields.

While the genesis of the workshop was the celebration of many years of scientific cooperation between Australia and Japan, and especially 25 years since CSSM hosted the first workshop outside of Japan on the physics of what was to become J-PARC, we look forward to a multi-national exchange of ideas which will help to drive our field forward.

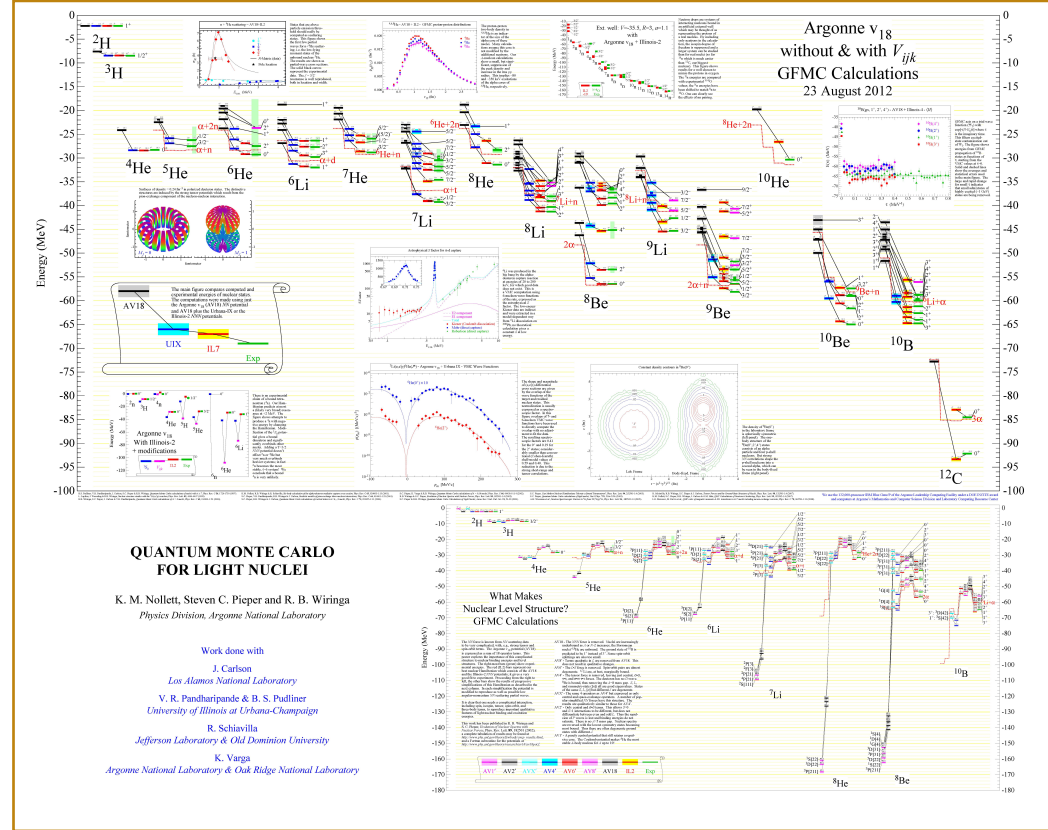
The diversity of topics to be covered is represented by the wide range of subject areas to be discussed, as shown in the list below.

ab initio theory for nuclear structure (and beyond)

2012: The Argonne group demonstrated that a Hamiltonian consisting of the **Argonne v18 (NN)** + **Illinois-2 (NNN)**, reproduced the observed spectra of light nuclei remarkably well.

AV18 provided an exceptionally accurate ‘realistic phenomenological’ description of NN interactions.

IL.2 showed the importance of NNN terms in describing nuclear structure.



<https://www.anl.gov/phy/manybody-theory>



ab initio theory for nuclear structure (and beyond)

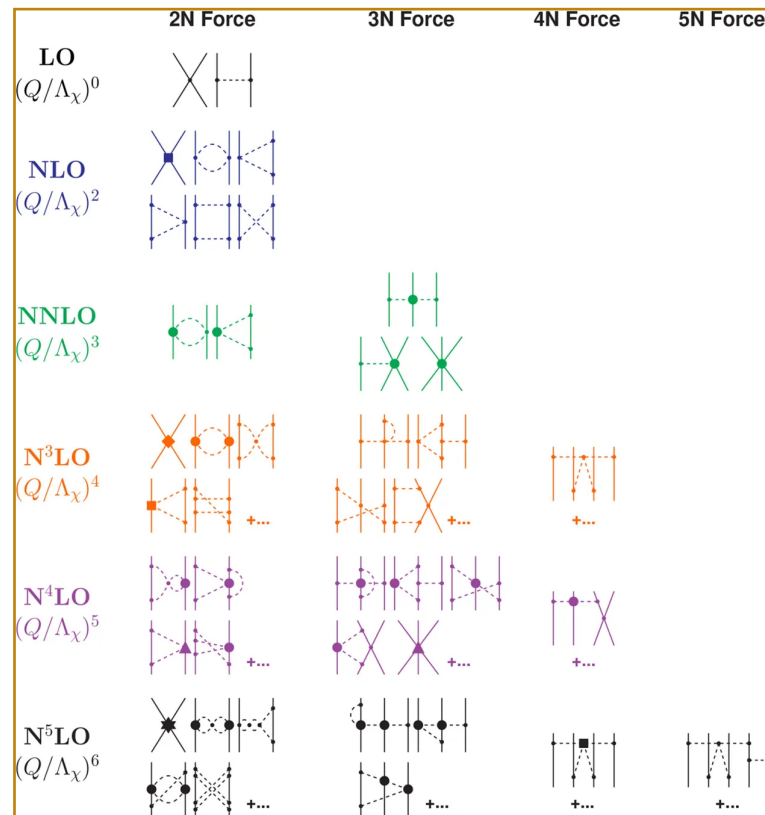
Modern view of the NN interaction is given in the framework of **Chiral Effective Field Theory (χ EFT)**.

Fundamental theory is given by Quantum Chromodynamics (QCD). However for nuclear systems, the relevant degrees of freedom are nucleons and pions, not quarks and gluons.

Chiral EFT uses the symmetries of QCD, especially chiral symmetry, to construct nuclear forces in a systematic expansion.

Natural hierarchy of forces emerges:

- NN forces dominate
- 3N forces appear at higher order
- 4N forces are even smaller



Rodrigues et al Front. Phys. **8** 57 (2020). doi: 10.3389/fphy.2020.00057

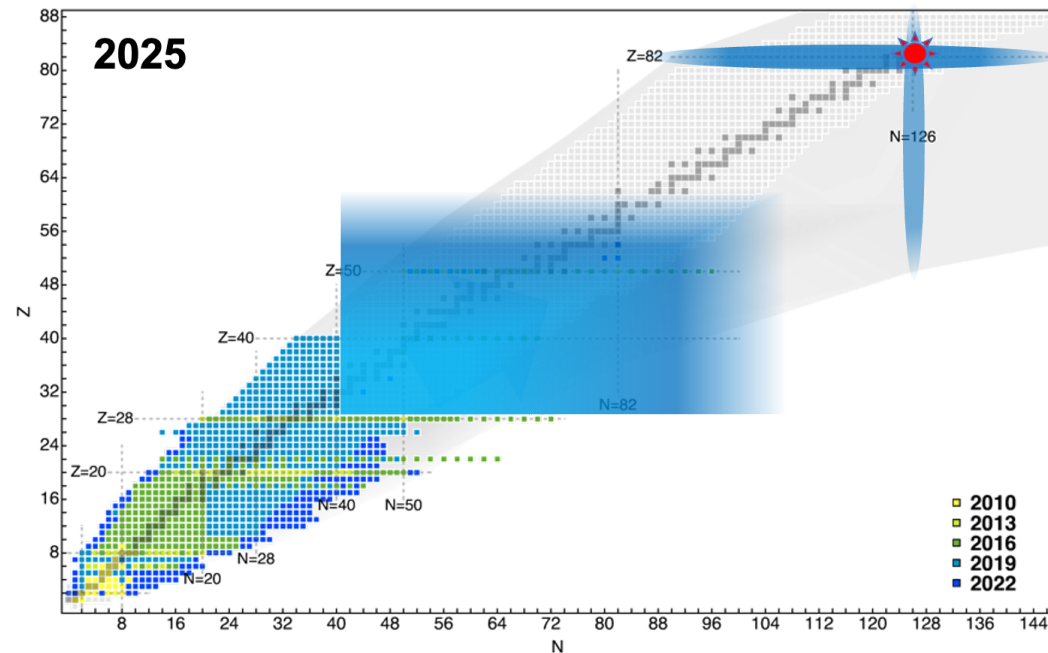


New many-body methods (Coupled Cluster, IMSRG, SCGF, NCSM, QMC) dramatically increased the range of nuclei accessible to first-principles calculations.

Most nuclei are **open-shell systems**, where strong correlations make direct ab initio calculations computationally demanding.

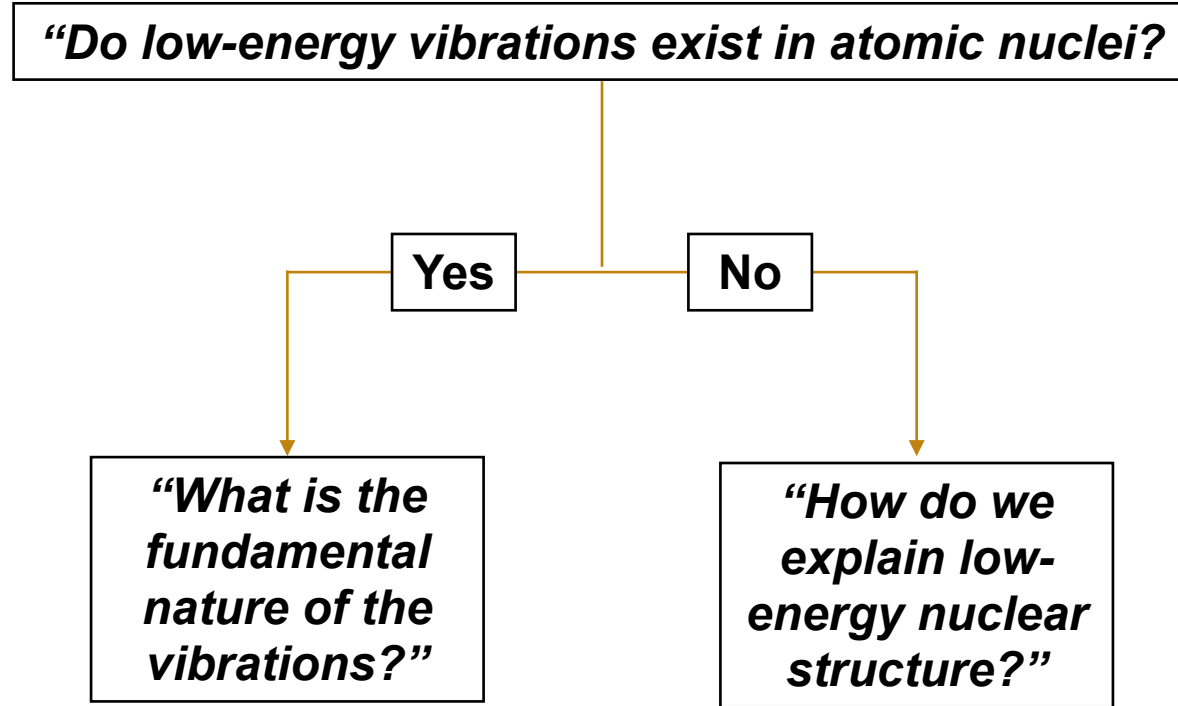
Valence-Space IMSRG (VS-IMSRG) uses continuous unitary transformations to derive an **effective shell-model Hamiltonian directly from chiral NN+3N interactions**, enabling large-scale spectroscopy calculations in open-shell nuclei.

Extended the reach of ab initio calculations to essentially all light- and medium-mass nuclei.



The frontier has shifted from describing nuclei to understanding emergence: **how do collective degrees of freedom arise from microscopic nuclear interactions?**





Collective models of atomic nuclei

- Bohr and Mottelson Volume 2
- Controversy #1 - nuclear shape coexistence
- Controversy #2 - triaxial rotations vs surface oscillations

Experimental probes to test/constrain models

- Rotational example: ^{162}Dy
- Vibrational example: ^{124}Te



Nobel Prize in Physics 1975



Photo from the Nobel Foundation archive.

Aage Niels Bohr

Prize share: 1/3

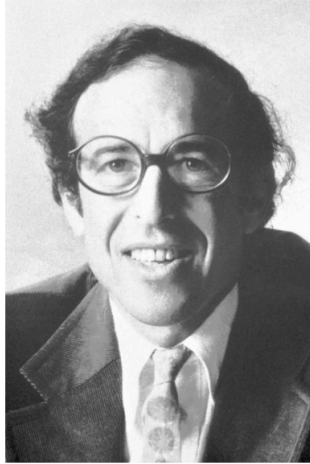


Photo from the Nobel Foundation archive.

Ben Roy Mottelson

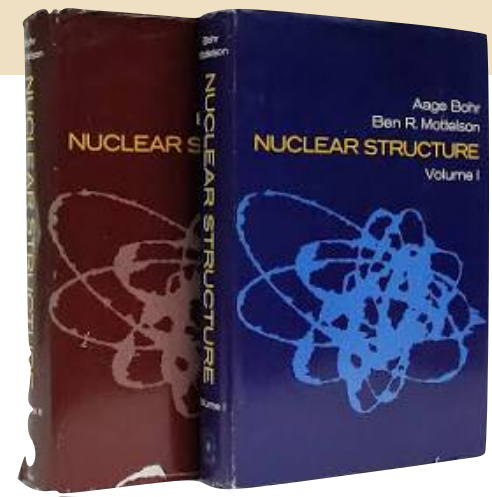
Prize share: 1/3



Photo from the Nobel Foundation archive.

Leo James Rainwater

Prize share: 1/3

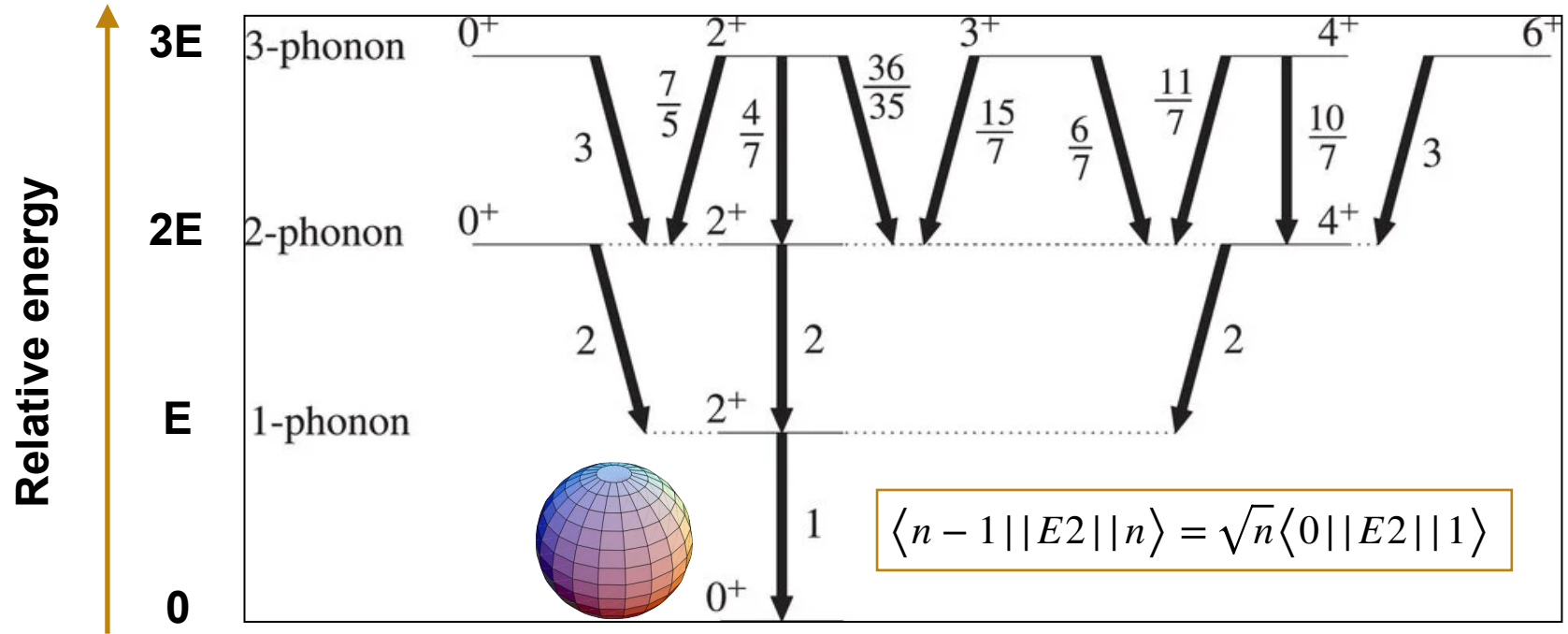


“for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection.”

<https://www.nobelprize.org/prizes/physics/1975/summary/>



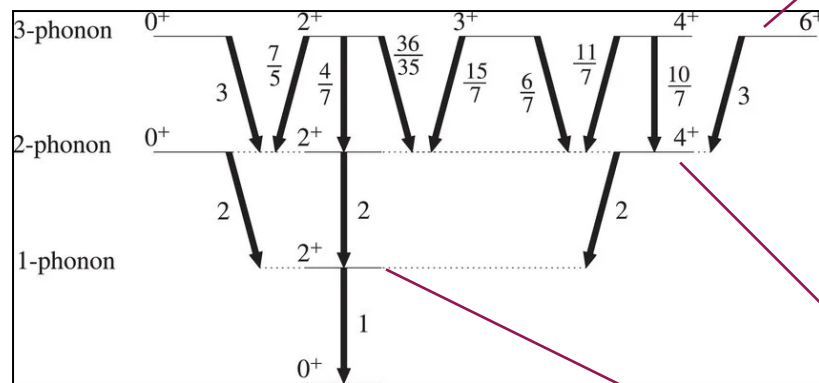
'Vibrations' of spherical ground states



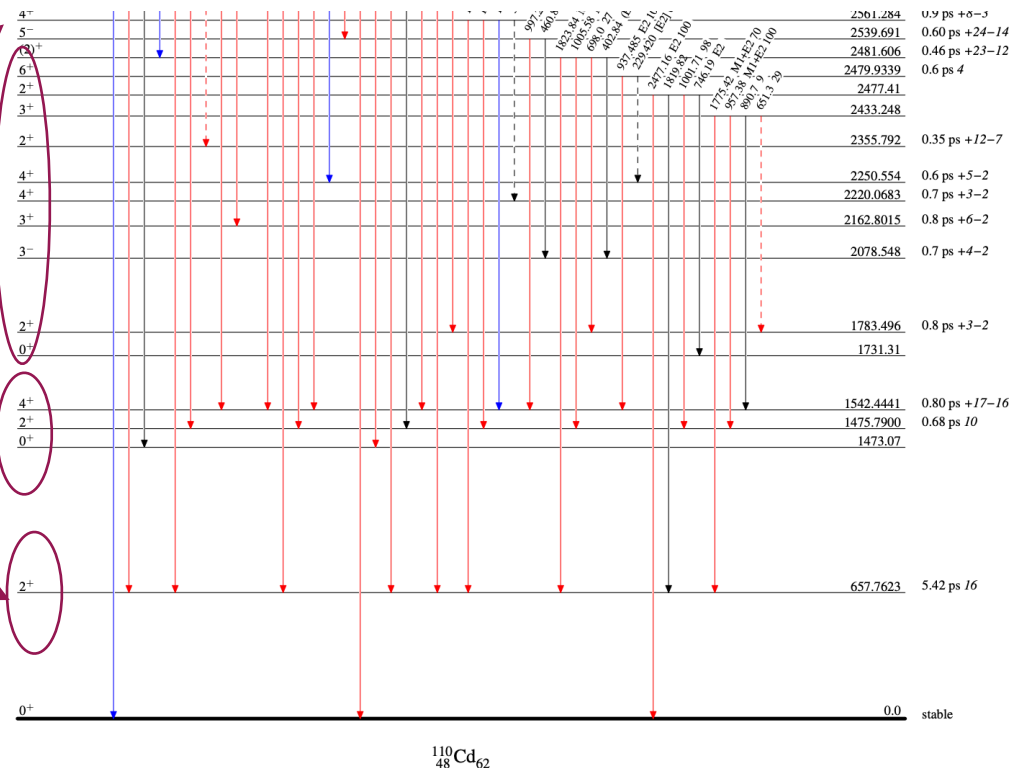
Bohr and Mottelson considered the **observation of multi-phonon states** and their **enhanced E2 transition strengths** to be the decisive evidence for vibrational motion.



'Vibrations' of spherical ground states

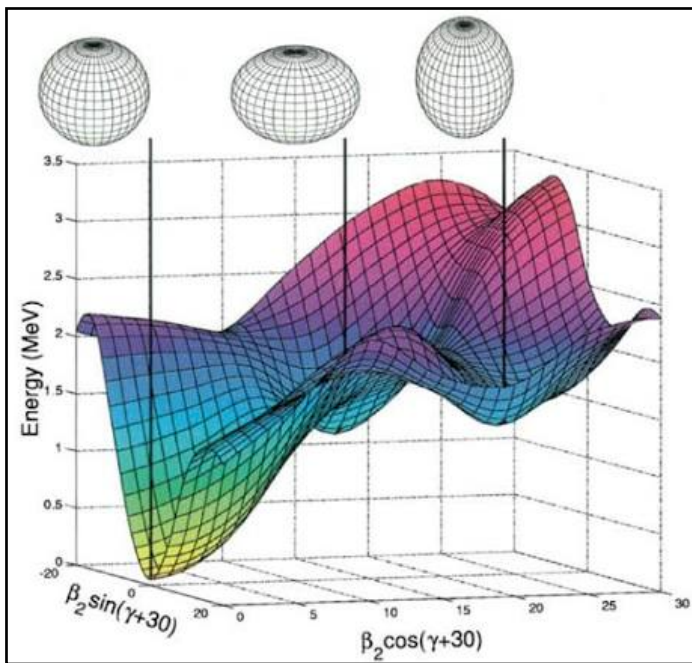


Cd isotopes often presented as 'textbook' examples of vibrational nuclei

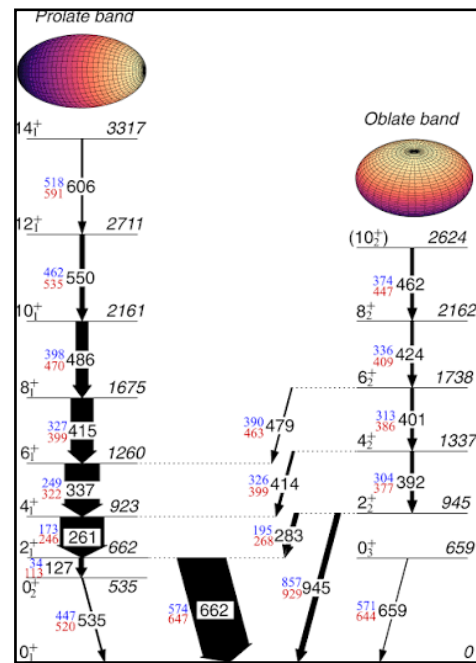


Controversy #1: Shape coexistence

Pb-186

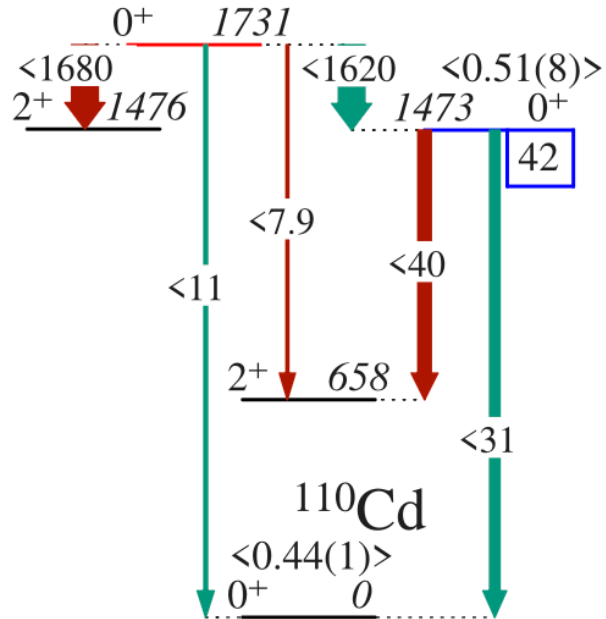


Nature **405**, 430–433 (2000).
<https://doi.org/10.1038/35013012>

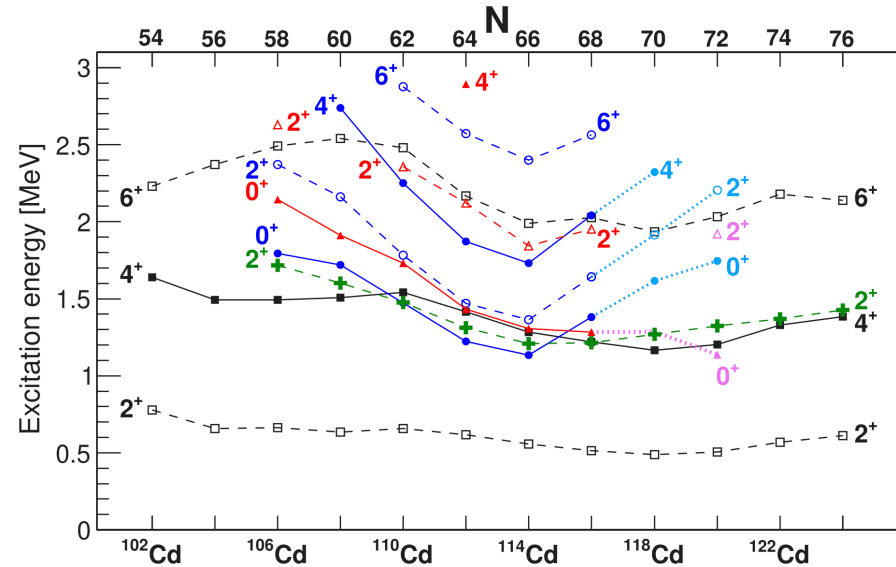


Commun Phys **5**, 213 (2022).
<https://doi.org/10.1038/s42005-022-00990-4>





- Strong population of 0_2^+ in two-proton transfer
- Weak population of 0_2^+ in two-neutron transfer
- Different quadrupole moment to 0_1^+

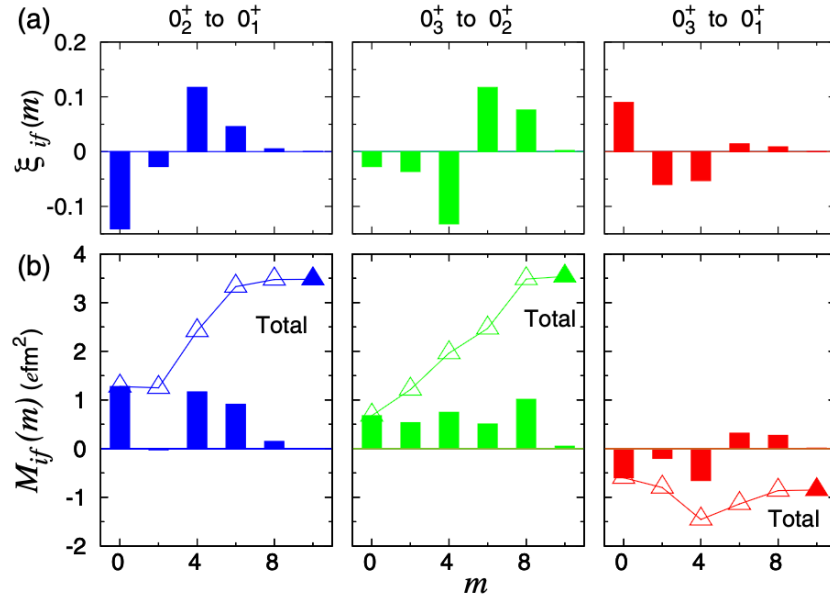
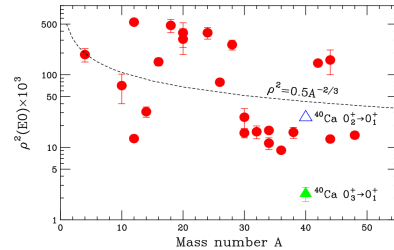
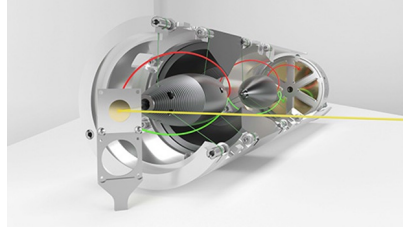
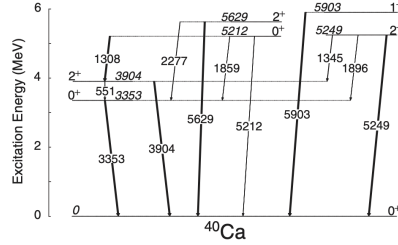


Shape coexistence often manifests as a parabola in the excitation energies of excited states across an isotopic chain.

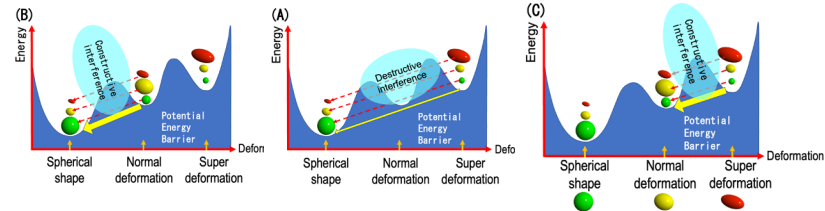
Intruder configurations are lowered towards mid-shell by increasing correlation energy, producing a characteristic minimum where competing shapes become nearly degenerate and strongly mixed.

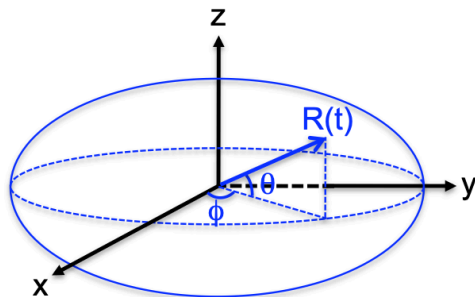


EXPERIMENT

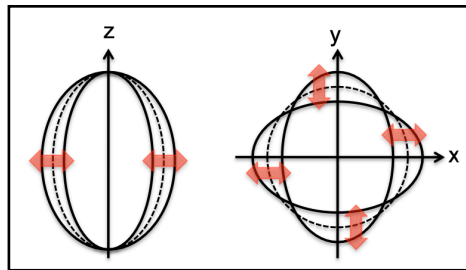


THEORY

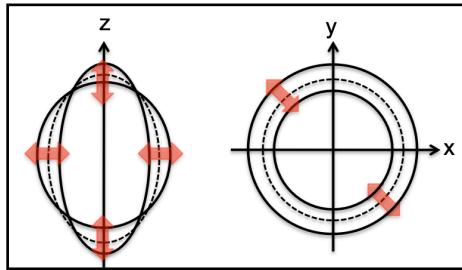




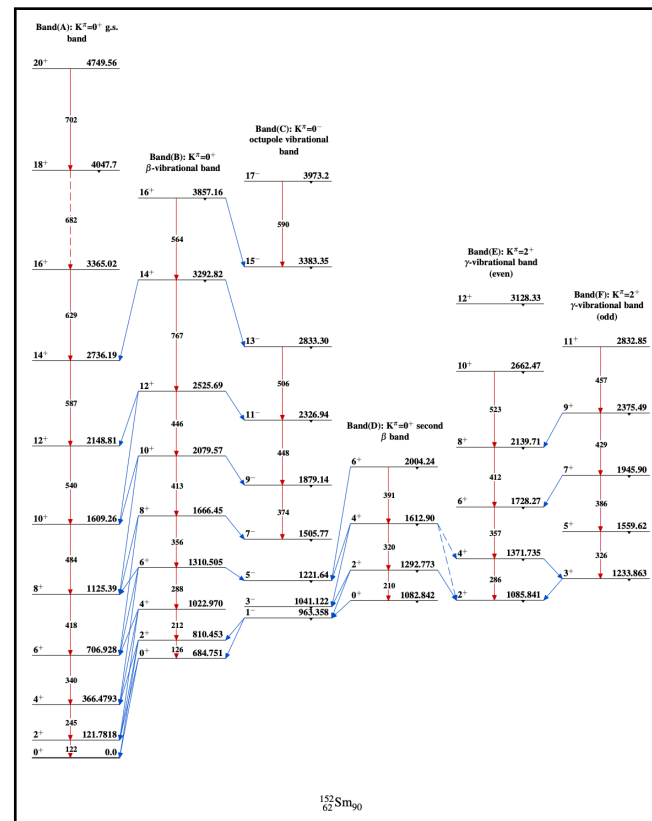
$$R(\theta, \phi) = R_0 \left\{ 1 + \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} \alpha_{\ell,m} Y_{\ell,m}(\theta, \phi) \right\}$$



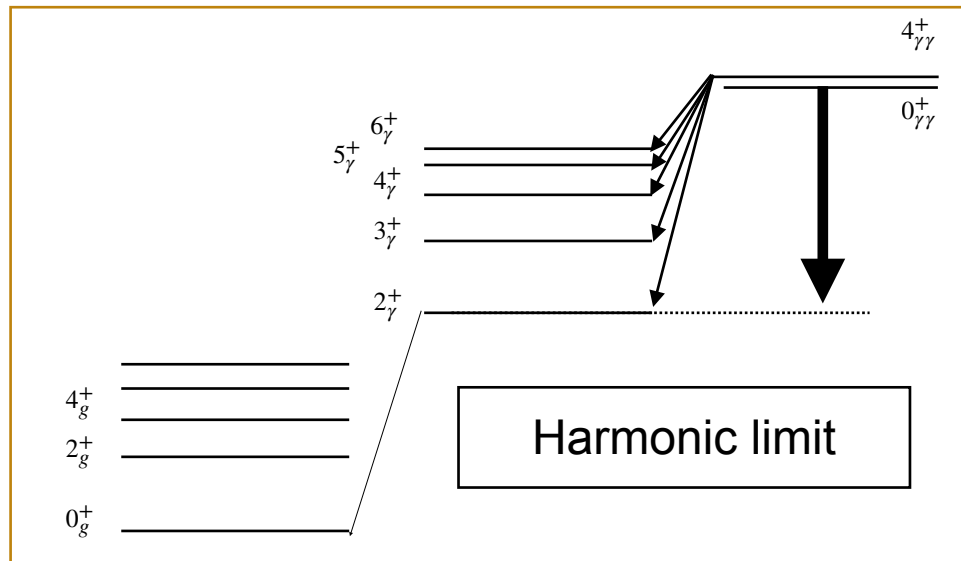
"Gamma"



"Beta"

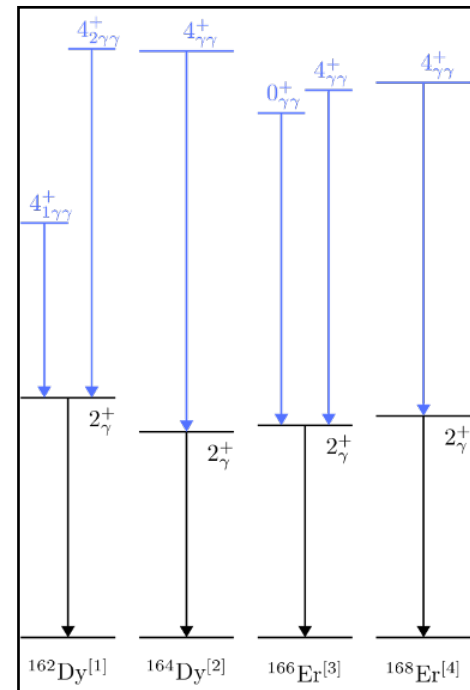


Experimental constraints of nuclear-structure theory



Vibrations model predicts:

- 0_γ^+ strongly decays to 2_γ^+ .
- $B(E2; 4_\gamma^+ \rightarrow 2_\gamma^+, 3_\gamma^+, 4_\gamma^+, 5_\gamma^+, 6_\gamma^+)$ follows 7:10:9:6:3.
- $B(E2; 4_\gamma^+ \rightarrow 2_\gamma^+)/B(E2; 2_\gamma^+ \rightarrow 0_g^+) = 2.78$

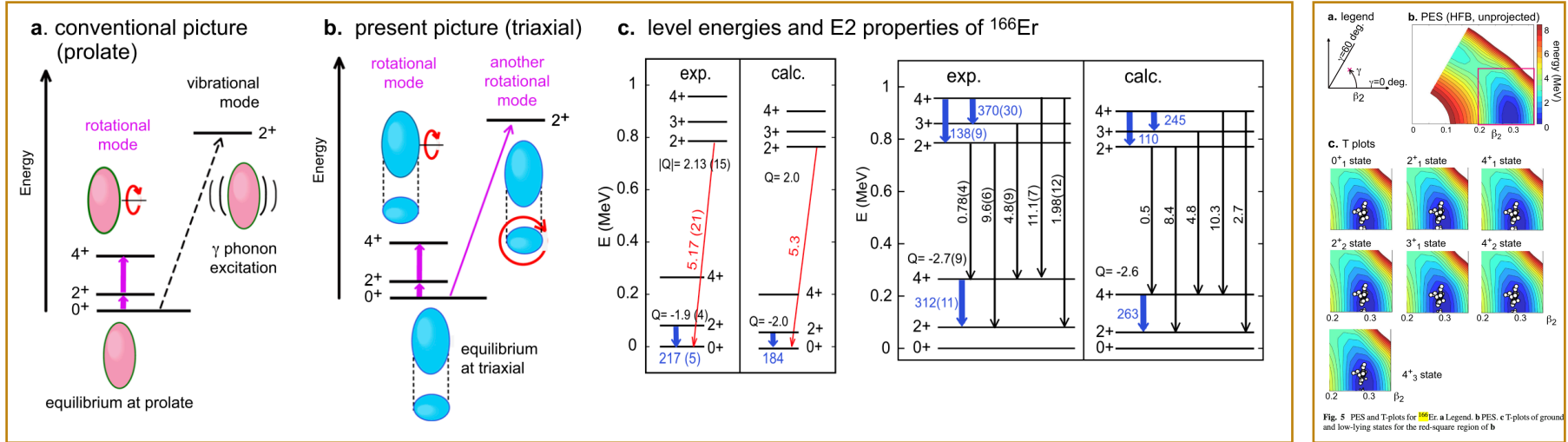


- [1] C. Y. Wu et al., Phys. Rev. C, vol. 64, no. 6, 2001.
 [2] F. Corminboeuf et al., Phys. Rev. C, vol. 56, no. 3, 1997.
 [3] C. Fahlander et al., Phys. Lett.B, vol. 388, no. 3, 1996.
 [4] H. G. Börner et al., Phys. Rev. Lett., vol. 66, 1991.



Controversy #2: Triaxial rotor vs shape oscillations

Recent Monte Carlo Shell Model calculations by Otsuka et al have renewed interest in triaxiality.



<https://doi.org/10.1140/epja/s10050-025-01553-1>

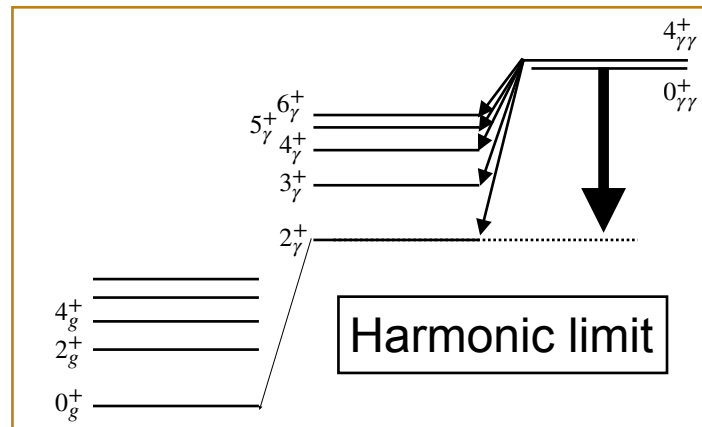
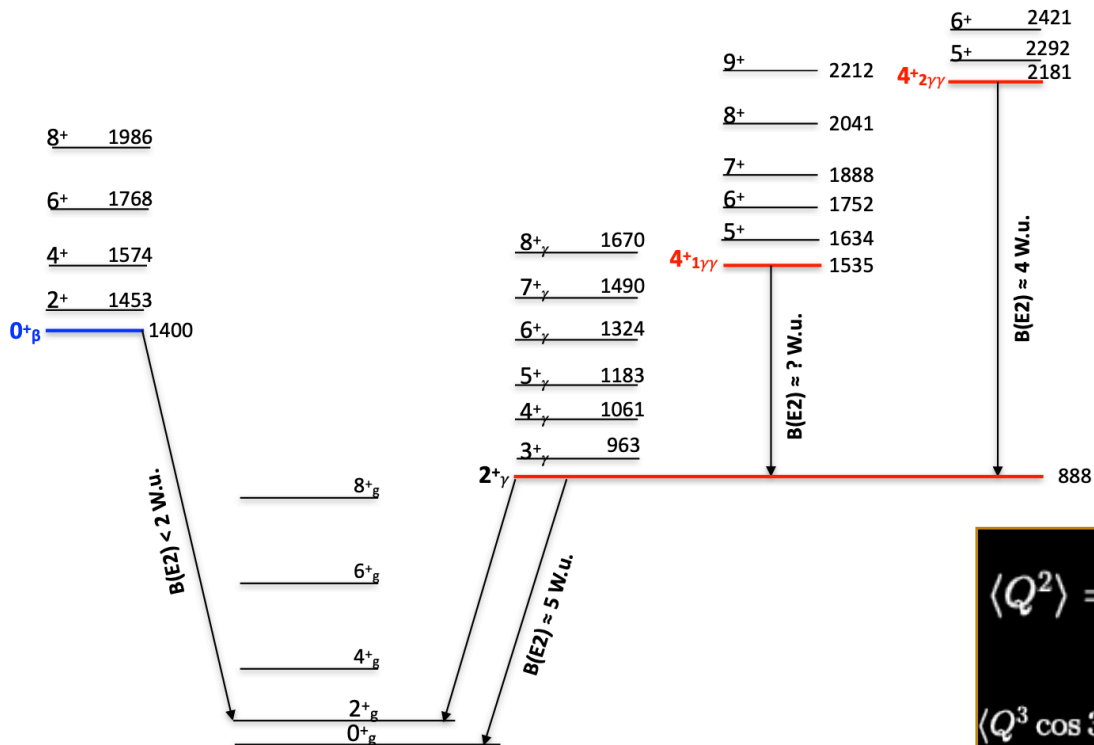
K remains a good approximate quantum number:

- γ and $\gamma\gamma$ bands emerge naturally from triaxial rotation
- No γ -phonon interpretation is required

Are the $K = 4$ bands in ^{162}Dy manifestations of two- γ phonons, or are they rotational excitations of a triaxial shape?



Example: 162Dy

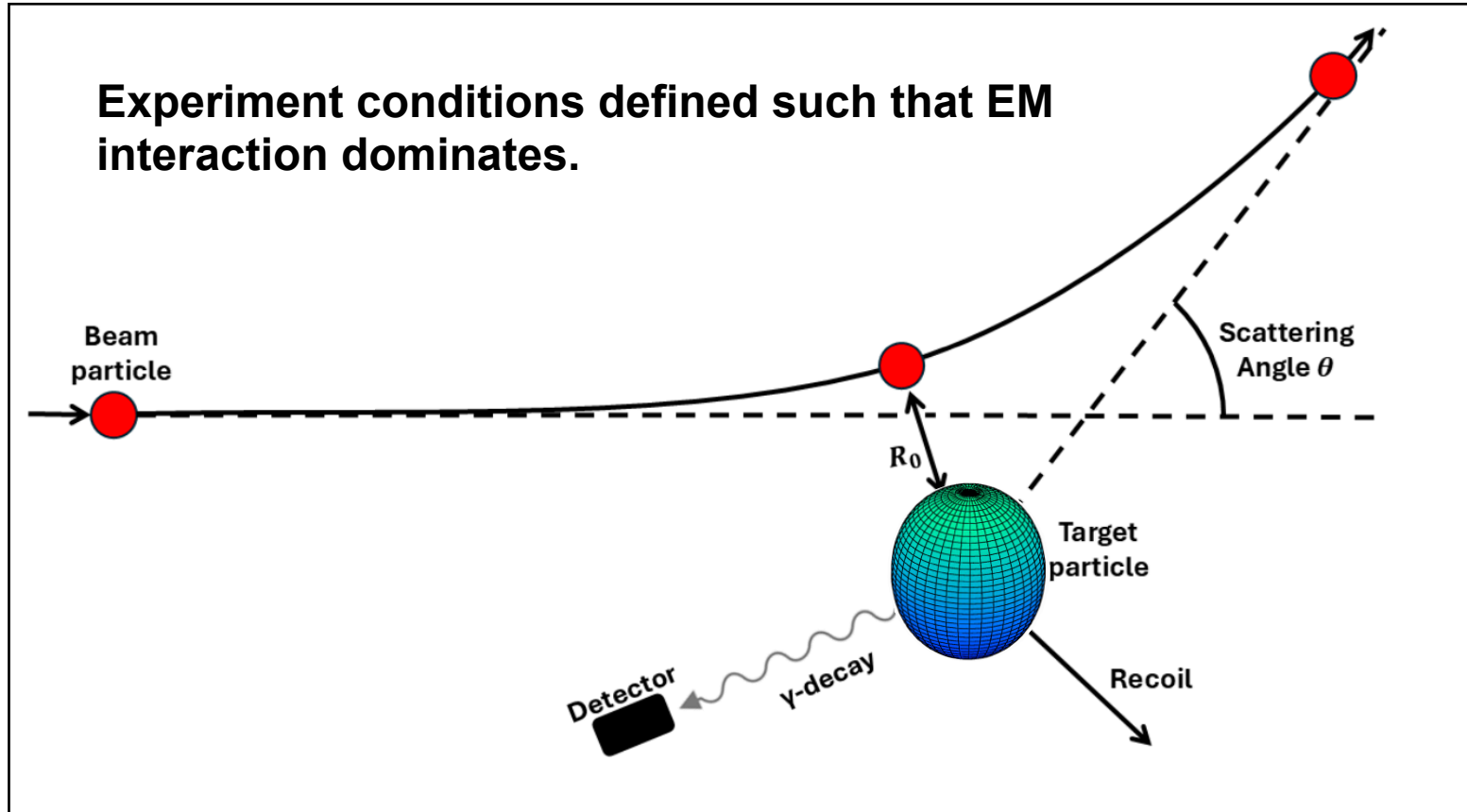


$$\langle Q^2 \rangle = \frac{1}{\sqrt{5}} \sum_i |\langle 0 || E2 || 2_i \rangle|^2$$

$$\langle Q^3 \cos 3\delta \rangle_s = -\sqrt{\frac{7}{10}} \sum_{ij} \langle 0_s || E2 || 2_i \rangle \langle 2_i || E2 || 2_j \rangle \langle 2_j || E2 || 0_s \rangle.$$



Coulomb excitation (Coulex) technique



Coulomb excitation (Coulex) technique

Experiment / User input

Spectroscopic data

Level scheme

Measured gamma-ray yields

Detector geometries

GOSIA

MINIMISATION

Error estimation

RESULTS

Set of matrix elements

Experimental conditions defined by the user
(Level scheme, matrix elements, collision partners, reaction kinematics)

GOSIA solves a set of coupled differential equations for level excitation amplitudes using electromagnetic matrix elements as parameters.

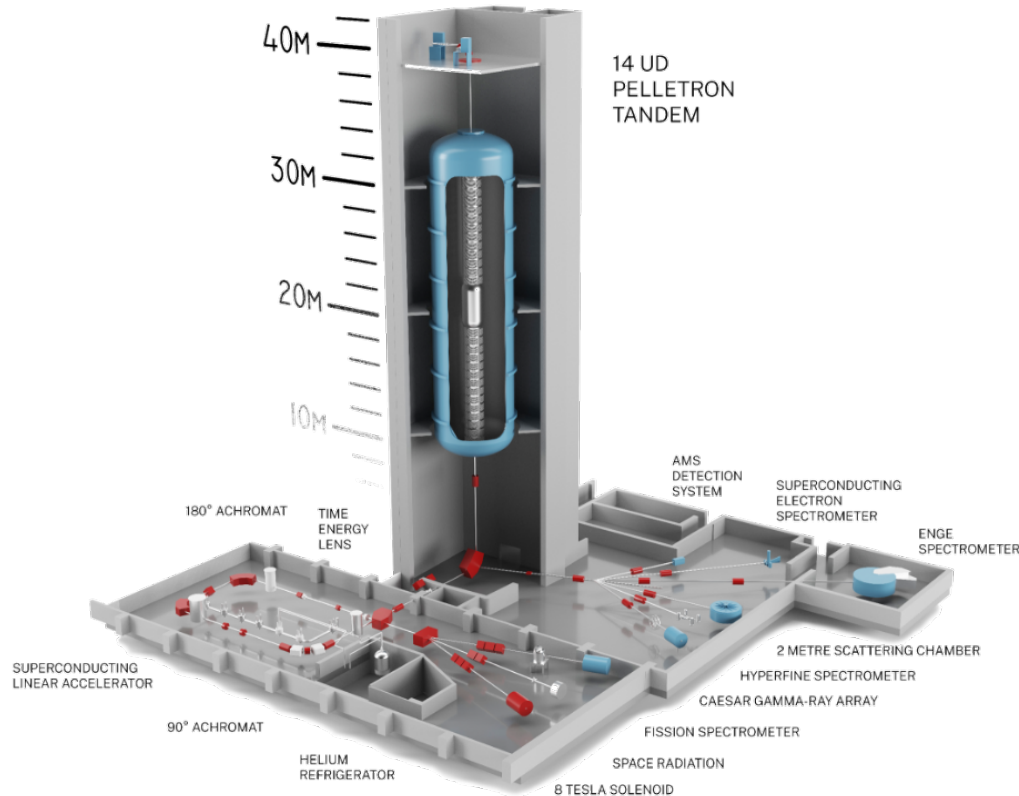
Decay of the populated states is calculated using information provided on detection geometry/efficiency, internal conversion etc.

χ^2 function **comparing calculated and experimental gamma-ray intensities and other spectroscopic data** related to electromagnetic matrix elements, is created and minimised.

A set of matrix elements that optimally reproduces the experimental data corresponds to the minimum of the χ^2 function. Uncertainties are deduced from the shape of the surface.



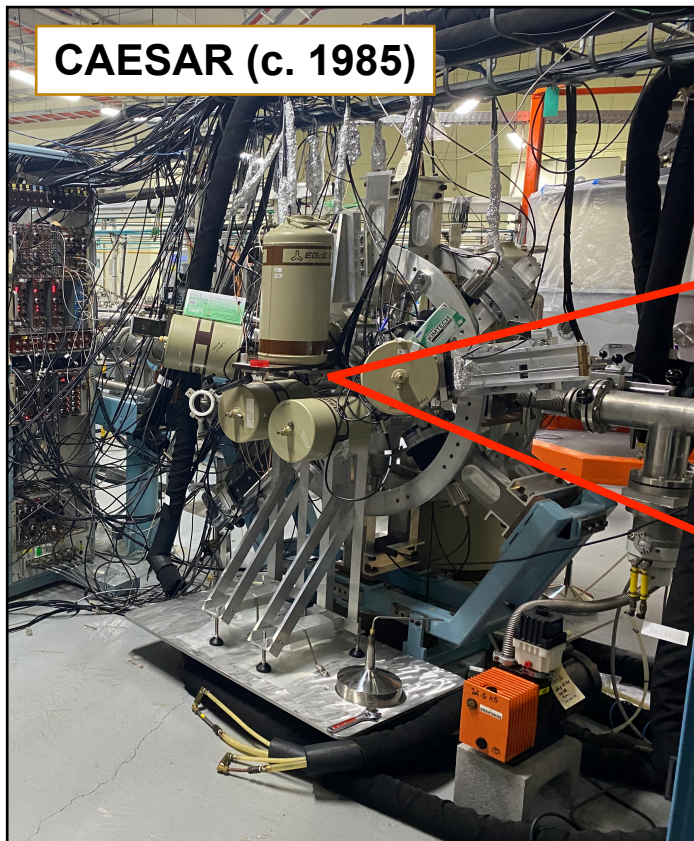
Australian Heavy Ion Accelerator Facility



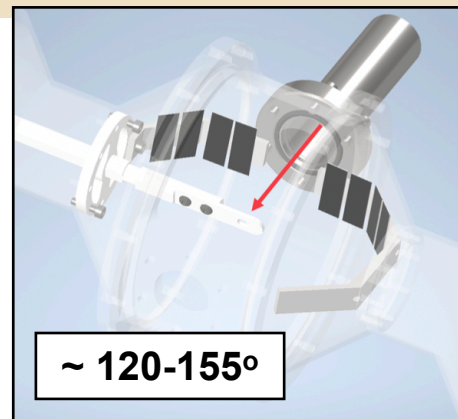
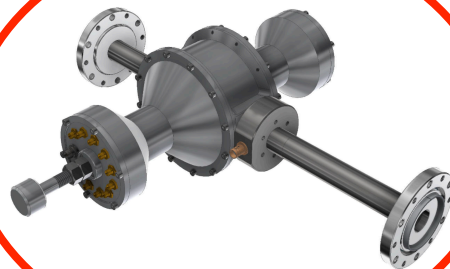
- Upgraded NEC 14UD Pelletron (nominal 15 MV maximum).
- 10+1 end stations across two target areas.
- LINAC superconducting booster
- Two ion sources (soon to be three).
- Protons to plutonium.
- Supports the work of the Department of Nuclear Physics and Accelerator Applications (NPAA) within the Research School of Physics.
- 15 Technical Support Staff
- Academic staff and students are the beam operators.



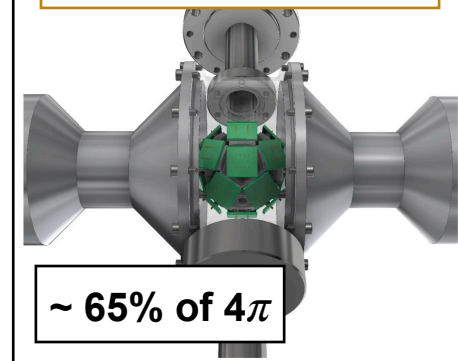
New infrastructure for Coulex @ HIAF



New target chamber (2022)

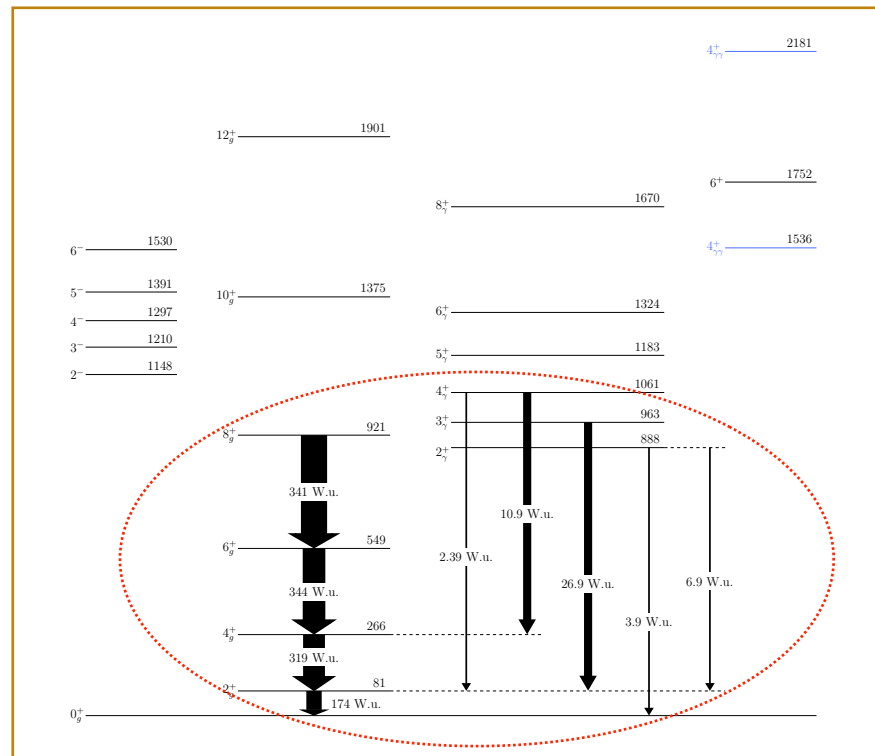
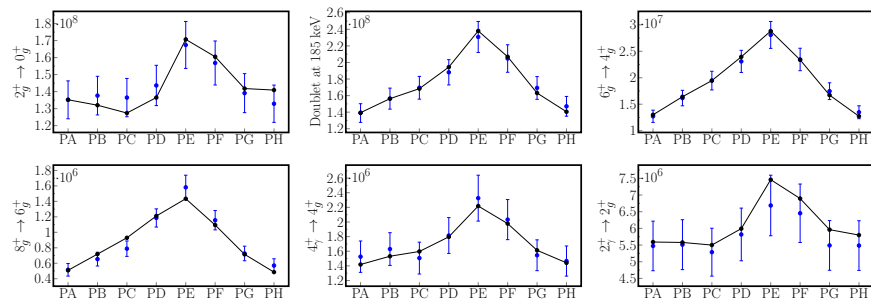
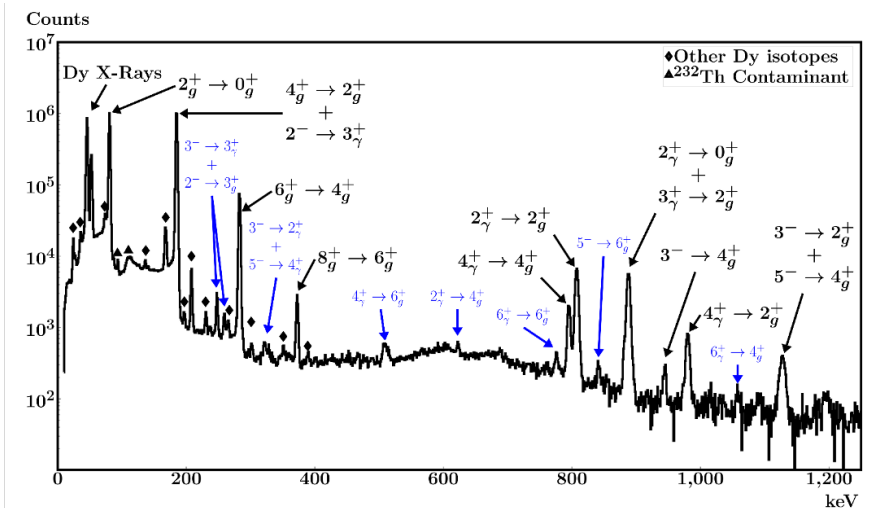


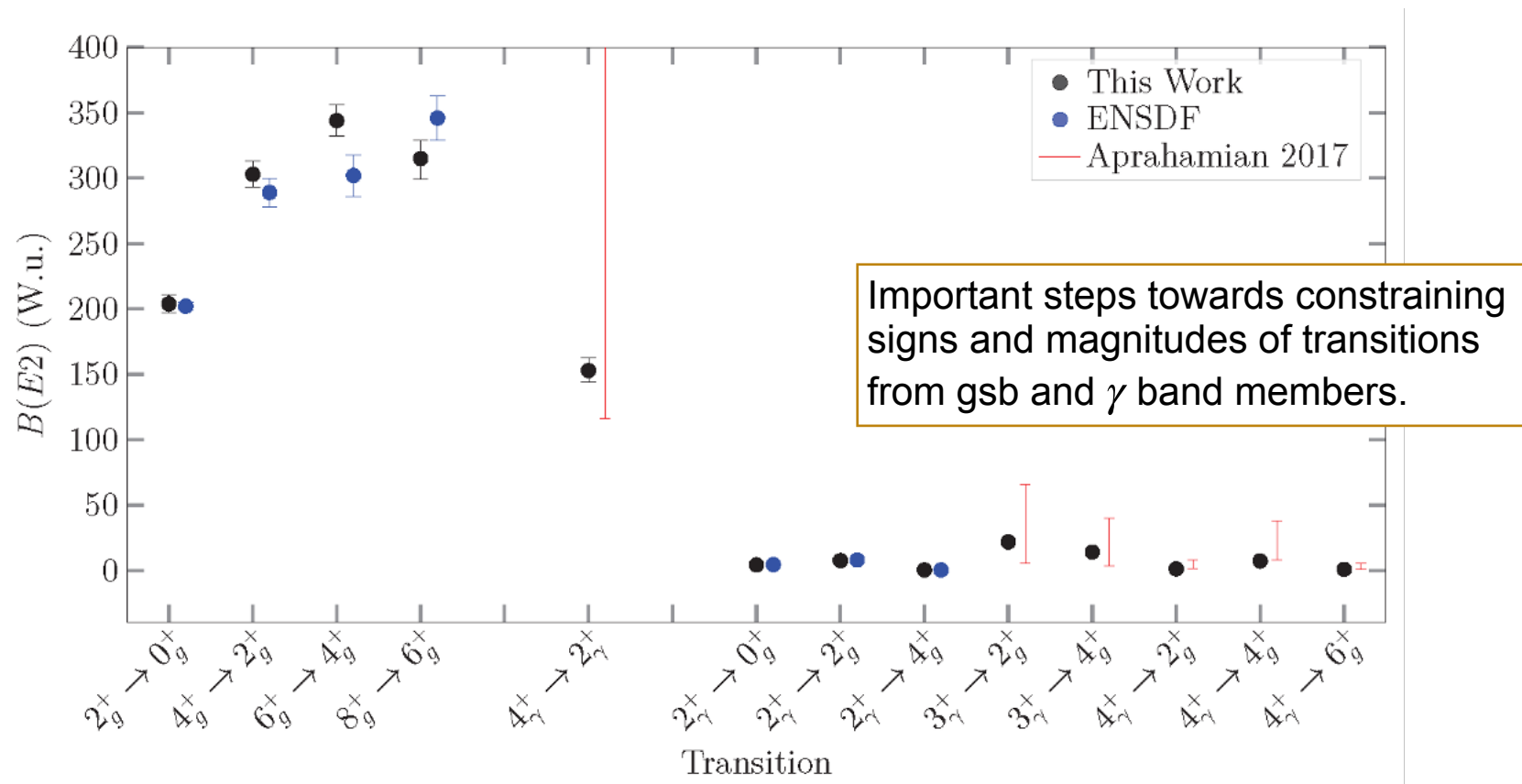
Stage II (2026/27)

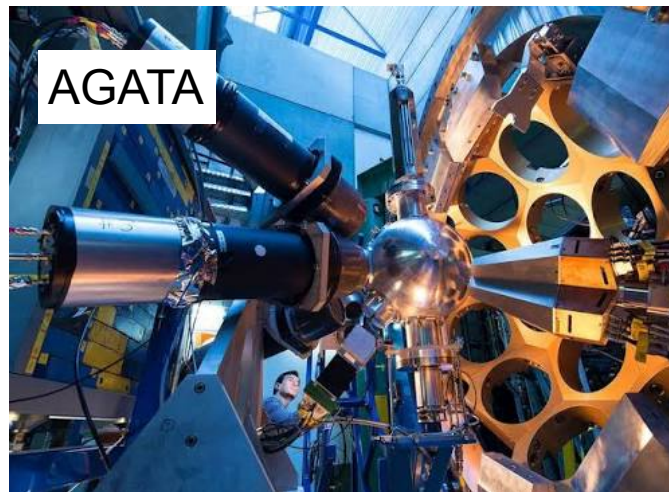


$\sim 65\%$ of 4π

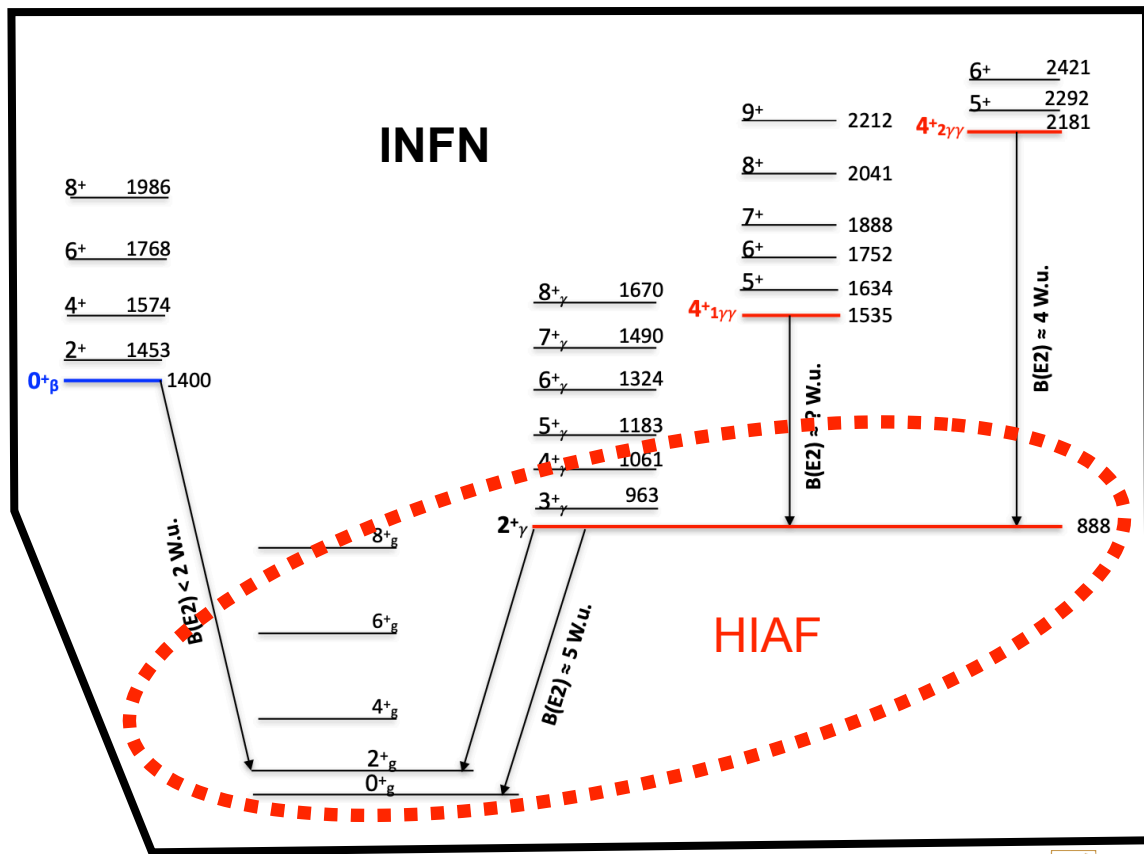


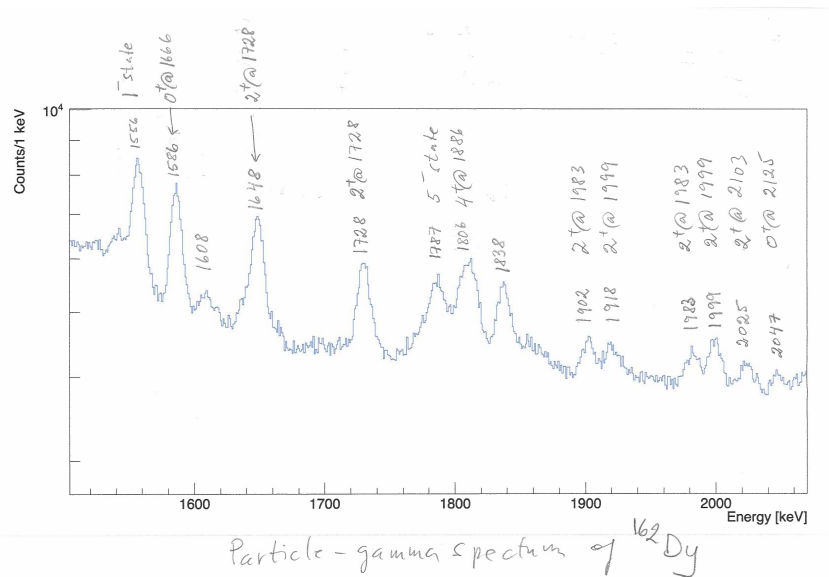




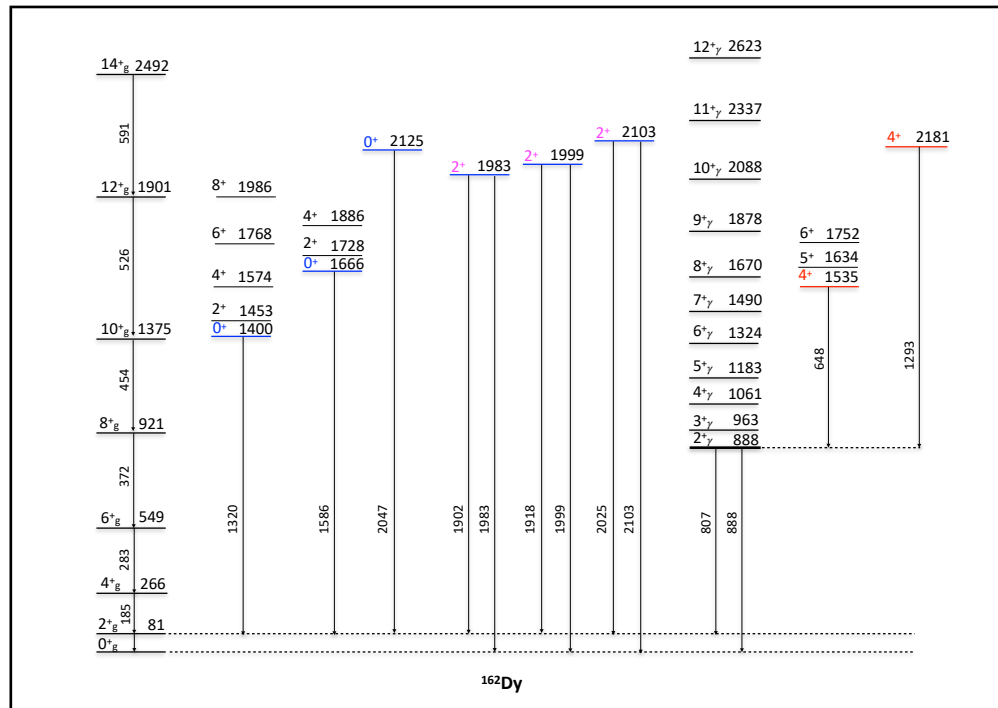


Aiming to determine a complete set of matrix elements constrained through combinations of beams and beam energies at different facilities.



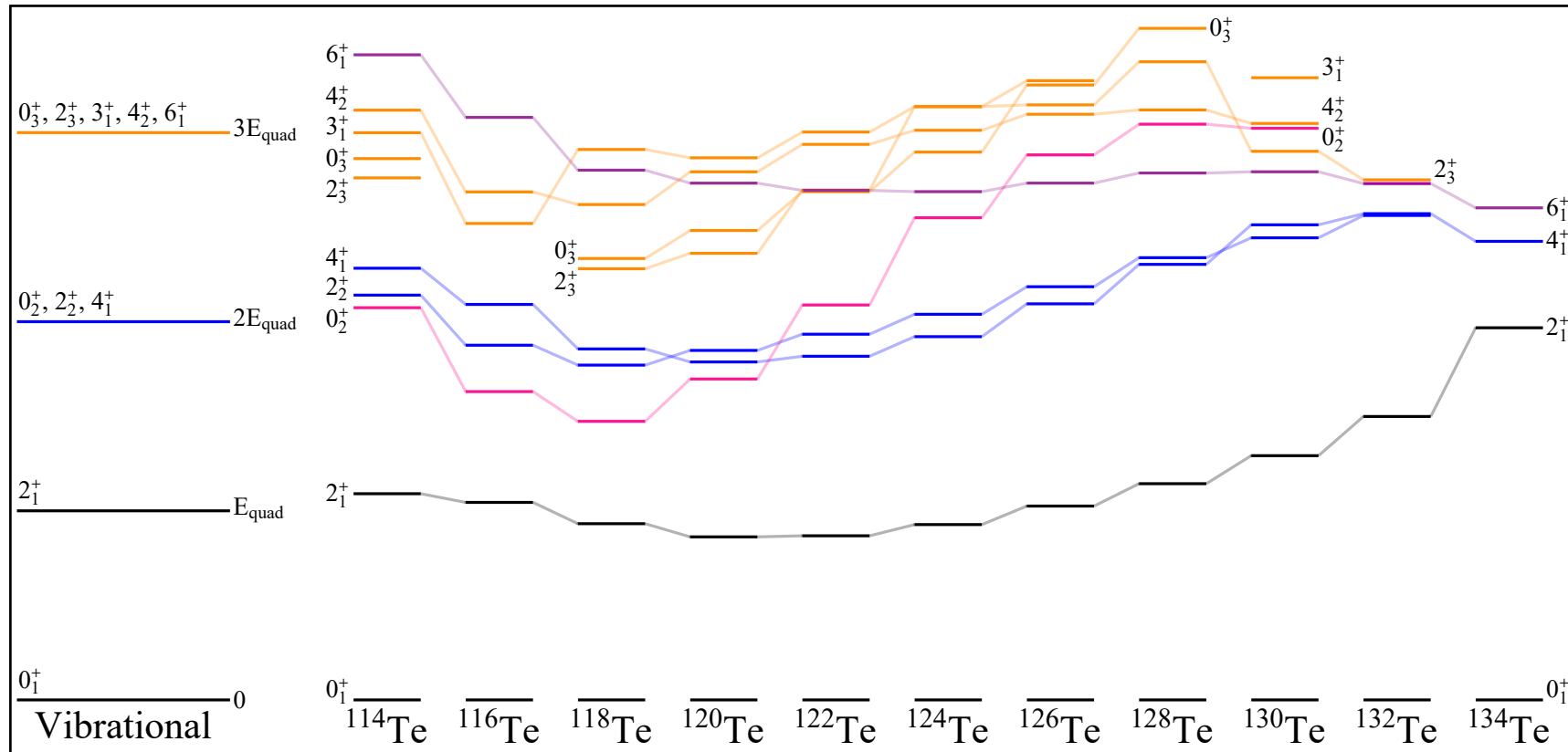


Partial online spectrum



Levels observed (preliminary)



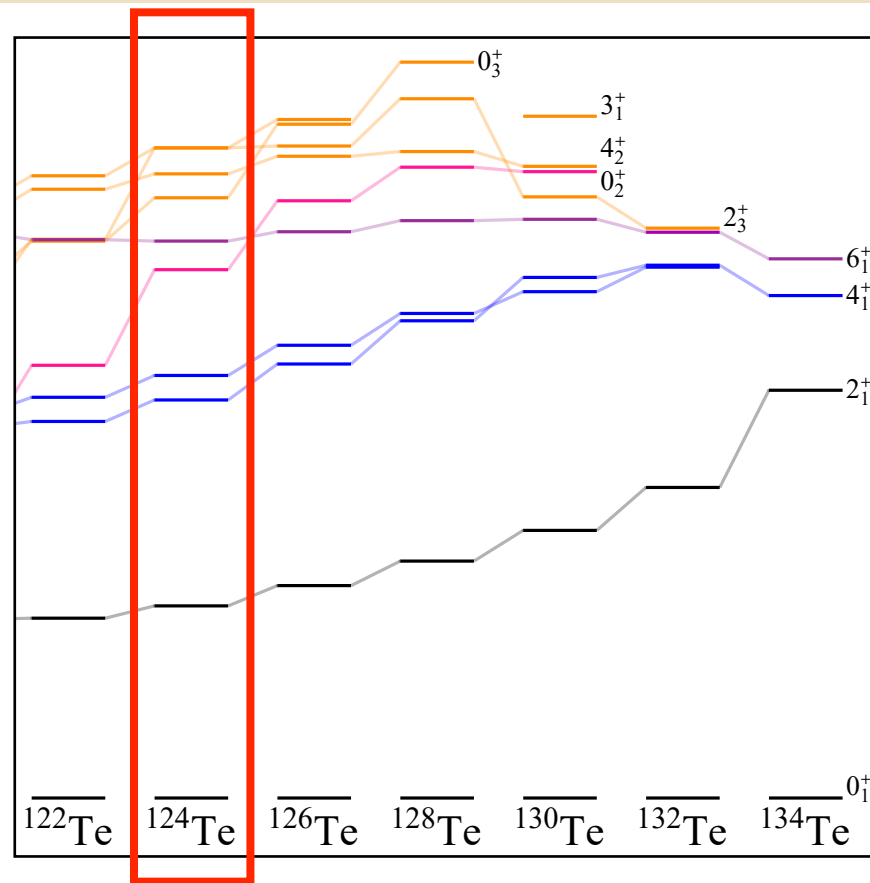


Te-124

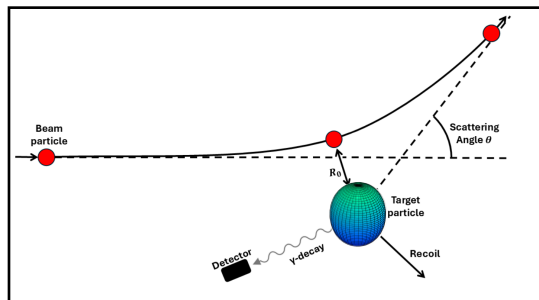
- From mid shell, it is the lightest isotope to deviate from the vibrational picture.

Prior work:

- Weakly deformed vibrational model (Gupta PRC 2023).
- E5 critical point symmetry (e.g. Clark et al PRC 2004, Hicks et al PRC 2017).
- Gamma-soft/triaxial (Tiwary EPJA 2019, Sharma NPA 2019)).



Target excitation



Beam:

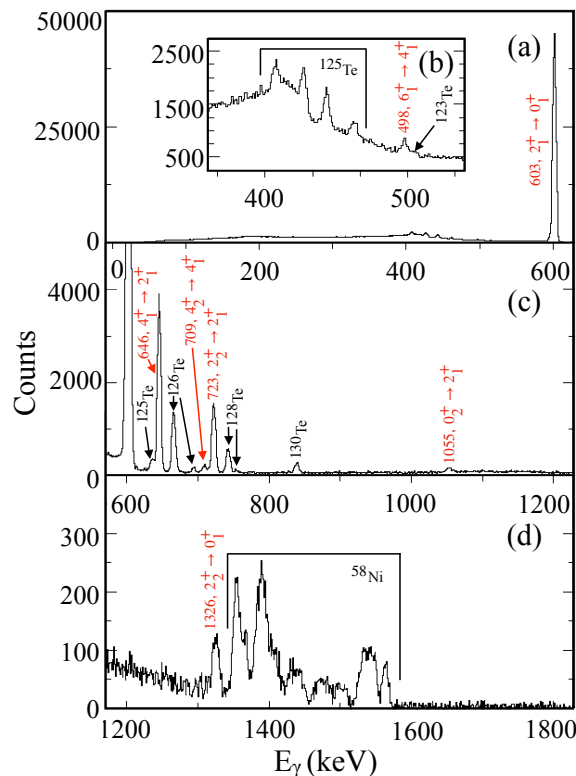
O-16 @ 45 MeV

Ni-58 @ 186 MeV

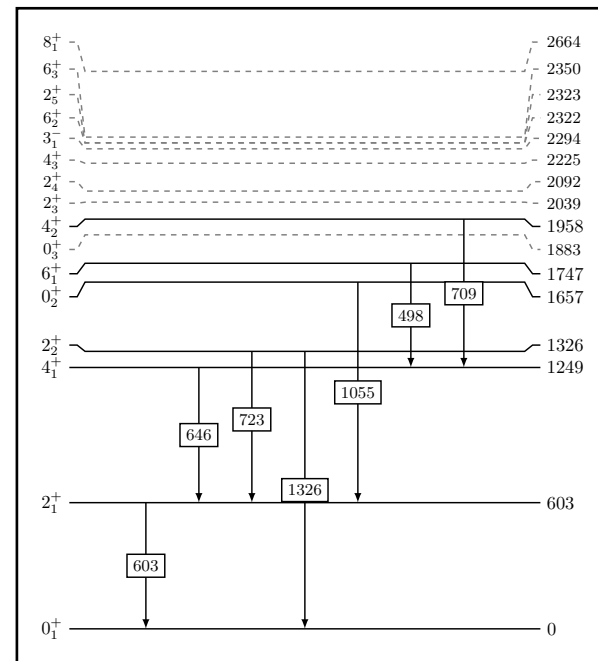
Target:

Te-124 @ $300\text{-}\mu\text{g}/\text{cm}^2$

Doppler-corrected, particle-gated gamma-ray spectrum



Level scheme



^{124}Te



- Yields
- Lifetimes
- Branching ratios
- Mixing ratios

GOSIA

**Matrix
elements**

$$\langle I_f || M(E2) || I_i \rangle^2 = (2I_i + 1) B(E2; I_i \rightarrow I_f).$$

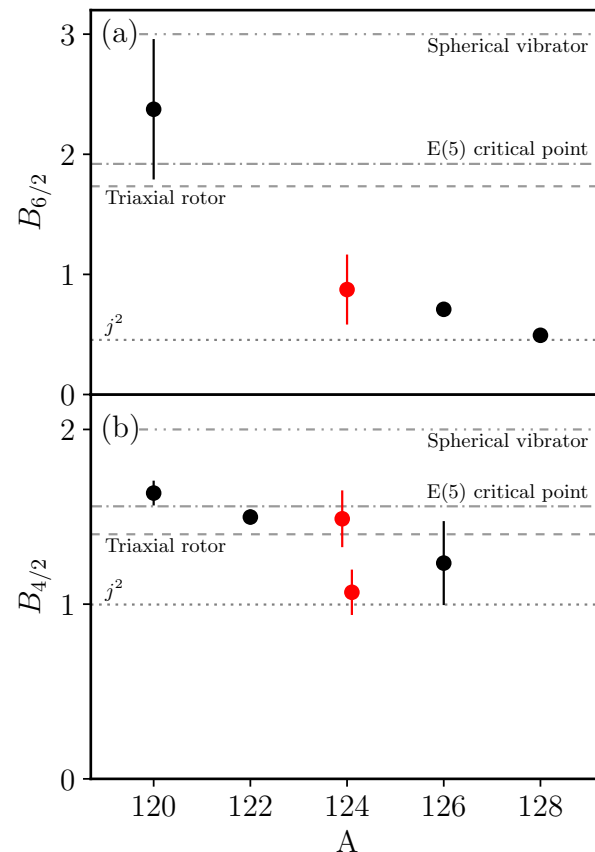
Red circles: This work

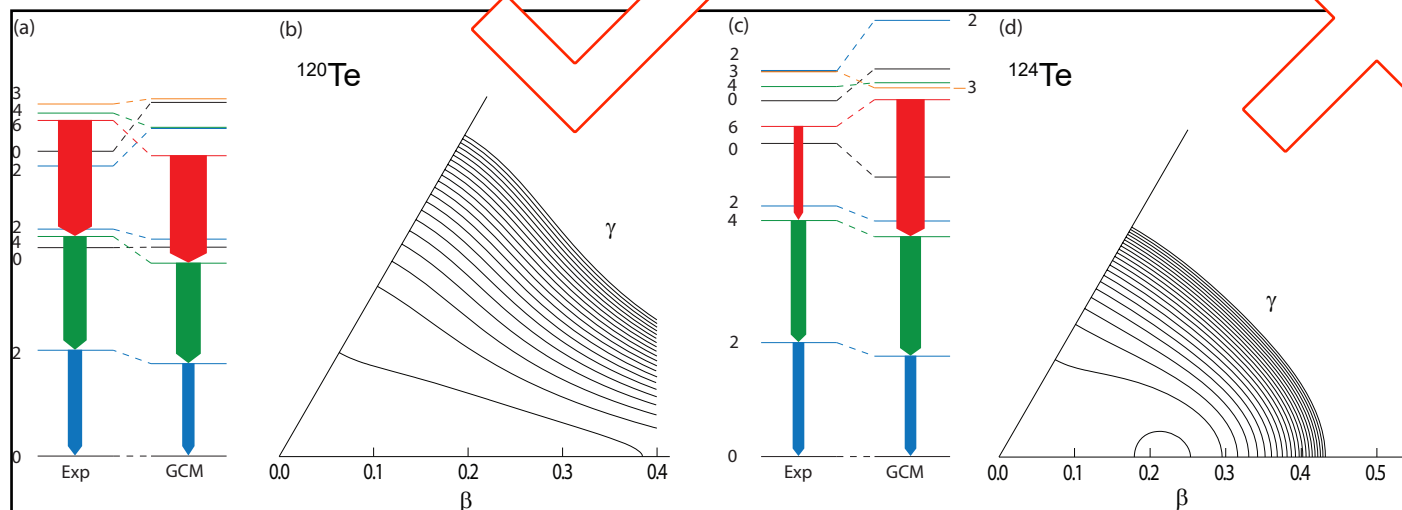
Black circles: NDS, Hick et al PRC (2017), Hicks et al PRC (2005), Stockstad and Hall NPA (1967).

Unable to fully constrain $B(E2; 4^+ \rightarrow 2^+)$.

$B(E2; 6^+ \rightarrow 4^+)$ measured for the first time.

No agreement with the spherical-vibration model.





General Collective Model

Phenomenological model of low-excitation collective nuclear states

Treats states as excitations of an incompressible liquid drop

Parameters determined by fitting the low-excitation spectrum and E2 properties.

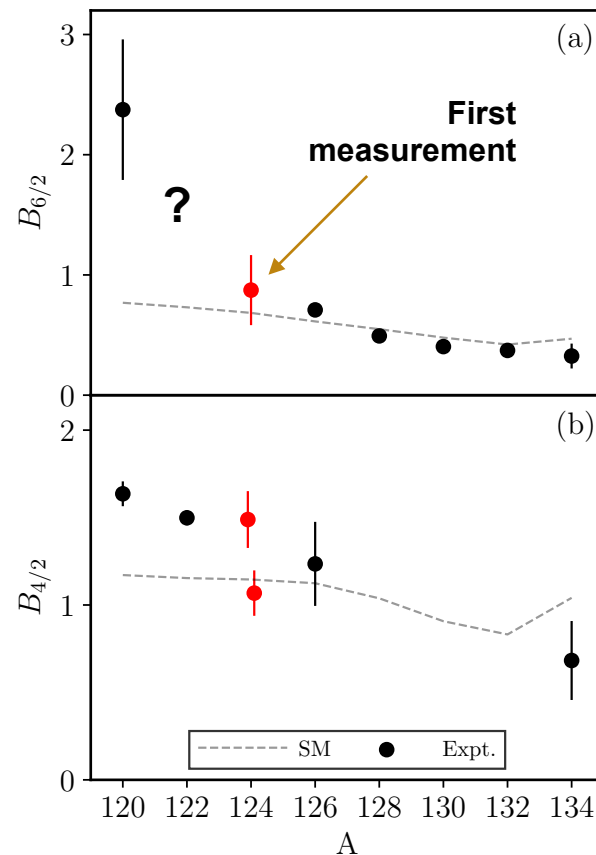
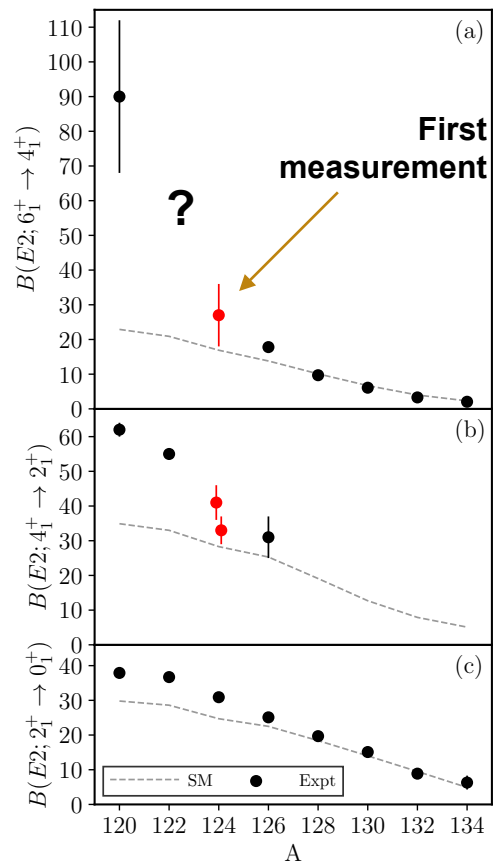
Large-scale shell-model calculations performed with KSHELL.

- Sn-100 core.
- CD-Bonn potential
- $e_p = 1.7$, $e_n = 0.9$

Theory and experiment agree well for $A = 128-134$

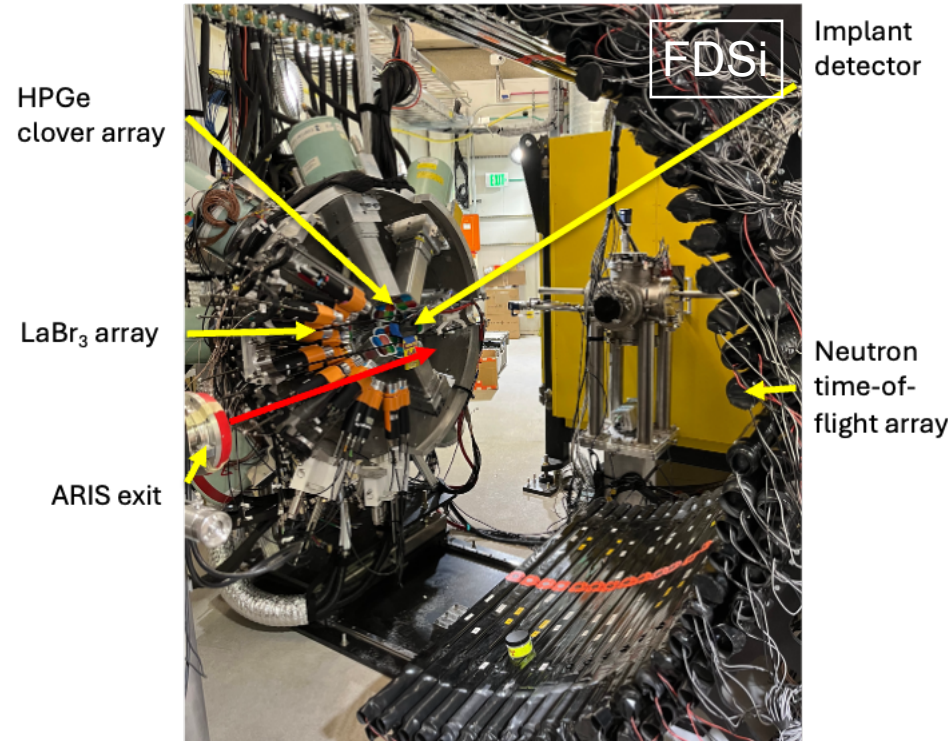
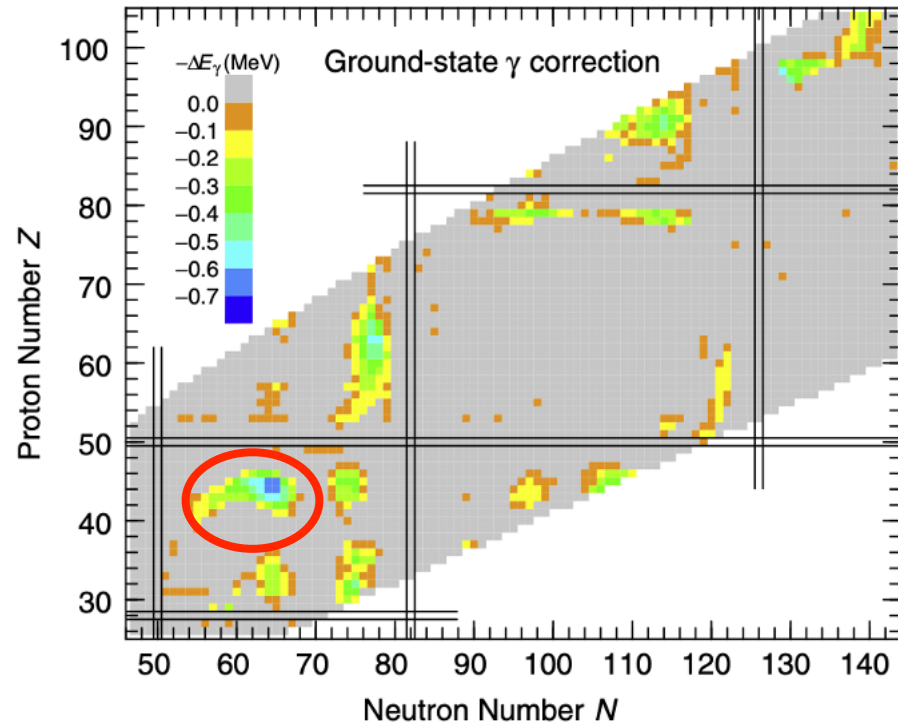
Additional collectivity appears in lighter isotopes.

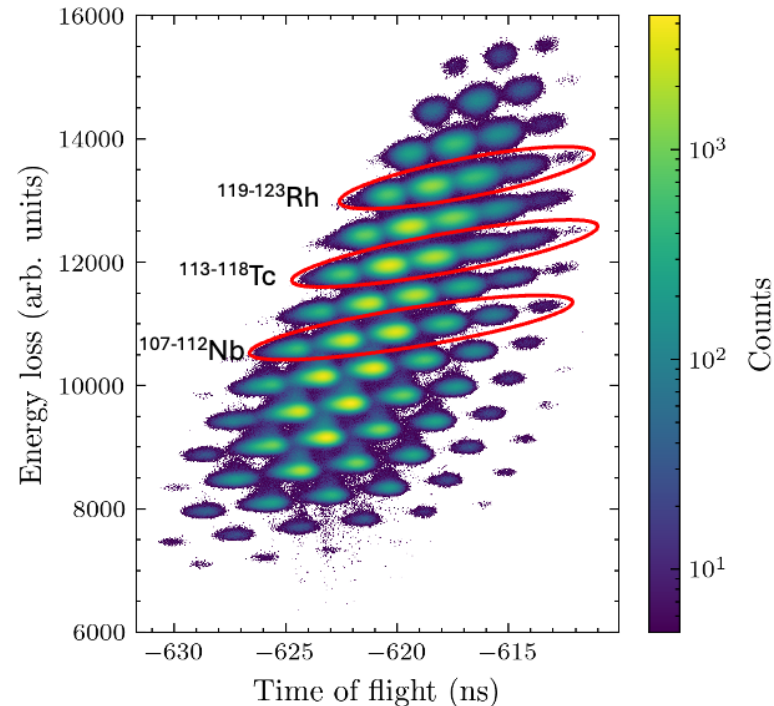
6^+ state in Te-124 retains a strong proton $g_{7/2}$ component.



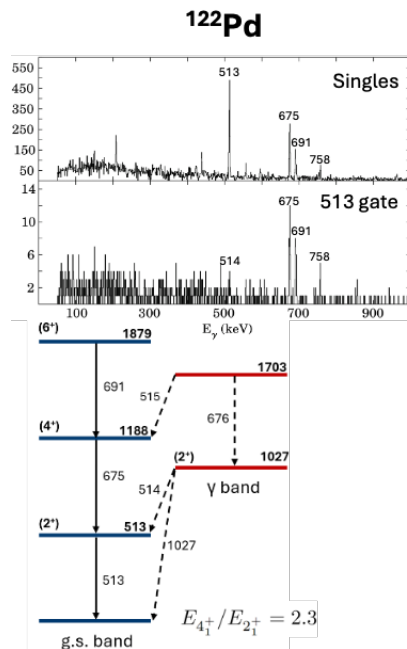
Searching for triaxial ground-states @ FRIB

P. Moller, et al., Atomic Data and Nuclear Data Tables, 94, 758 (2008).

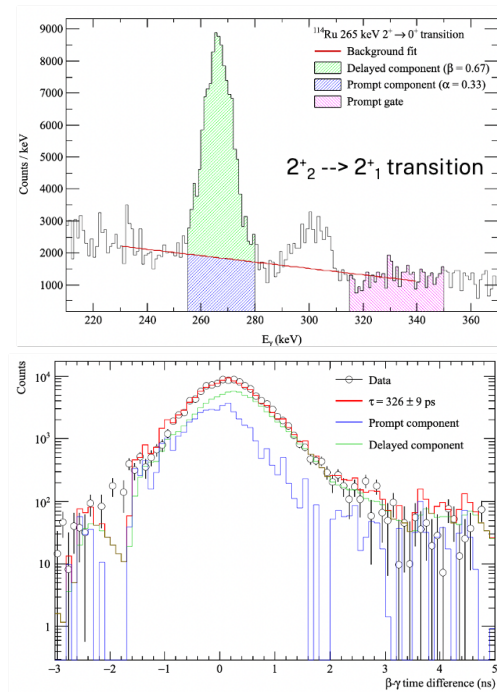




Implant ID
- >120 nuclides



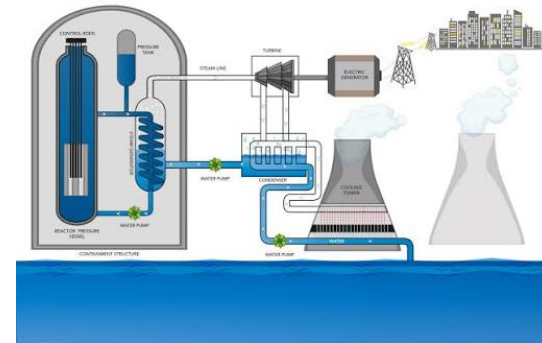
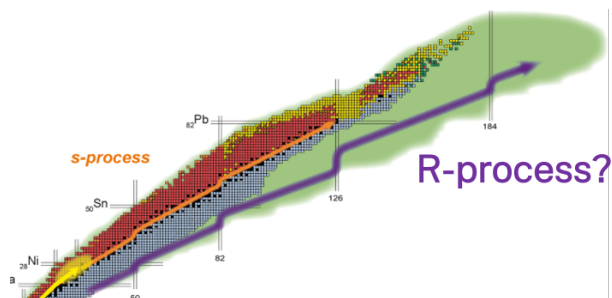
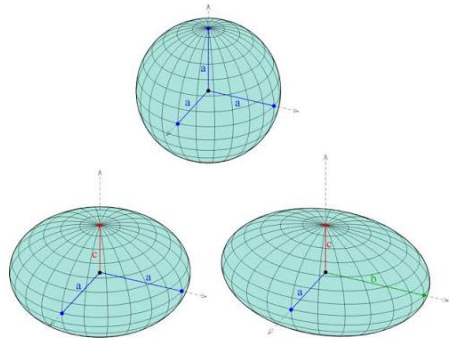
Decay spectroscopy
- identify levels



State lifetimes
- $\tau \rightarrow B(E2)$



Searching for triaxial ground-states @ FRIB



More testing grounds for
Otsuka *et al*?

Impacts on shell-
structure evolution in
very-neutron-rich
systems

Impact of ground-state half-
lives, and masses, beta-
delayed neutron probabilities
and nuclear isomer
discovery on stellar
nucleosynthesis

Impact of ground-state half-
lives, and masses, beta-
delayed neutron probabilities
and nuclear isomer
discovery on reactor physics.



Where next?

In summary, we are really discussing the emergence of effective collective degrees of freedom from the strong interaction. How to predict them, and how to confirm them.

Where to next? ...

Nuclear structure starting at the quark level

 Sep 27, 2026, 11:30 AM

 30m

 Novotel Cairns Oasis Resort

Speaker

 Anthony Thomas

Description

One challenging aspect of the modern study of atomic nuclei is to understand how they emerge from QCD. After reviewing the development of the quark meson coupling model, we show that it does indeed provide a quantitative theory of nuclear structure starting at the quark level. We then present some of the latest results obtained with the model, from superheavy nuclei to the potential interaction with a particular form of dark matter.

Authors

 Anthony Thomas
 Dr Kay Martinez (Adelaide University)



Nuclear Structure a...

... maybe we'll find out on Sunday.



THANK YOU

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W physics.anu.edu.au



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