Exploring the emergence of nuclear collectivity through moments and monopoles

Andrew Stuchbery

Department of Nuclear Physics & Accelerator Applications

The Australian National University

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Outline/Overview

- Introduction
- Emerging collectivity near ^{132}Sn: Te g factors E0s and B(E2)s
- Conclusions

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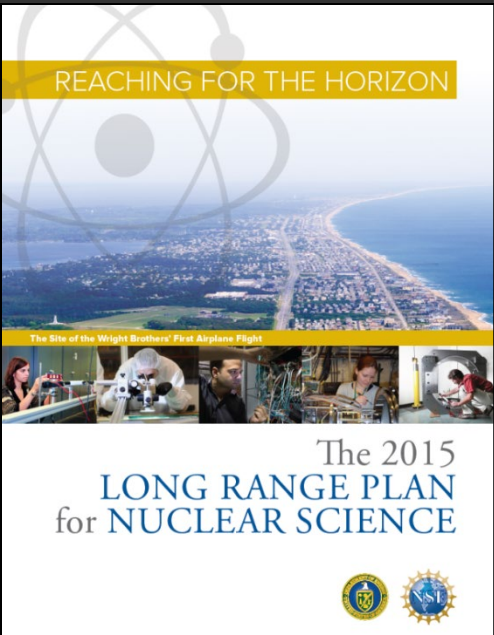
Recent ANU nuclear structure focus



How does subatomic matter organize itself and what phenomena emerge?

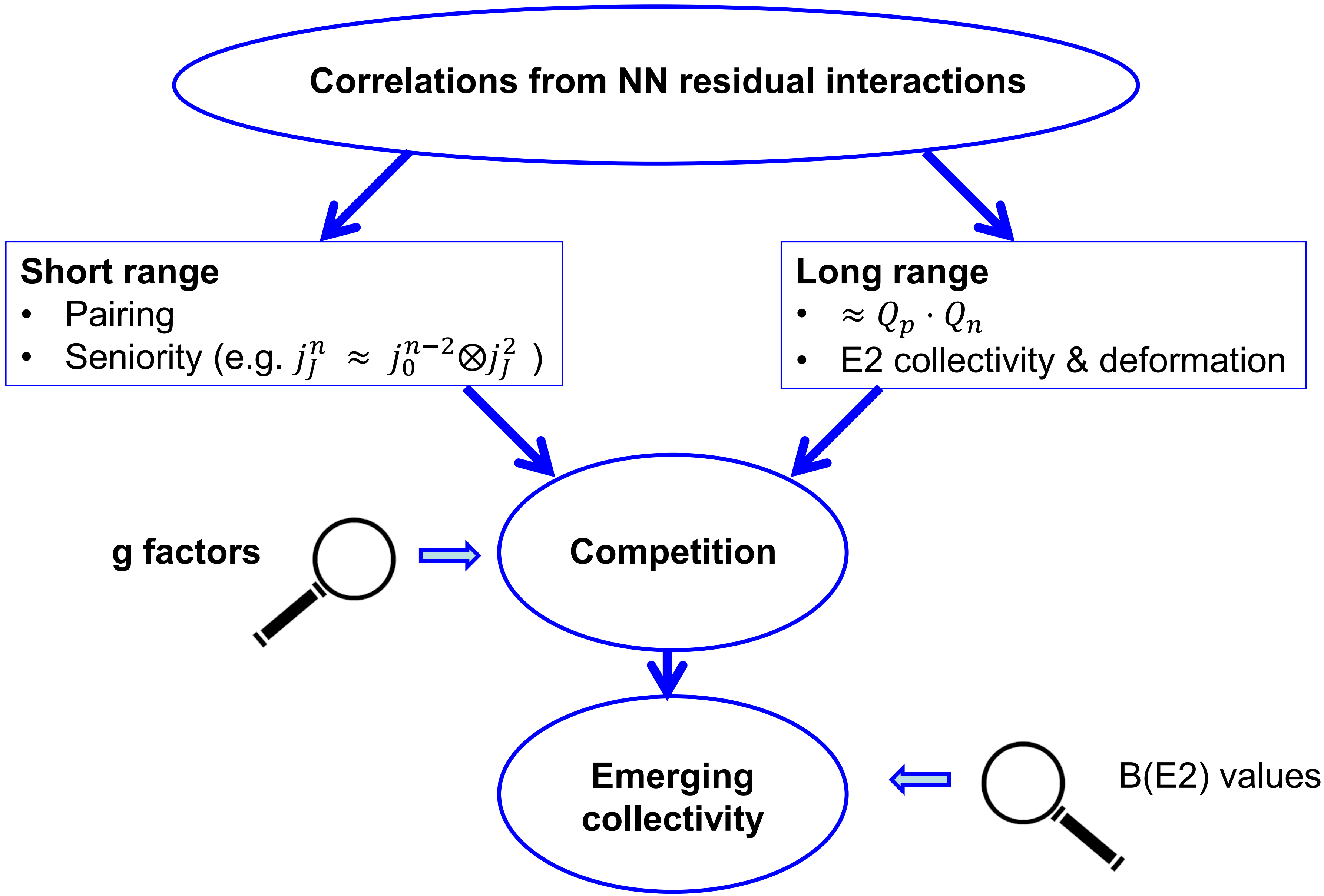
Dancing in Unison

It is remarkable that a heavy nucleus consisting of hundreds of rapidly moving protons and neutrons can exhibit a regular behavior, reflecting collective properties of many nucleons operating together.

Key contributions at ANU:

- Magnetic moments (AES)
- Electric monopole (E0) transitions (Tibor Kibédi)
- Electromagnetic transition rates (e.g. E6 in ^{53}Fe) lifetimes; Coulomb excitation) (Greg Lane)
- Transfer reactions (AJ Mitchell)

Probes and path of emerging collectivity



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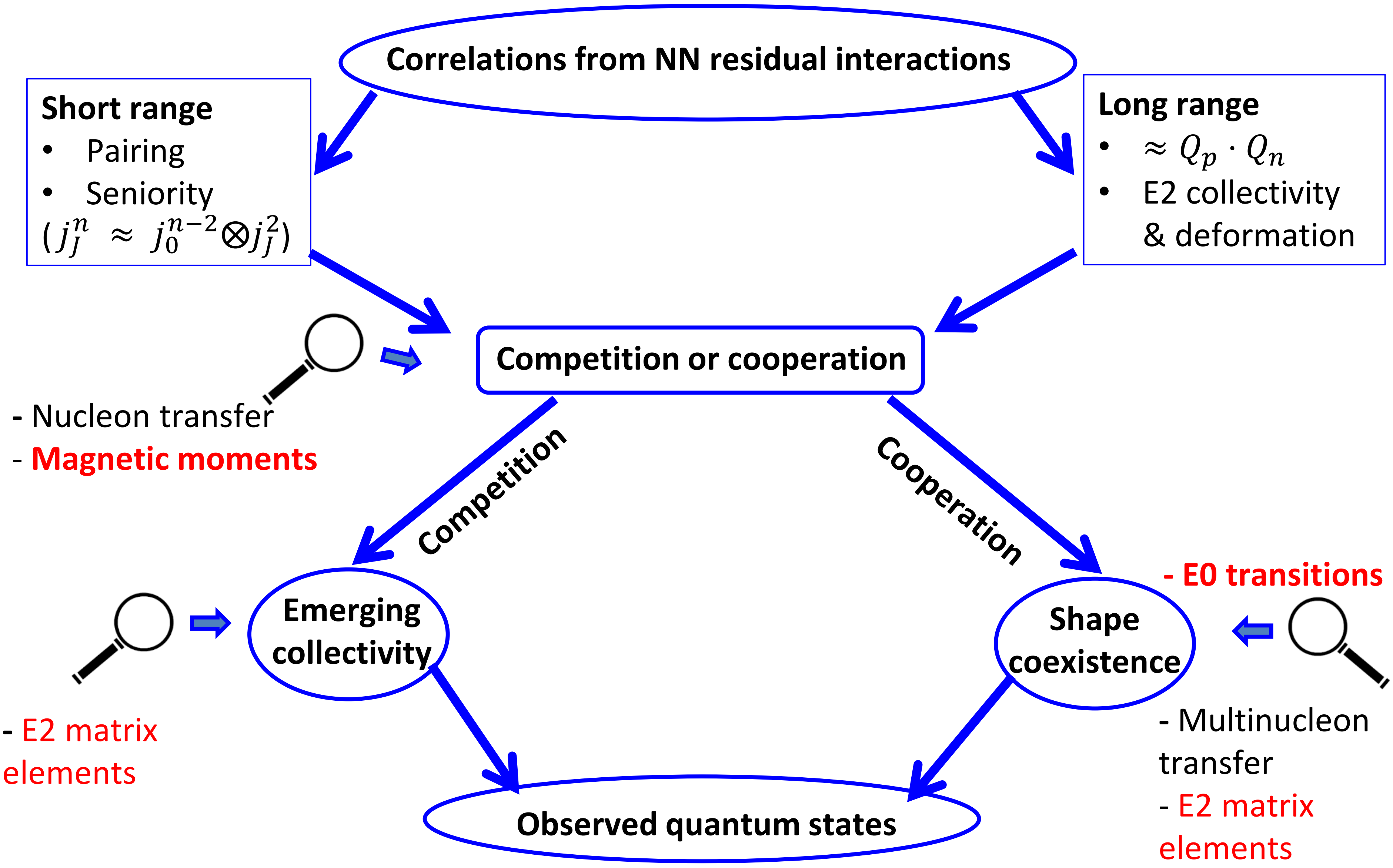
Probes and path of emerging collectivity



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Why Tellurium?

- Near ^{132}Sn shape coexistence is not a key factor

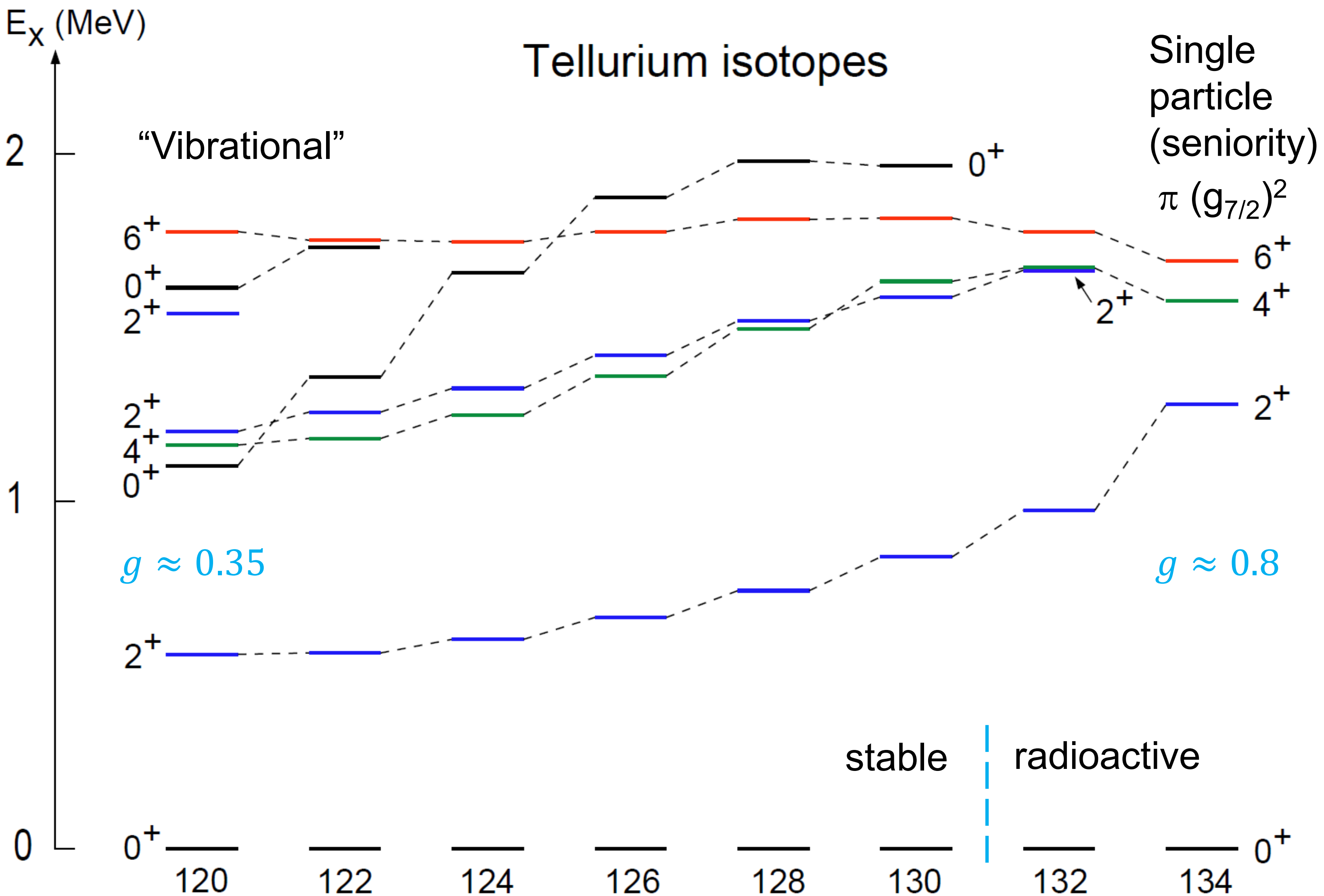
- A long sequence of stable isotopes ($^{120\text{-}130}$Te) accessible for Coulex and Transient Field g-factor measurements

- Z=52 – tractable for SM calculations near N=82

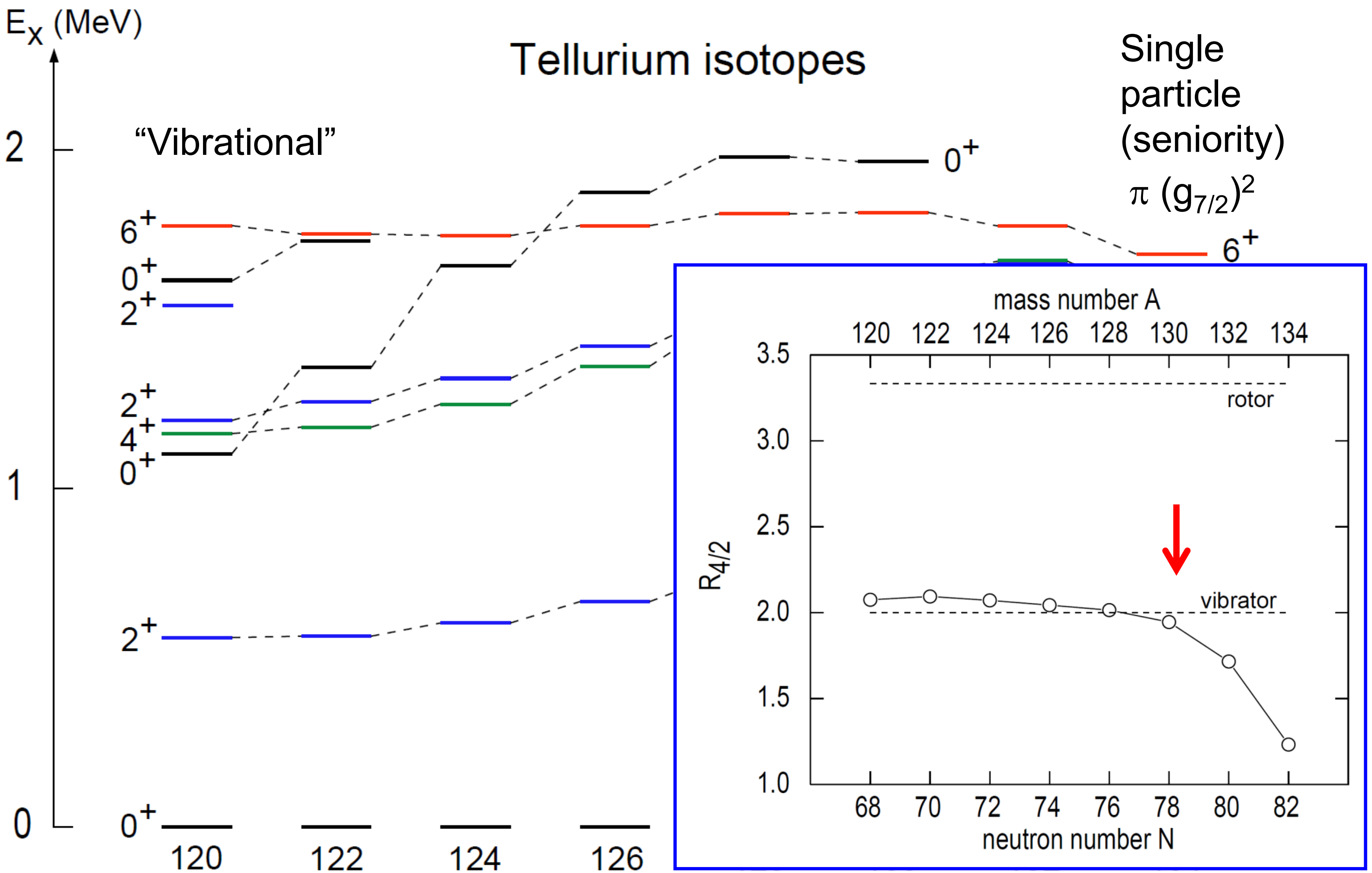
- Extensive data from (n,n'γ) from Kentucky group,
  - Erin Peters et al. PRC 99, 064321 (2019)
  - Sally Hicks et al. PRC 105, 024329 (2022)

- Level structures show transition from $\pi(g_{7/2})^2$ structure at N=82 (^{134}Te) to vibrational-like at ^{120}Te

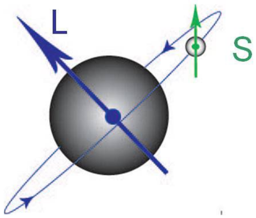
Experimental levels Te isotopes



Experimental levels Te isotopes



Magnetic moments & nuclear structure

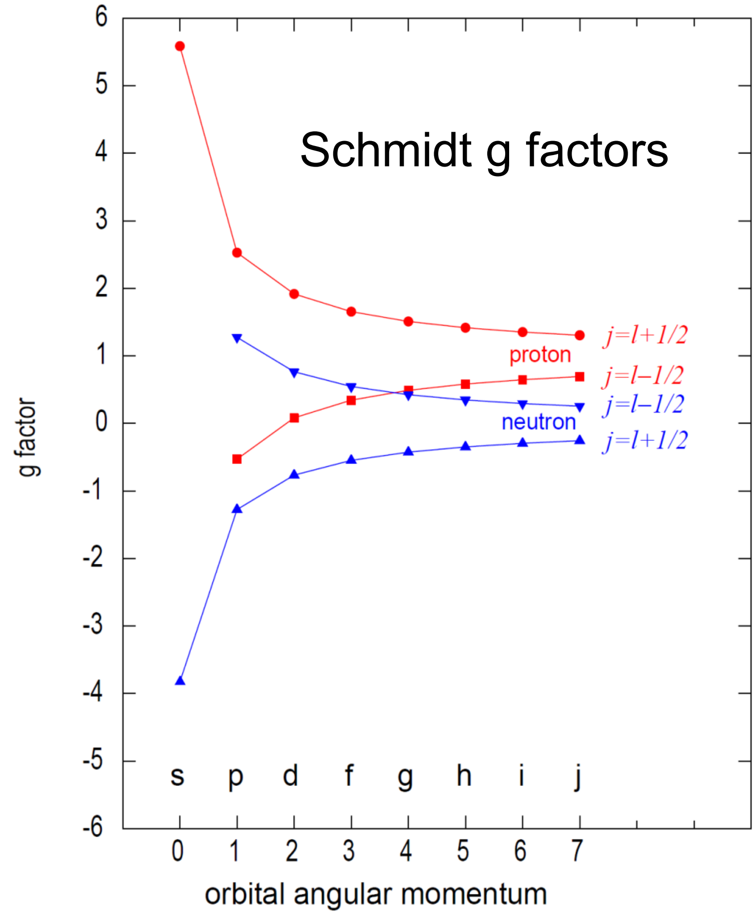


$$\mu = g_l l + g_s s \qquad J = l + s$$

g factor: $g = \mu/J$

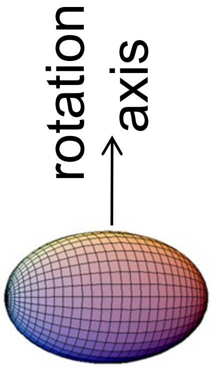
Orbital g factors: $g_l(p) = 1;\ g_l(n) = 0$

Spin g factors: $g_s(p) = +5.586;\ g_s(n) = -3.826$



- indicate how the nucleus carries its angular momentum
- distinguish between proton versus neutron excitations
- for few-particle states g factors typically vary from ~ –0.5 to ~+1.5

g factors of collective states



Assume spin contributions cancel:

$$g \approx \frac{J_p}{J_p + J_n}$$

Angular momentum of protons

Total angular momentum

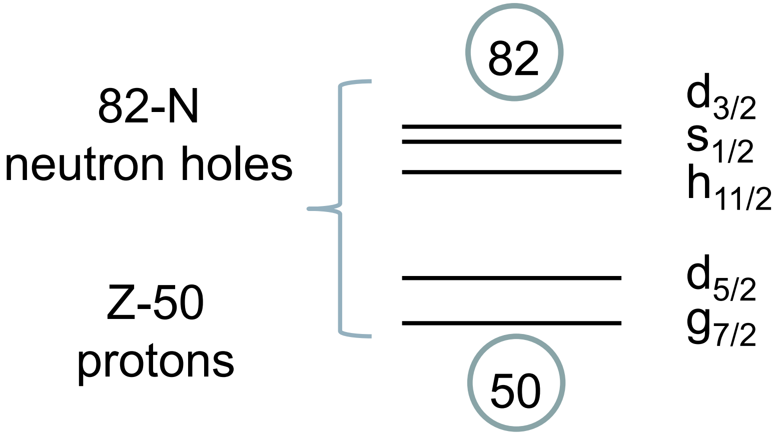
In collective models the *g* factor measures the fraction of the spin carried by the protons

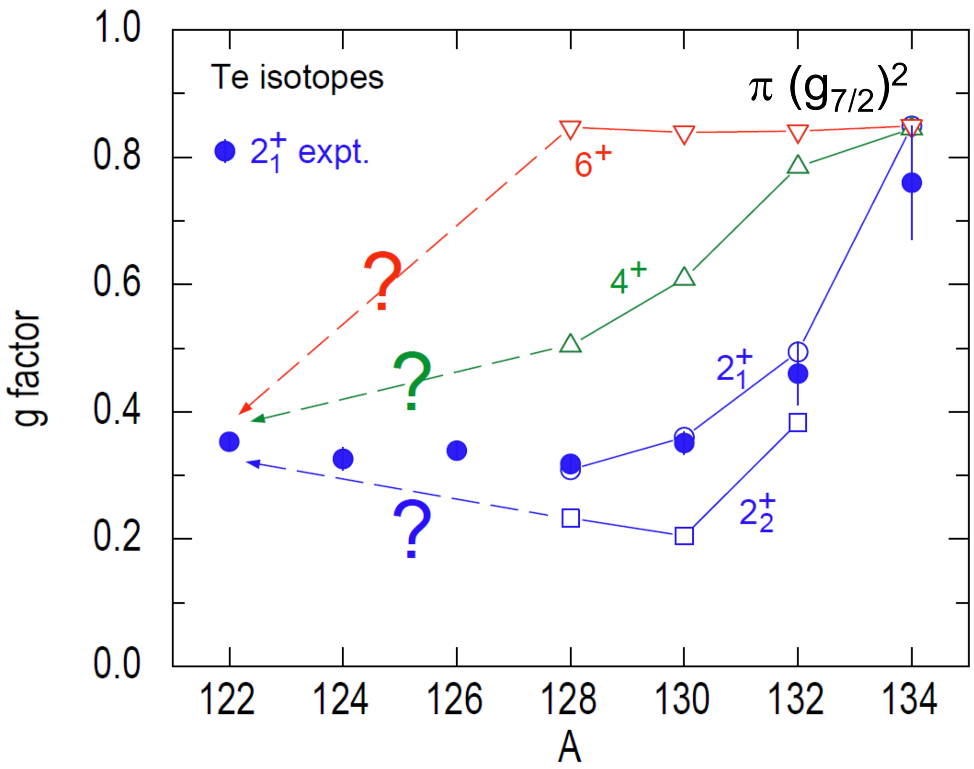
Bohr collective model
(vibrations/rotations of charged spheroid): $g \approx \frac{Z}{A} \approx 0.4$

Generally observed : $g \approx 0.8\frac{Z}{A} \approx 0.3$

Even-even collective nuclide: all states have the *same* g factor

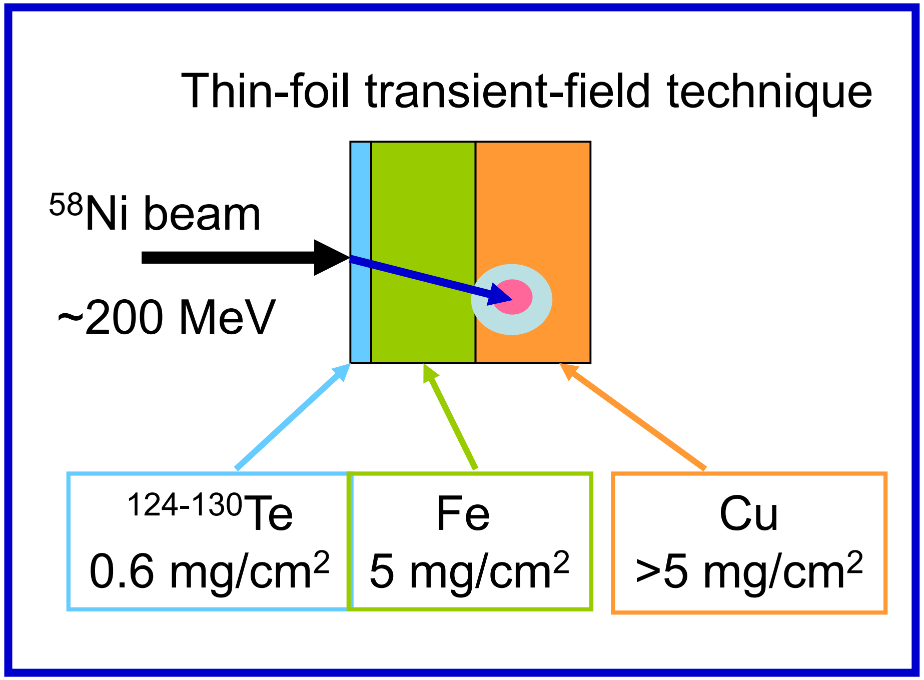
g factors: shell model & collectivity





Nushellx with jj55pn interactions from Alex Brown – PRC **71**, 044317 (2005)
Data: ANU & ORNL: PRL **94,** 192501 (2005); PRC **76**, 034306 (2007); PRC **76**, 034307 (2007); PRC **88**, 051304(R) (2013)

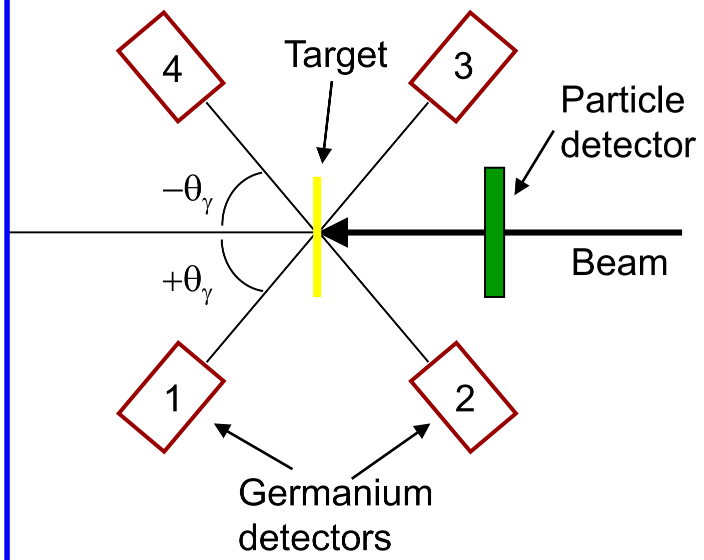
Transient-field g-factor measurements



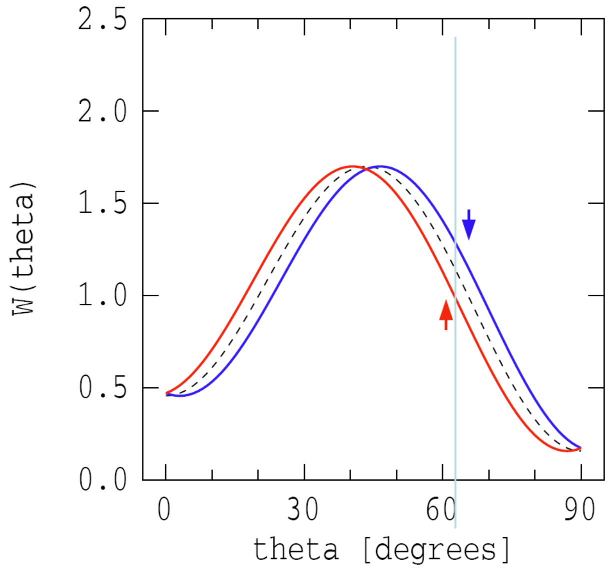
- Coulomb excitation
- TF (~ few kT) acts as ion traverses Fe layer
- Measure $g(4^+)$ relative to $g(2^+)$
- $g(2^+)$ from PRC **76**, 034306 (2007)

Measuring small precession angles

Place detectors on opposite sides of the beam line, reverse the magnetic field frequently, and form double ratios



Plan view of apparatus
Magnetic field up out of page



Angular shift determined from change in intensity for field ‘up’ and ‘down’

Details:

$$\rho = \sqrt{\frac{N(+\theta)\uparrow N(-\theta)\downarrow}{N(+\theta)\downarrow N(-\theta)\uparrow}} = \frac{W(\theta-\Delta\theta)}{W(\theta+\Delta\theta)}$$

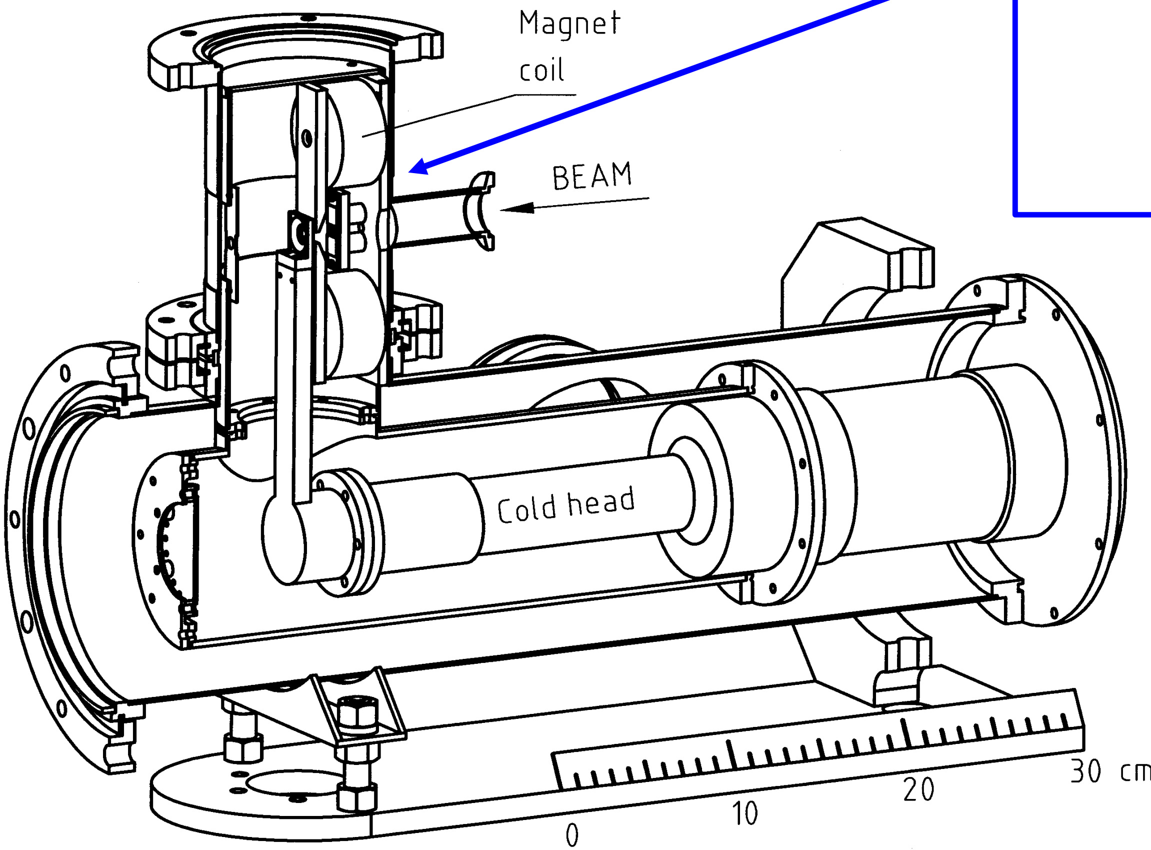
$$W(\theta \pm \Delta\theta) = W(\theta) \pm \frac{\mathrm{d}W}{\mathrm{d}\theta}\Delta\theta$$

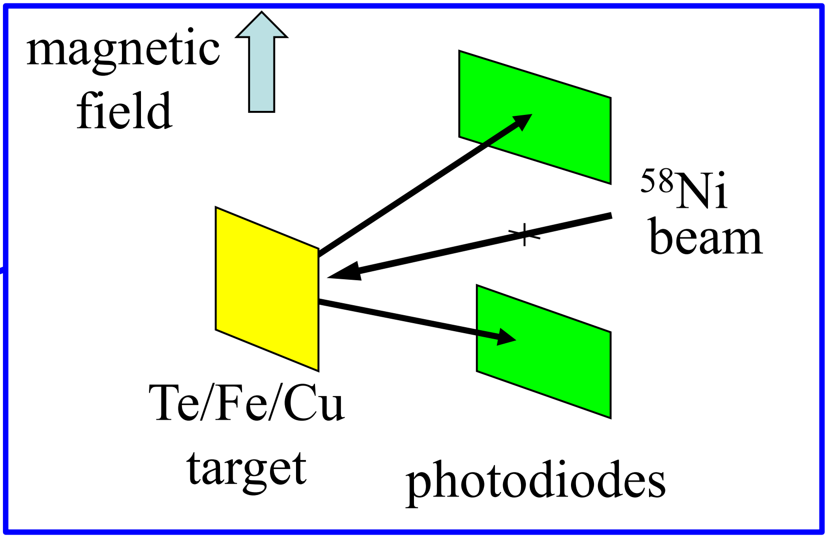
$$\rho = \frac{W(\theta) - \frac{\mathrm{d}W}{\mathrm{d}\theta}\Delta\theta}{W(\theta) + \frac{\mathrm{d}W}{\mathrm{d}\theta}\Delta\theta}$$

$$S = \frac{1}{W}\frac{\mathrm{d}W}{\mathrm{d}\theta}\bigg|_\theta \qquad \varepsilon = \frac{1-\rho}{1+\rho}$$

$$\Delta\theta = \varepsilon / S$$

Apparatus: “Hyperfine spectrometer”

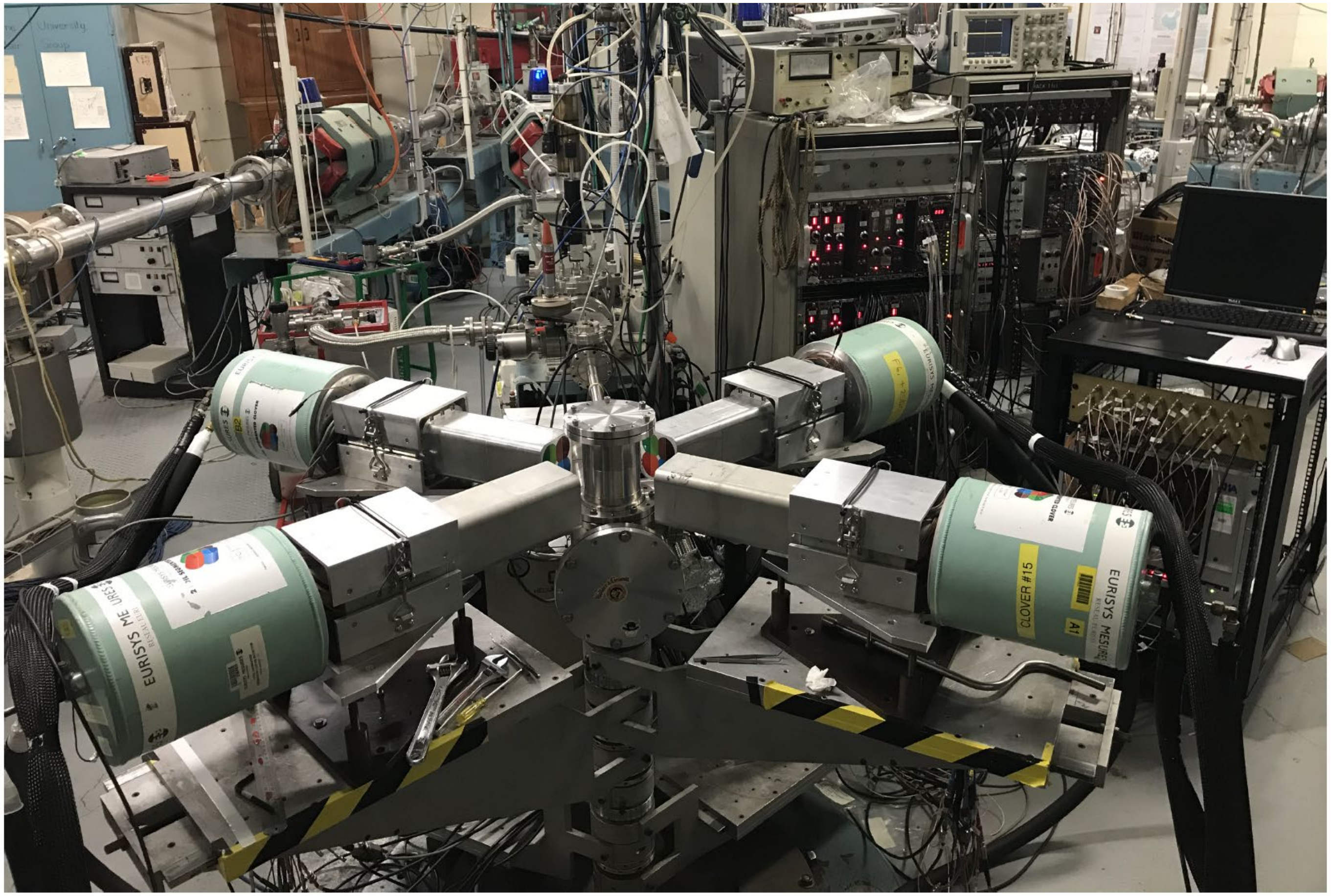




CRYOCOOLER:
1 W cooling power at 4K
(~10 W at 10 K)
Sumitomo RDK 408D

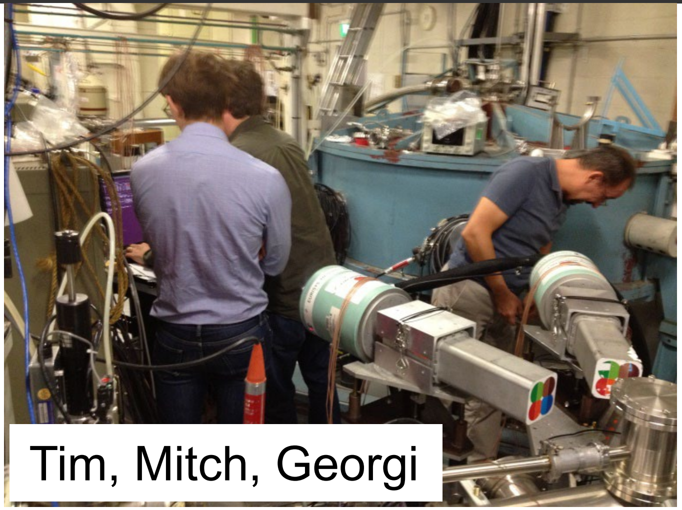
Apparatus

A view of the hyperfine spectrometer on the beam line with 4 clover detectors for the $^{124\text{-}130}$Te 4^+ g-factor measurements



In the lab @ ANU: Te g-factor runs

Ben Coombes



Tim, Mitch, Georgi

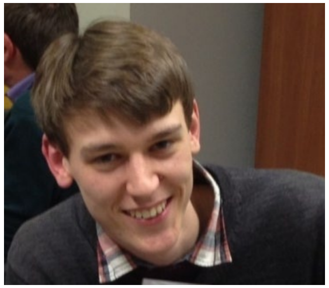
Mitch Allmond

Georgi Georgiev, AES (making targets)

Tim Gray, Ben Coombes

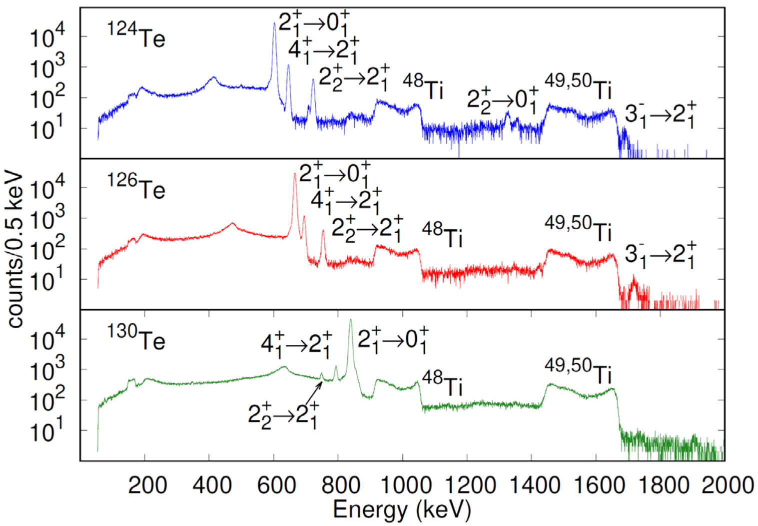
Fixing things in the night!

Gamma-ray spectra

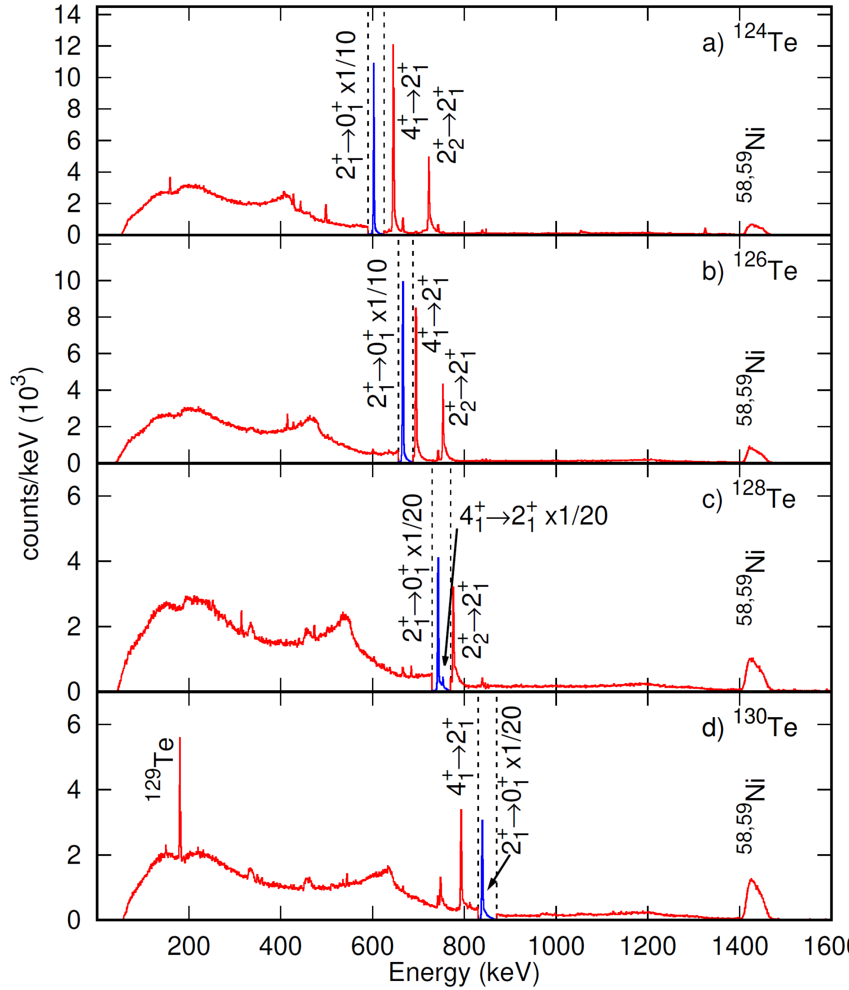


Ben Coombes
PhD 2021

Two-step Coulex is weak!



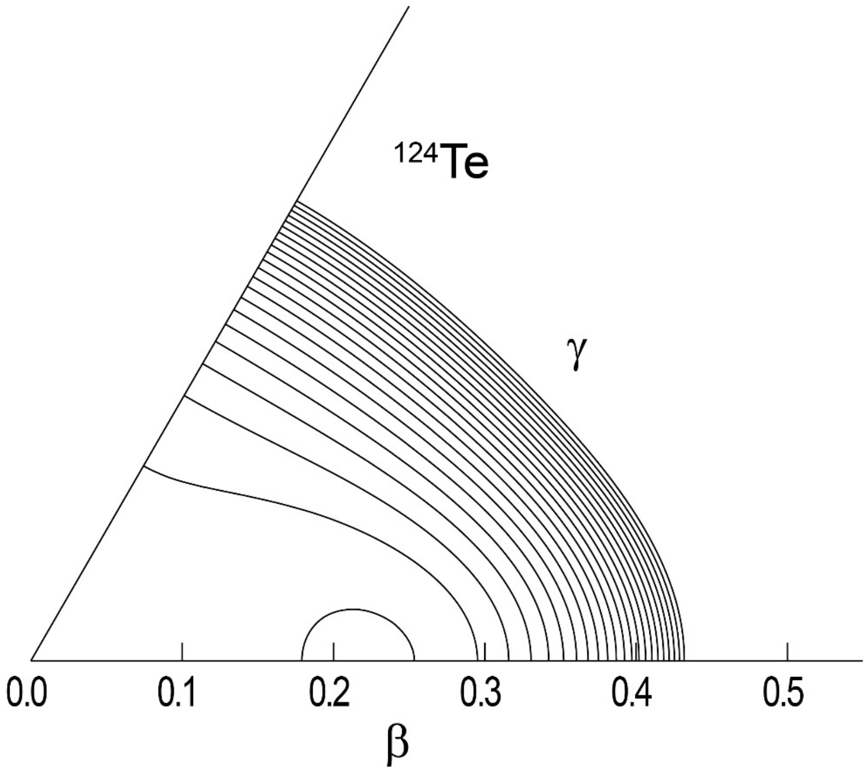
Inverse kinematics Coulex at HRIBF (ORNL)



Transient field g-factor measurements at ANU

^{124}Te – General Collective Model (GCM)

GCM: fit to lowest 10 levels
RMS deviation 134 keV



B(E2)↑ comparison: exp & theory

	exp	theory	
$0 \to 2$	0.571	0.564	✓
$2 \to 4$	0.243	0.368	×
$4 \to 6$	0.165	0.398	×
$2 \to 2$	0.121	0.136	✓

Q(2^+) comparison: exp & theory
-0.45 -0.44 ✓

GCM over predicts $6^+ \to 4^+$ transition

Shell model better: predicts
$g(6^+) \approx \pi g_{7/2}$ value

We need to measure the 6^+ g factors

g(6$^+$) in $^{130-134}$Te – ILL experiment

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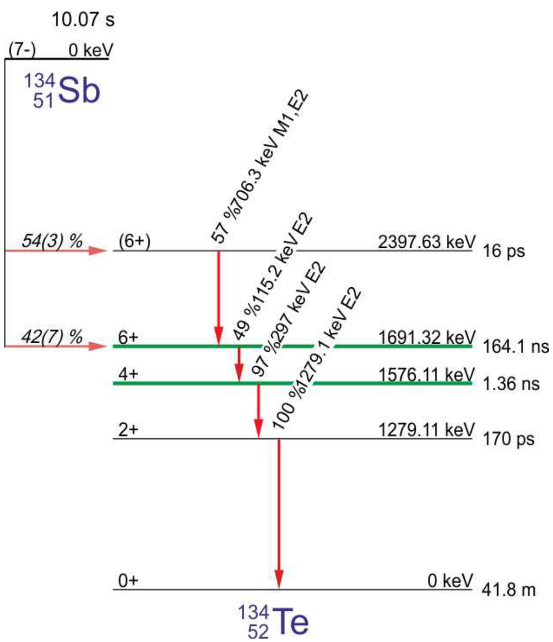
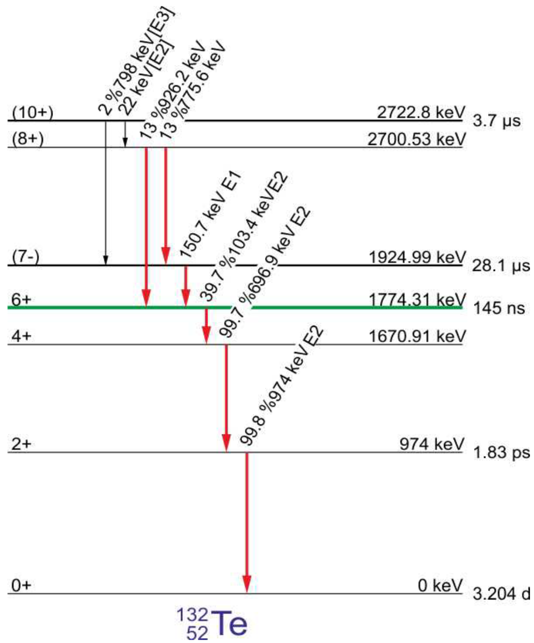
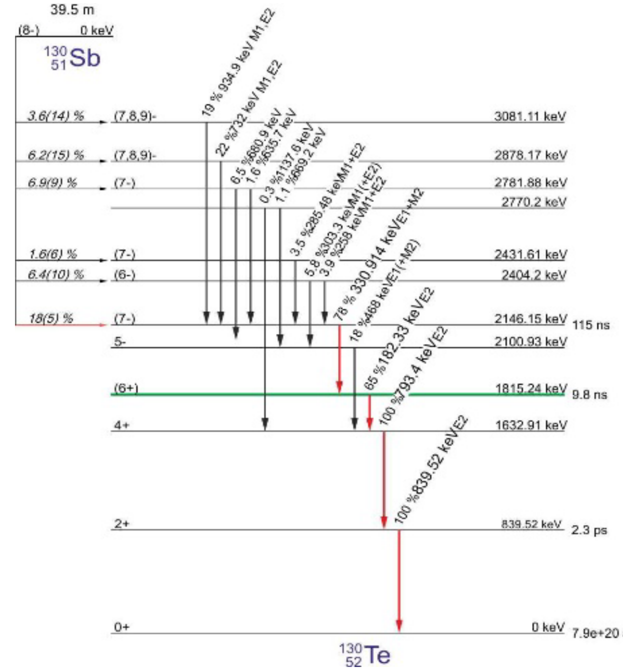


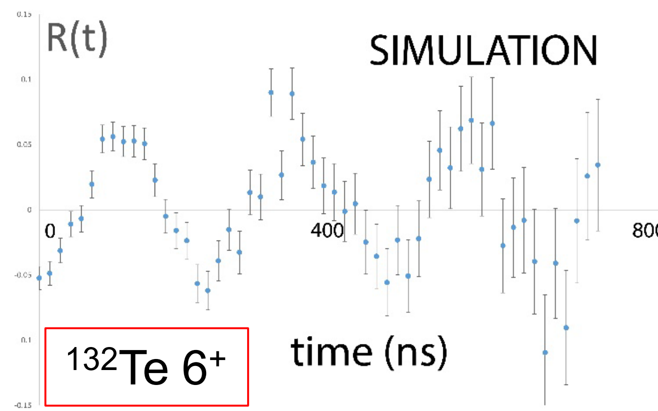




$\gamma\gamma$ TDPAC after β decay.

G Georgiev et al. ILL (3-01-724)

Important to extend to $^{130,128,126\ldots}$ Te



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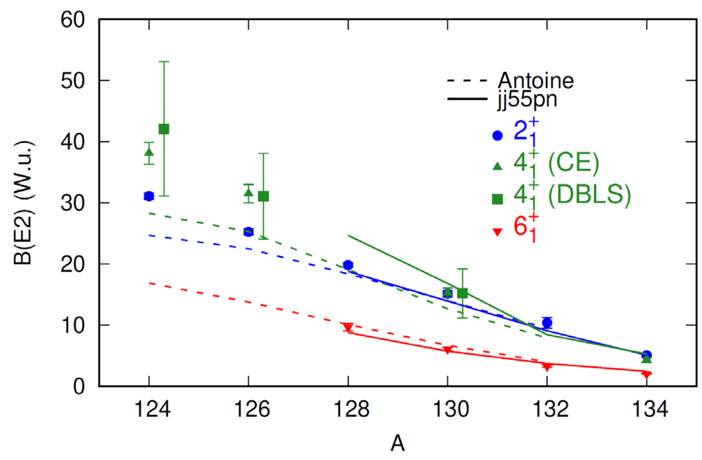
Rotational invariants – Kumar-Cline sum rules

Deformation: a sum of B(E2) values

$$\langle i|[E2\otimes E2]_0^{(0)}|i\rangle = \frac{1}{\sqrt{5}}\frac{1}{2I_i+1}\sum_t |\langle i\|E2\|t\rangle|^2$$
$$= \frac{1}{\sqrt{5}}\langle Q^2\rangle.$$

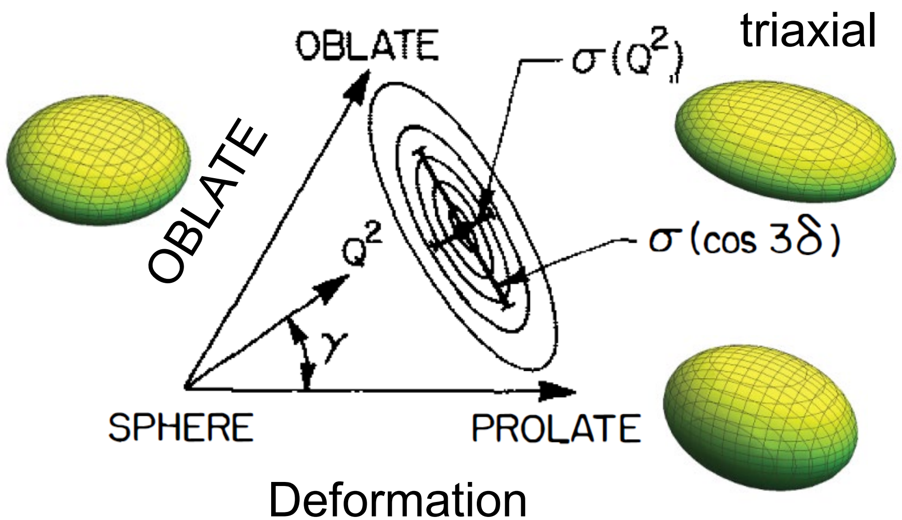


Triaxiality

$$\langle i|[[E2\otimes E2]^{(2)}\otimes E2]_0^{(0)}|i\rangle = -\sqrt{\frac{2}{35}}\langle Q^3\cos(3\delta)\rangle.$$

Determine the shape of each nuclear state

Also the variance around the average shape

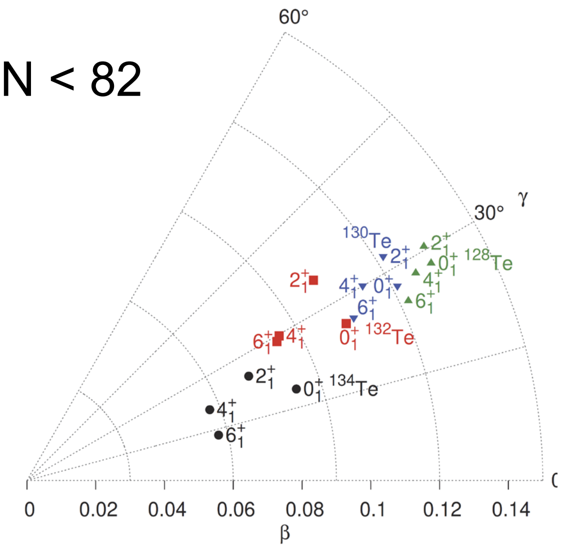


K. Kumar, Phys. Rev. Letters 28, 249 (1972)
D. Cline, Annu. Rev. Nucl. Part. Sci. 36, 683 (1986)

Triaxiality in Te, Xe isotopes?

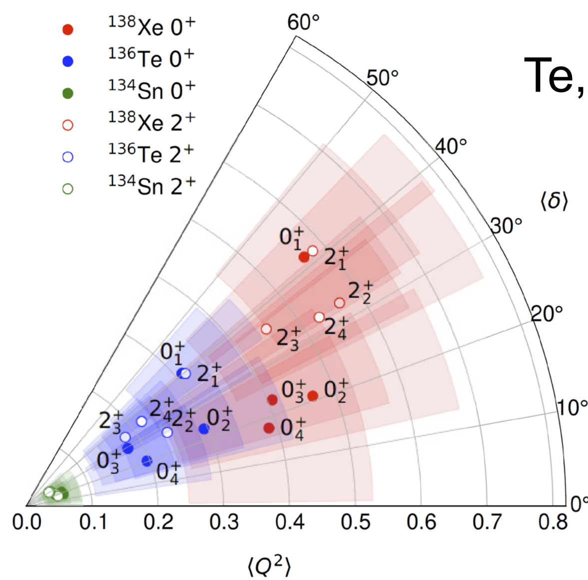
Shell model calculations + Kumar-Cline evaluation of shape parameters:

Te N < 82



Ben Coombes, Thesis, 2021

Te,Xe N > 82



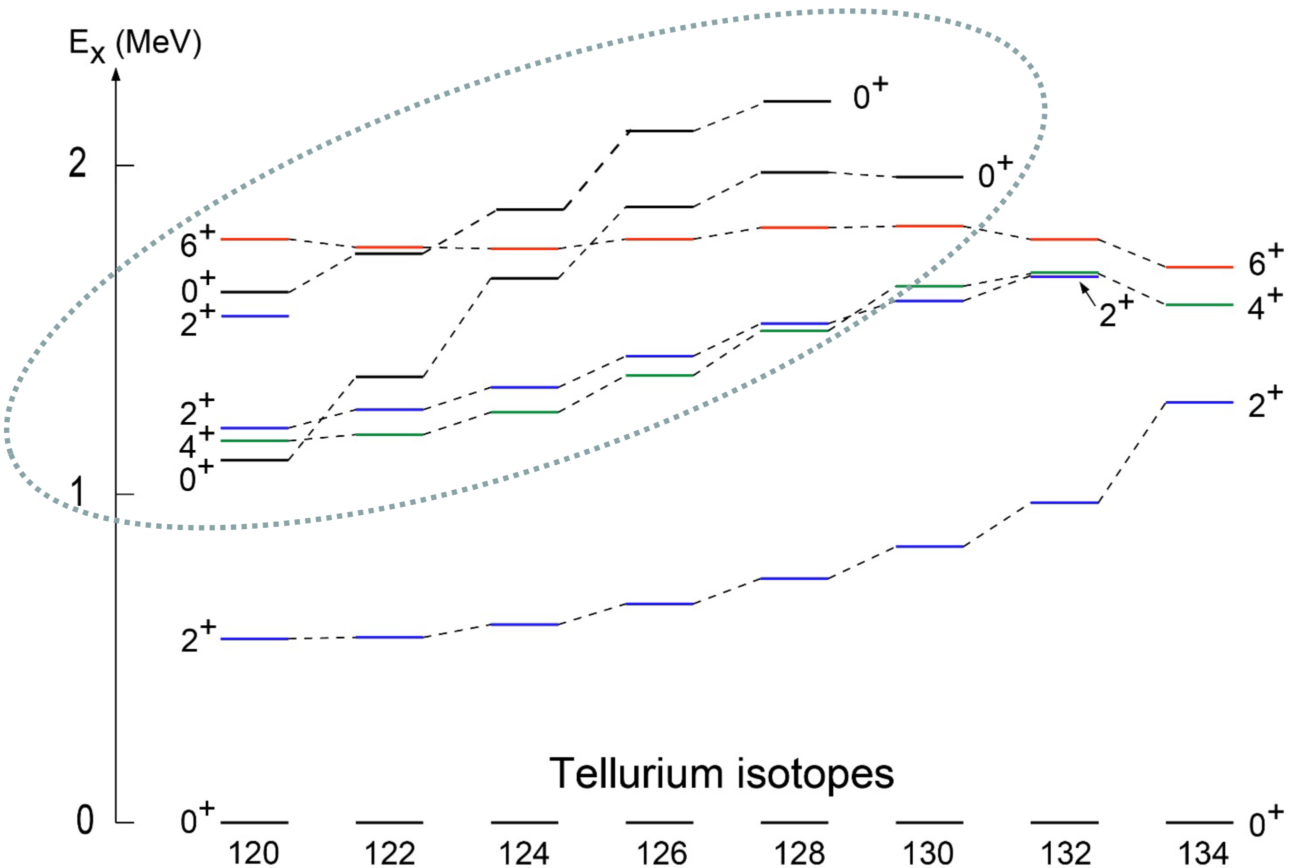
Tim Gray, Thesis, 2021

- Deformation increases with valence nucleons
- All states appear triaxial but soft
- The shape is not rigid and g factors etc. show these nuclei are not triaxial rotors; but the low-excitation states have an average triaxial shape

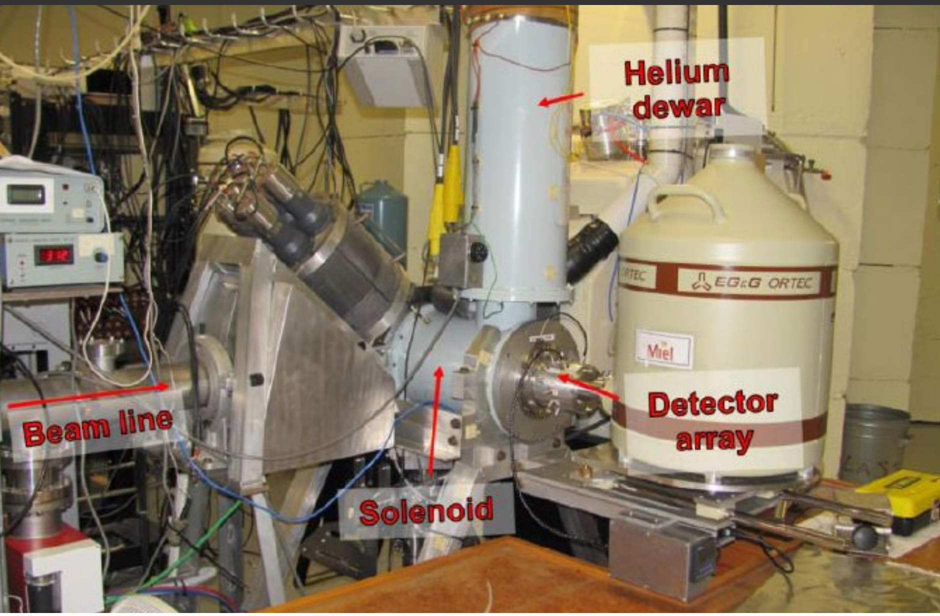
Everything looks triaxial! Possible path of emerging collectivity:
spherical → weakly-deformed triaxial → well-deformed prolate?

Hints of shape coexistence

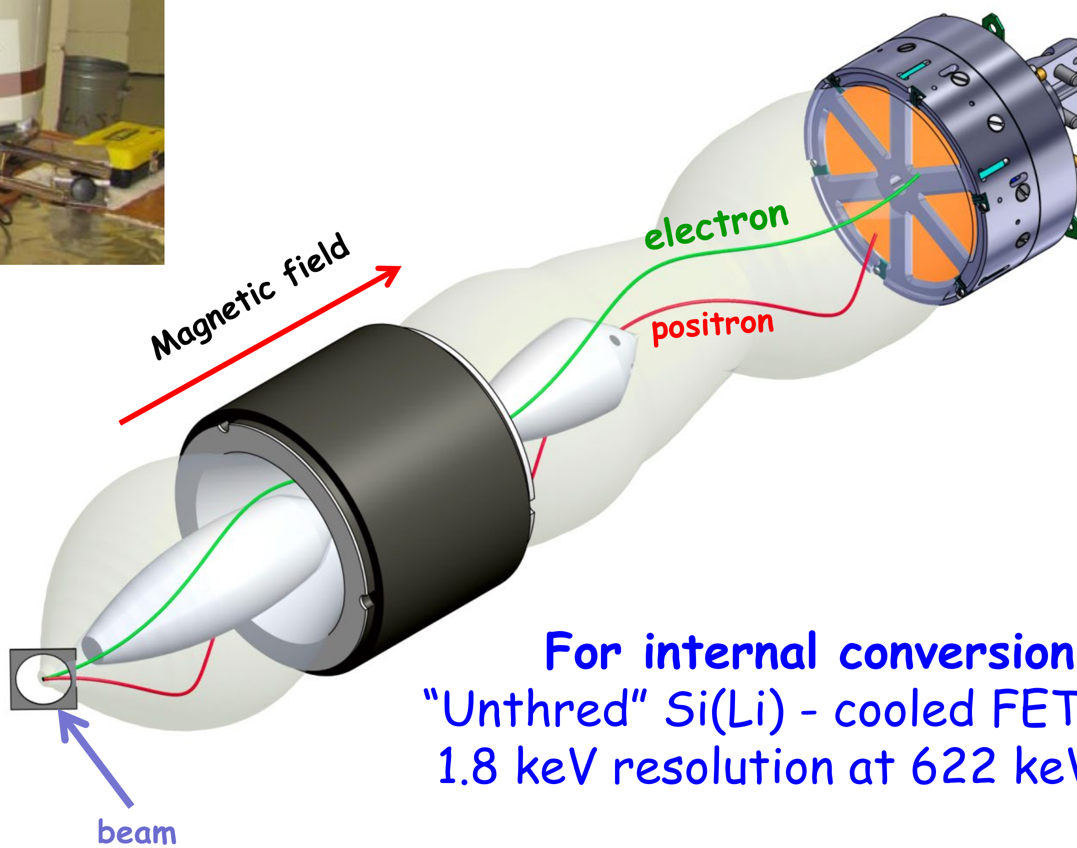
Parabolic trend in 0+ states



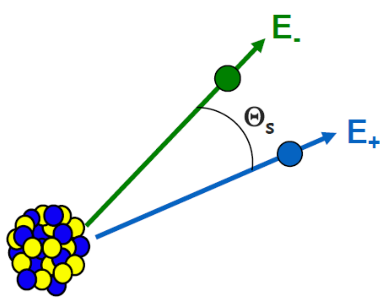
Super-e: IC & Pair spectrometer



For pairs:
Si(Li) array of six detectors "Miel"
Thickness: 9 mm; Area: 236 mm^2
FWHM ≈ 2.5 keV; Semikon GmBh

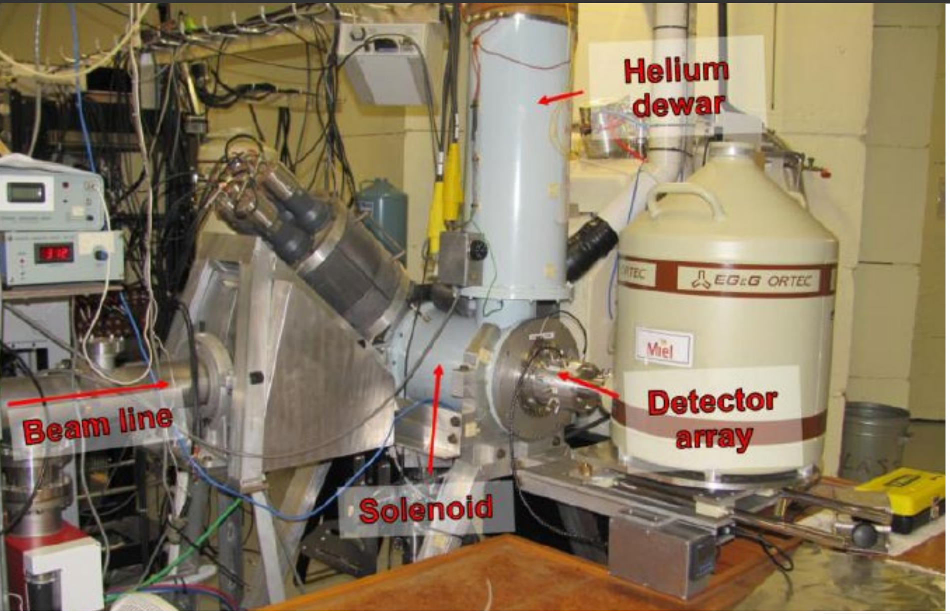


Energy shared: $E_+ + E_- = E_\gamma - 2m_0c^2$



For internal conversion:
"Unthred" Si(Li) - cooled FET,
1.8 keV resolution at 622 keV

Super-e: IC & Pair spectrometer

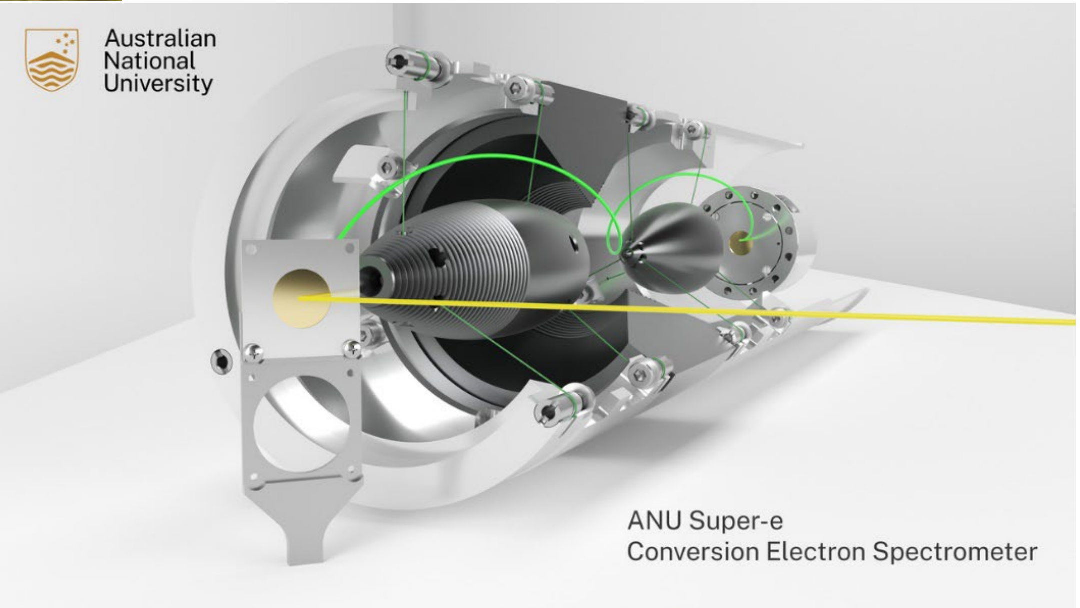


For internal conversion:
"Unthred" Si(Li) - cooled FET,
1.8 keV resolution at 622 keV

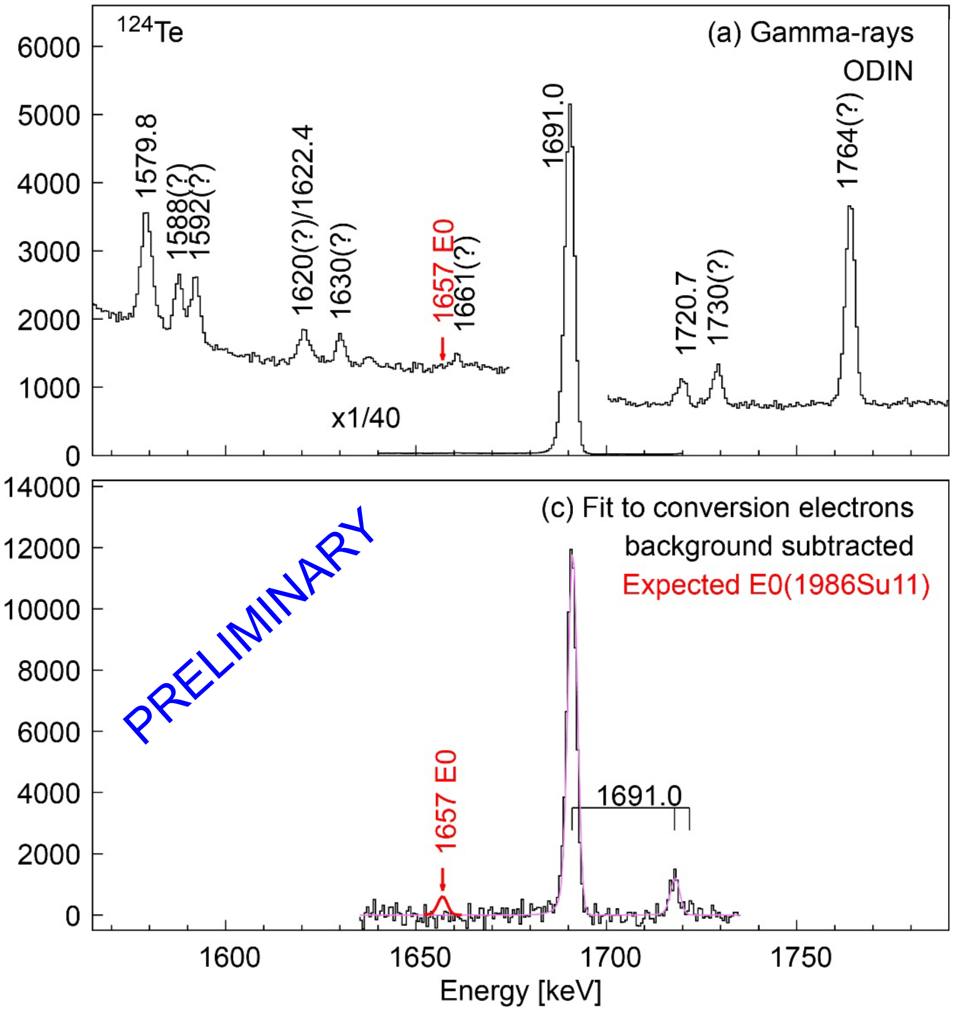
^{124}Te populated in ^{124}Sb β decay
$T_{1/2} = 60$ d.

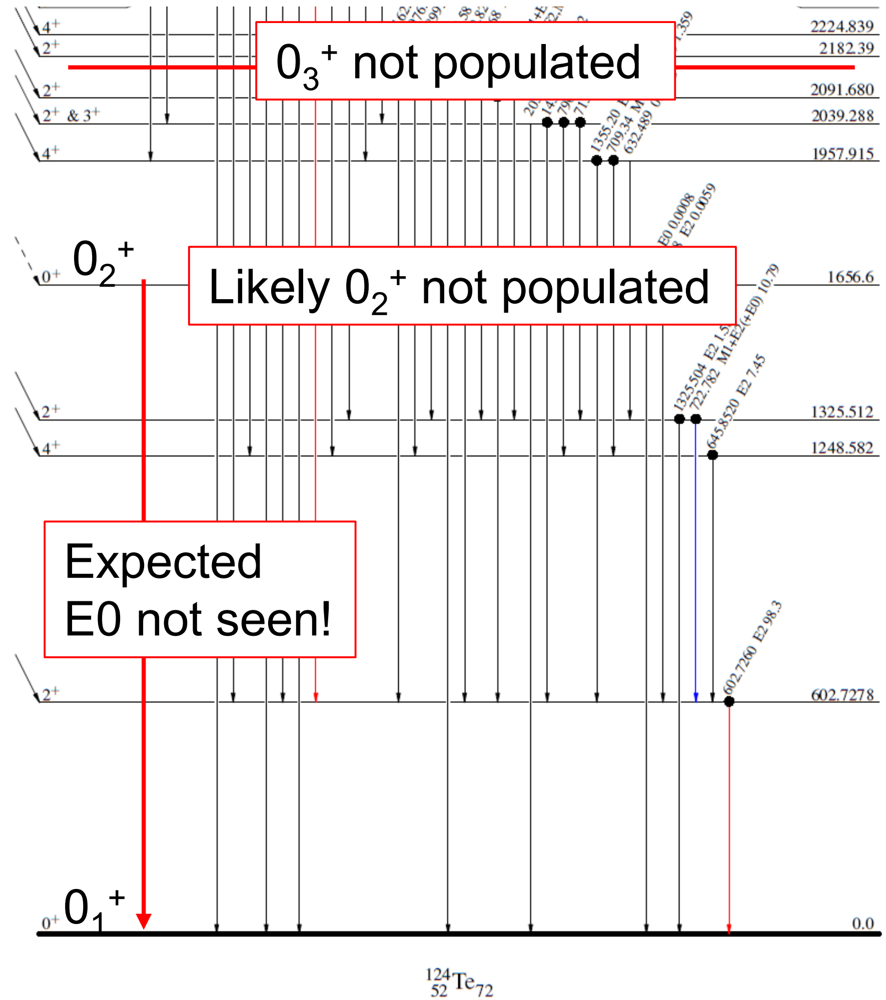
Source prepared by neutron irradiation of ^{123}Sb in OPAL reactor (Sydney)

Magnetic field swept



^{124}Te Conversion Electrons

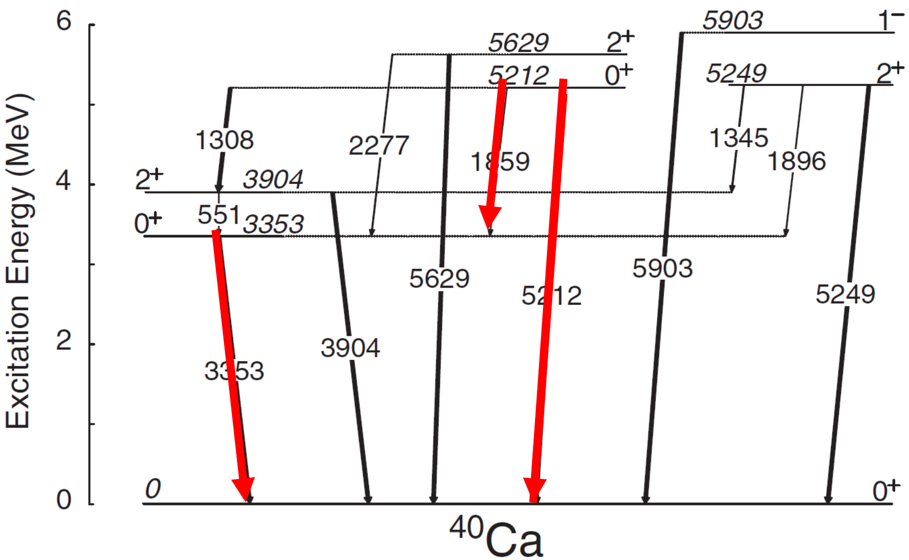


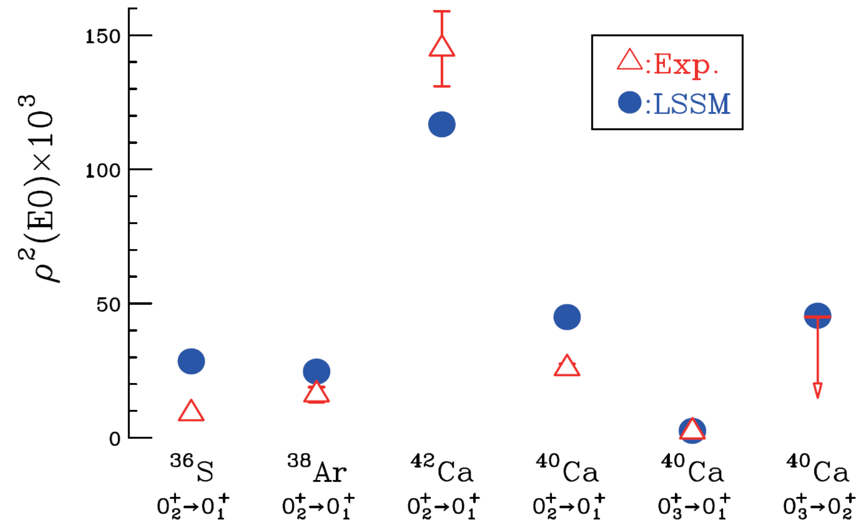


Previous 0_2^+ from (n,γ) J.Phys. G **12**, 881 (1986)

Shape co-existence in ^{40}Ca

ANU Super-e measurements





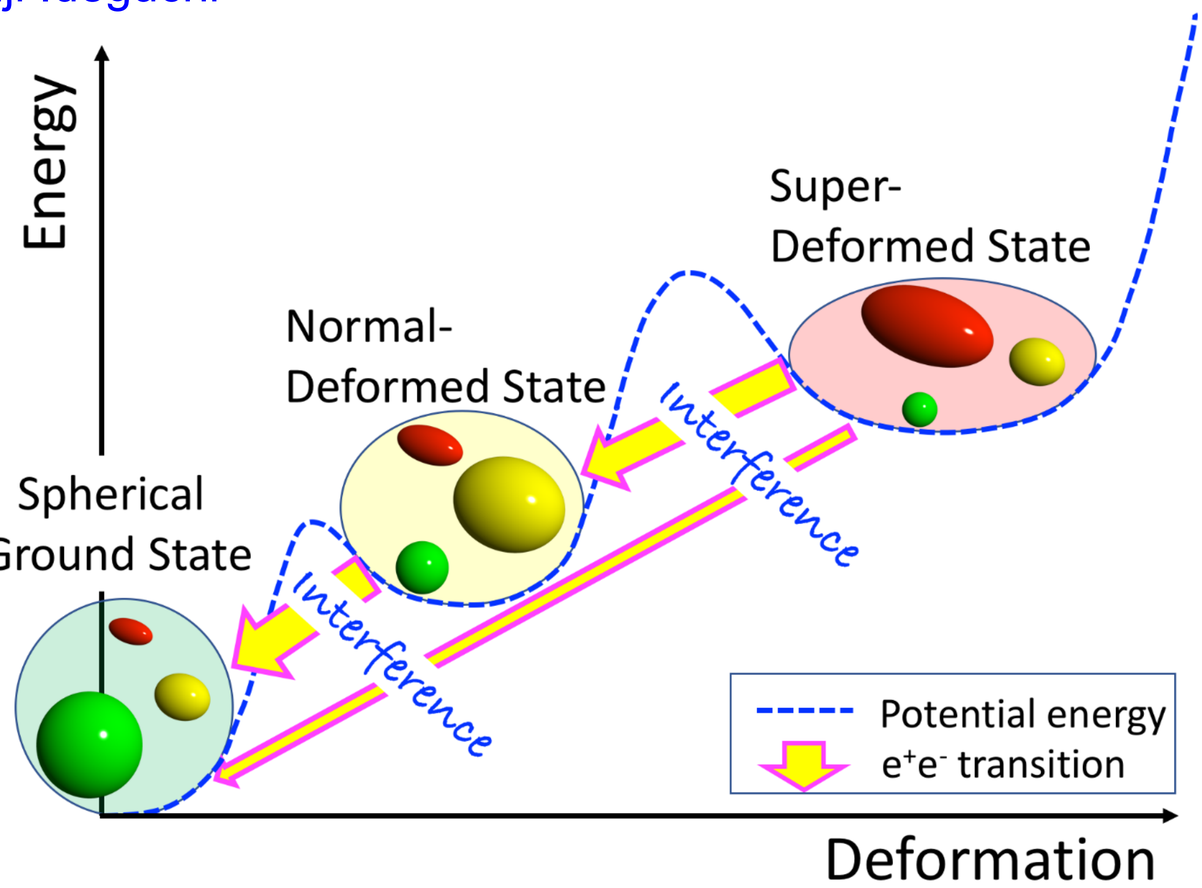
PHYSICAL REVIEW LETTERS **128,** 252501 (2022)

Electric Monopole Transition from the Superdeformed Band in ^{40}Ca

E. Ideguchi (井手口 栄治),[1,*] T. Kibédi,[2] J. T. H. Dowie,[2] T. H. Hoang,[1] M. Kumar Raju,[1,3] N. Aoi (青井 考),[1] A. J. Mitchell,[2] A. E. Stuchbery,[2] N. Shimizu (清水 則孝),[4,†] Y. Utsuno (宇都野 穣),[5,4] A. Akber,[2] L. J. Bignell,[2] B. J. Coombes,[2] T. K. Eriksen,[2] T. J. Gray,[2] G. J. Lane,[2] and B. P. McCormick[2]

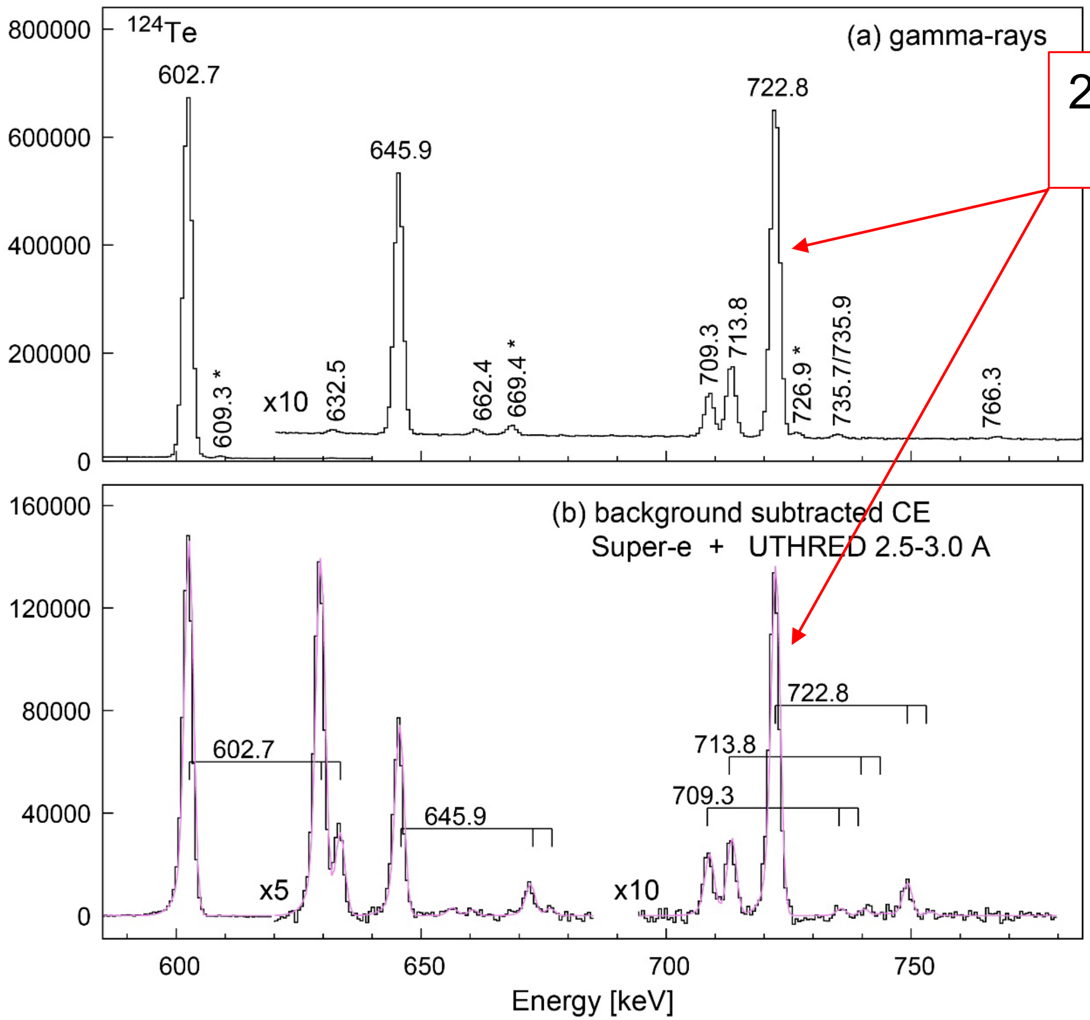
Shape co-existence in ^{40}Ca

Figure credit: Eiji Ideguchi



- Significant mixing between co-existing shapes
- 3-state mixing leads to destructive interference

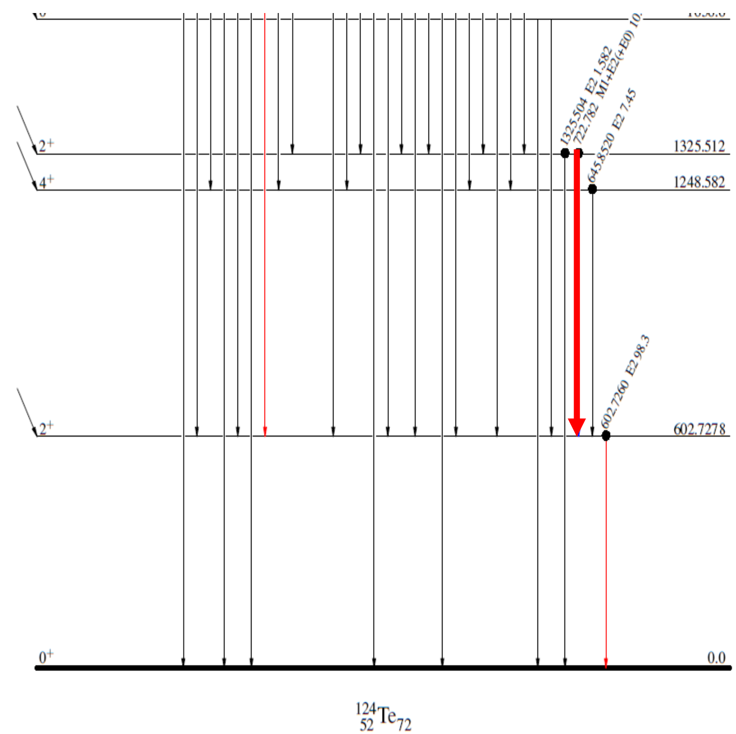
^{124}Te Conversion Electrons



$2_2^+ \rightarrow 2_1^+$ shows E0 strength:

$$10^3\rho^2 = 100^{+40}_{-30}$$

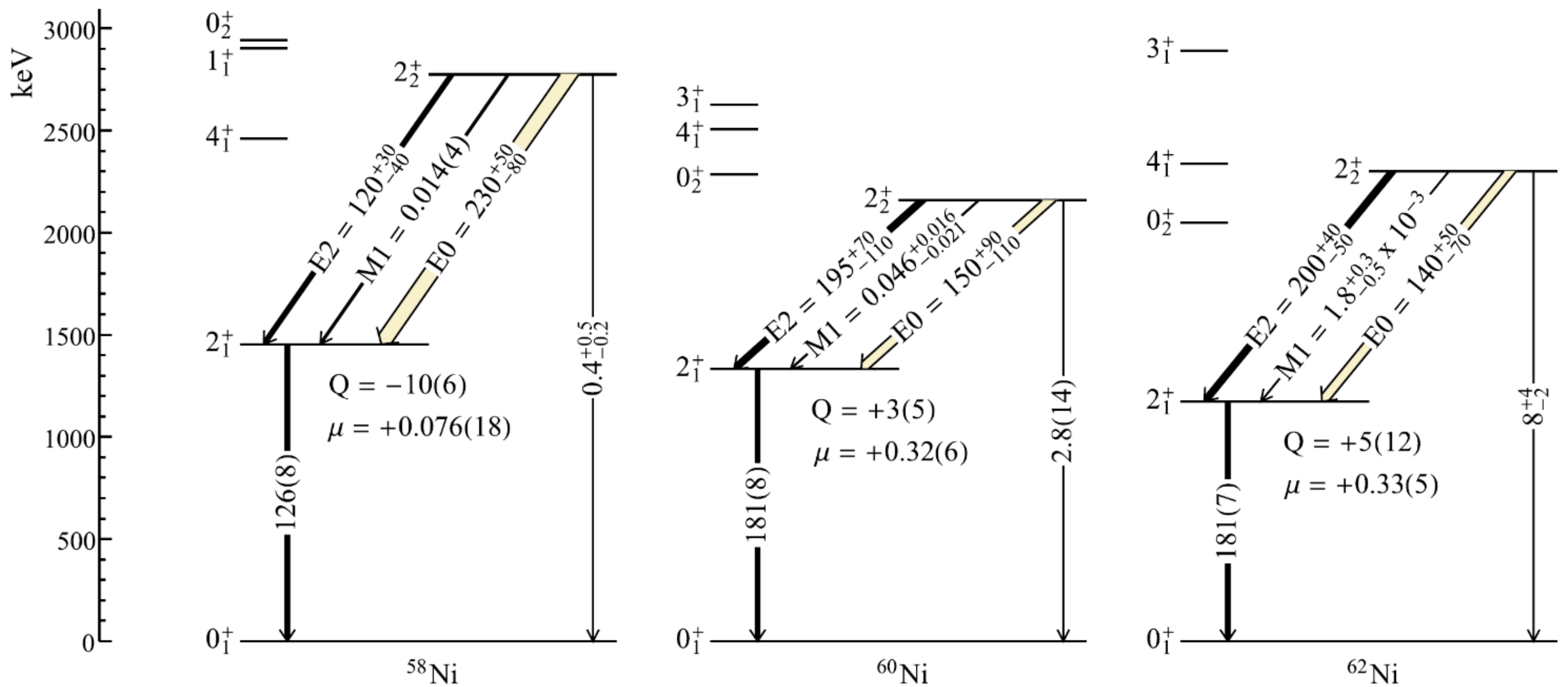
PRELIMINARY



Comparison of E0 strengths

$2_2^+ \rightarrow 2_1^+$ shows E0 strength: $10^3\rho^2 = 100^{+40}_{-30}$

Cf. Ni isotopes, for example:



From Evitts et al. Physics Letters B779 (2018) 396

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- Emerging collectivity near ^{132}Sn: Te g factors E0s and B(E2)s
- Conclusions

Conclusions / Next steps

Conclusions

- Collectivity seems to build up from lowest 2^+ state, whereas the seniority structure seems to persist longer in the 4^+ and 6^+ states
  - *Pre-collective* level structures – cannot force collective models

- $g(4^+)/g(2^+)$ suggest R_{42} ~ 2.1 is correlated with emerging collectivity in $^{124-130}$Te, but E2 rates show that this is not vibrational collectivity

- Overall, shell model descriptions are good, but there is evidence of more collectivity than accounted for by the shell model (SM) - even with effective charges

To do …

- Investigate triaxiality (Coulex and Kumar-Cline)
  - $Q(2^+)$ not well reproduced in the SM calculations
  - Does the use of effective charges in the SM compromise the evaluation of Kumar-Cline sum rules?

- Measure $g(6^+)$ in Te isotopes – ILL 3-01-724

- Measure E0 transitions – comprehensive studies to get ρ^2

General Conclusions

- Some nuclei between near-spherical and well-deformed are better described as *pre-collective* than weakly collective
  - States that are dominated by seniority coexist with states that are becoming collective.
  - These weakly collective nuclei appear to favour an average triaxial shape: Is the pathway from near-spherical doubly magic nuclei to rotors: spherical → weakly-deformed triaxial → well deformed prolate?

- Shape co-existence and shape mixing are critical but not well characterized: need E0 transitions, g factors & quadrupole moments, along with B(E2)s

Acknowledgments

The ANU Nuclear Structure Group

Tibor Kibédi, Greg Lane, Georgi Georgiev (on sabbatical from CSNSM in 2018-19), AJ Mitchell, Lindsey Bignell, Jackson Dowie, Tim Gray, Ben Coombes, Brendan McCormick, Martha Reece

John Wood
(ideas and discussion)

Mitch Allmond (ORNL)

Tim & Ben

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END