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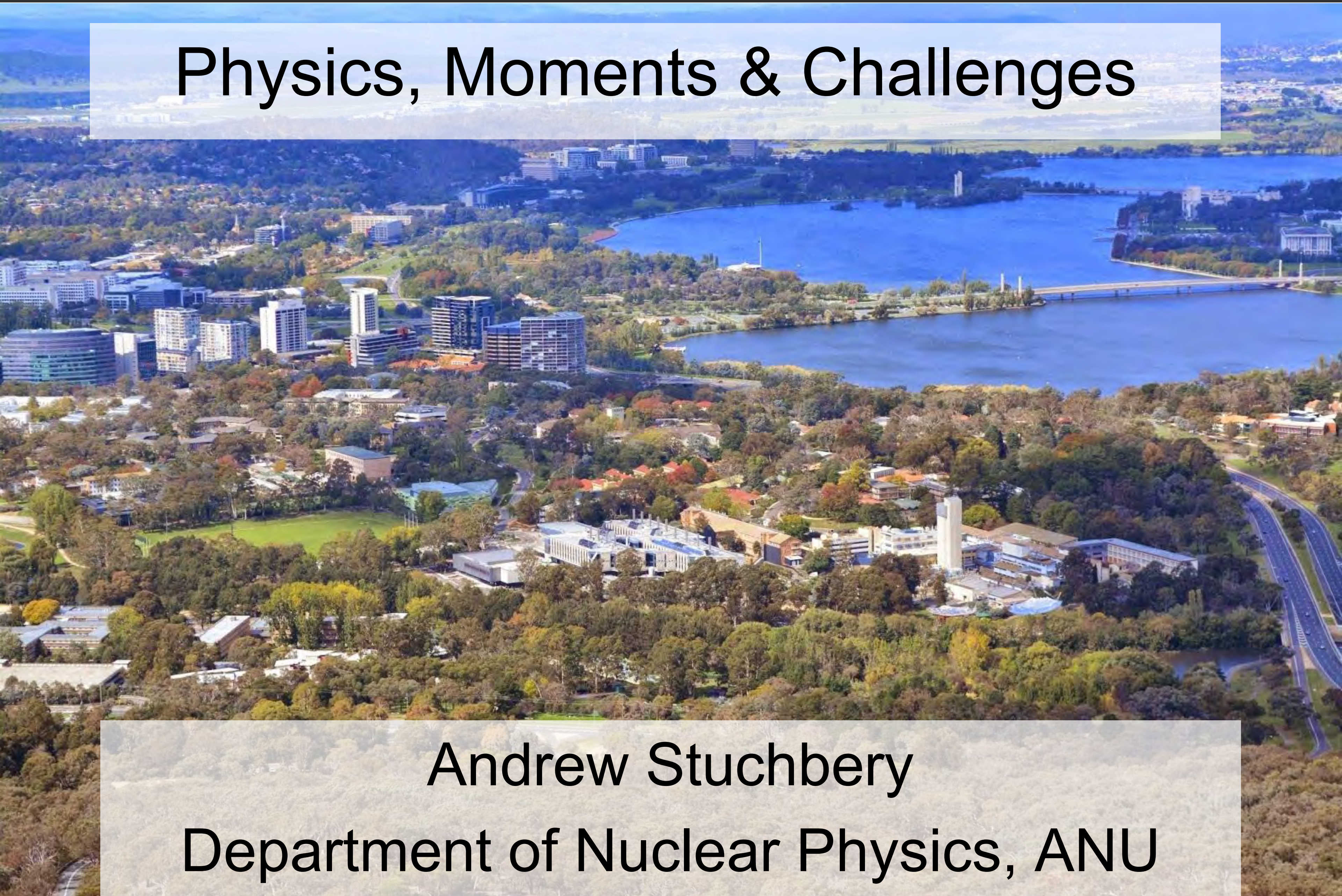
Physics, Moments & Challenges



Andrew Stuchbery

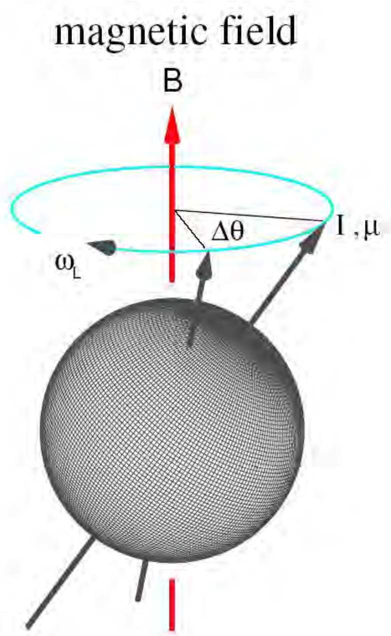
Department of Nuclear Physics, ANU

Australian National University

Excited-state g factors

gSPEC – g factors at FAIR

- Fast beams
- Focus on excited states & γ-ray measurements
- TDPAD/Transient Field/Recoil in Vacuum/Decay spectroscopy – IPAC
- Isomeric states/short-lived states



Nuclear spectroscopy
with a twist!

Outline

- Some physics of moments
  - ✓ Nuclear collectivity
  - ✓ Emerging collectivity
  - ✓ Shell model applications
  - ✓ Isomers – High-spin and K-isomers

- Experimental methods – opportunities and challenges
  - ✓ Transient fields
  - ✓ Recoil in vacuum (including TDRIV)
  - ✓ Decay spectroscopy IPAC method
  - ✓ TDPAD external (and internal?) fields

↓ Increasing relevance for FAIR

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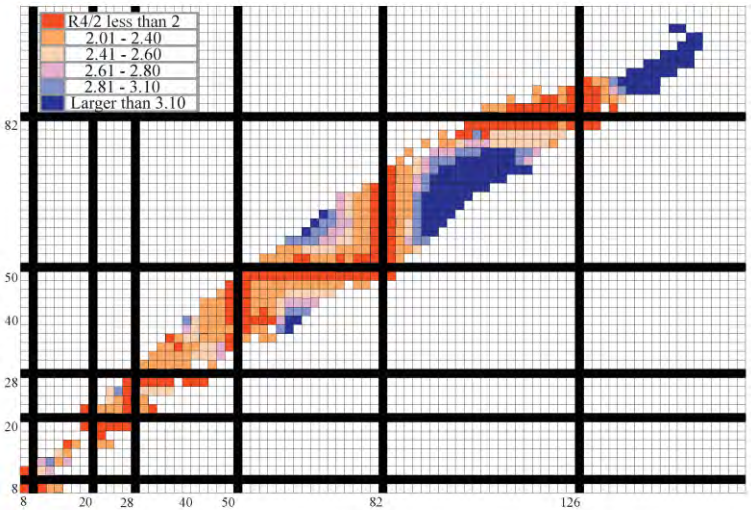
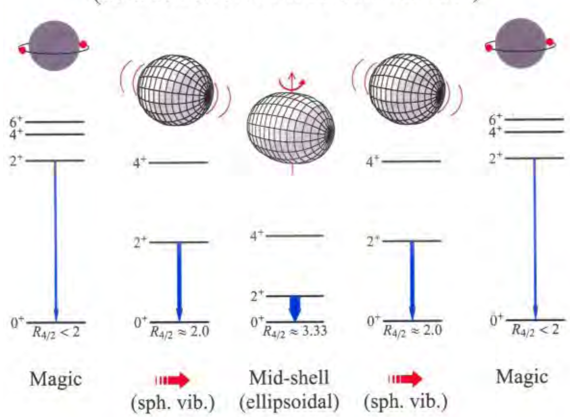
Nuclear Collectivity

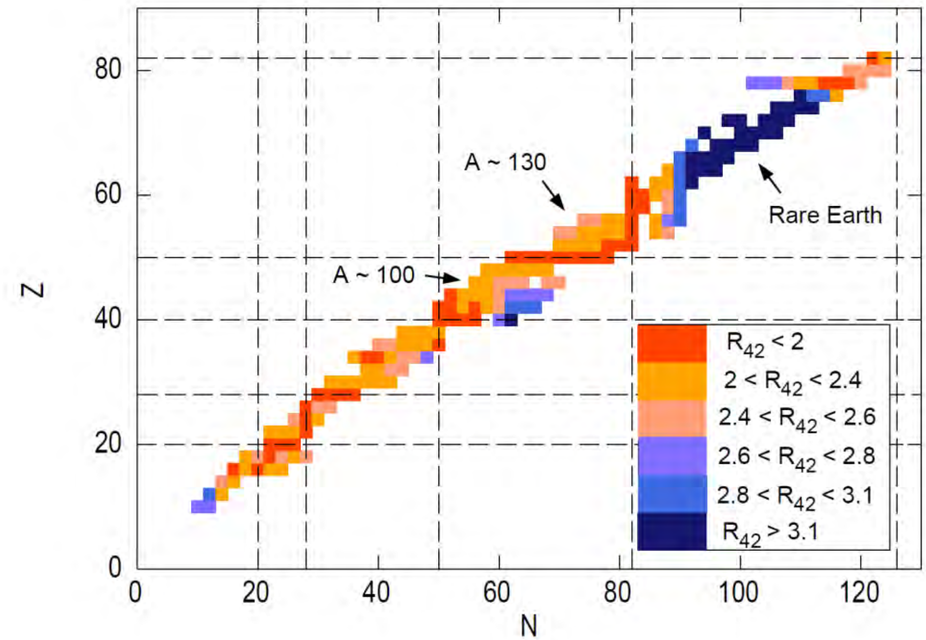
R(E(4⁺) / E(2⁺)) Systematics plot (Burcu Cakirli)



Evolution of nuclear structure
(as a function of nucleon number)



g factor data for first 2⁺ states



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

Angular momentum of protons

Total angular momentum

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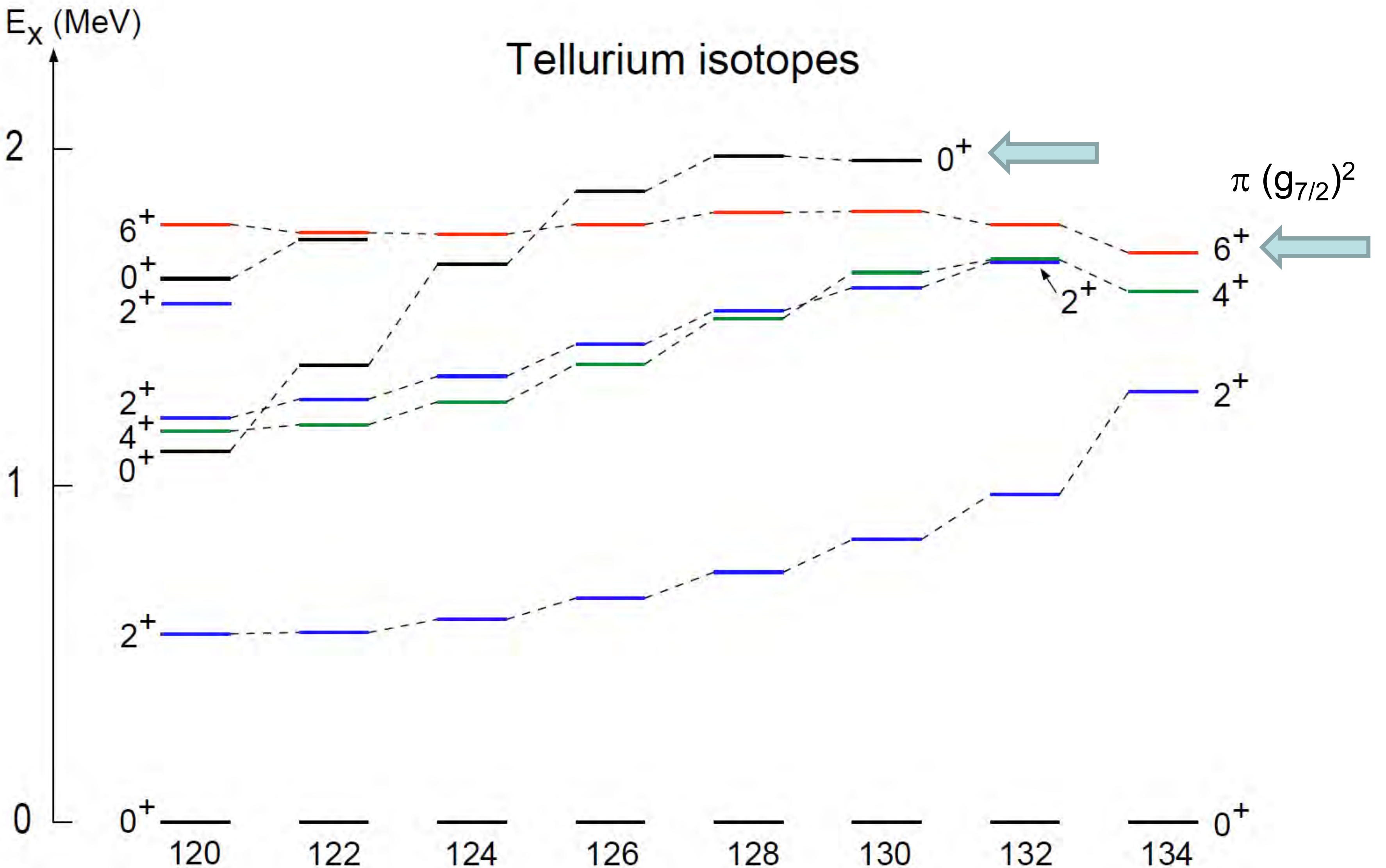
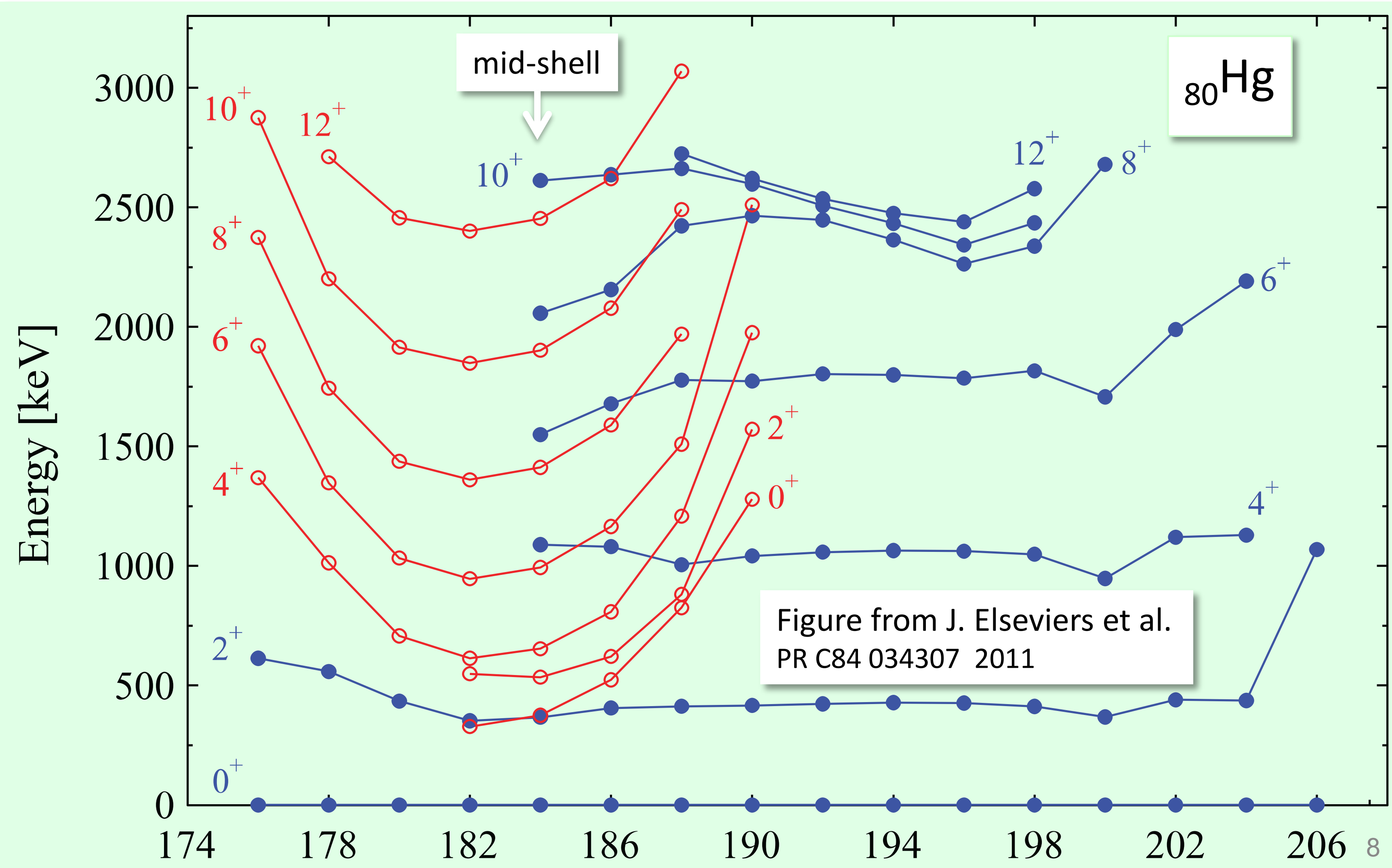
Emerging nuclear collectivity



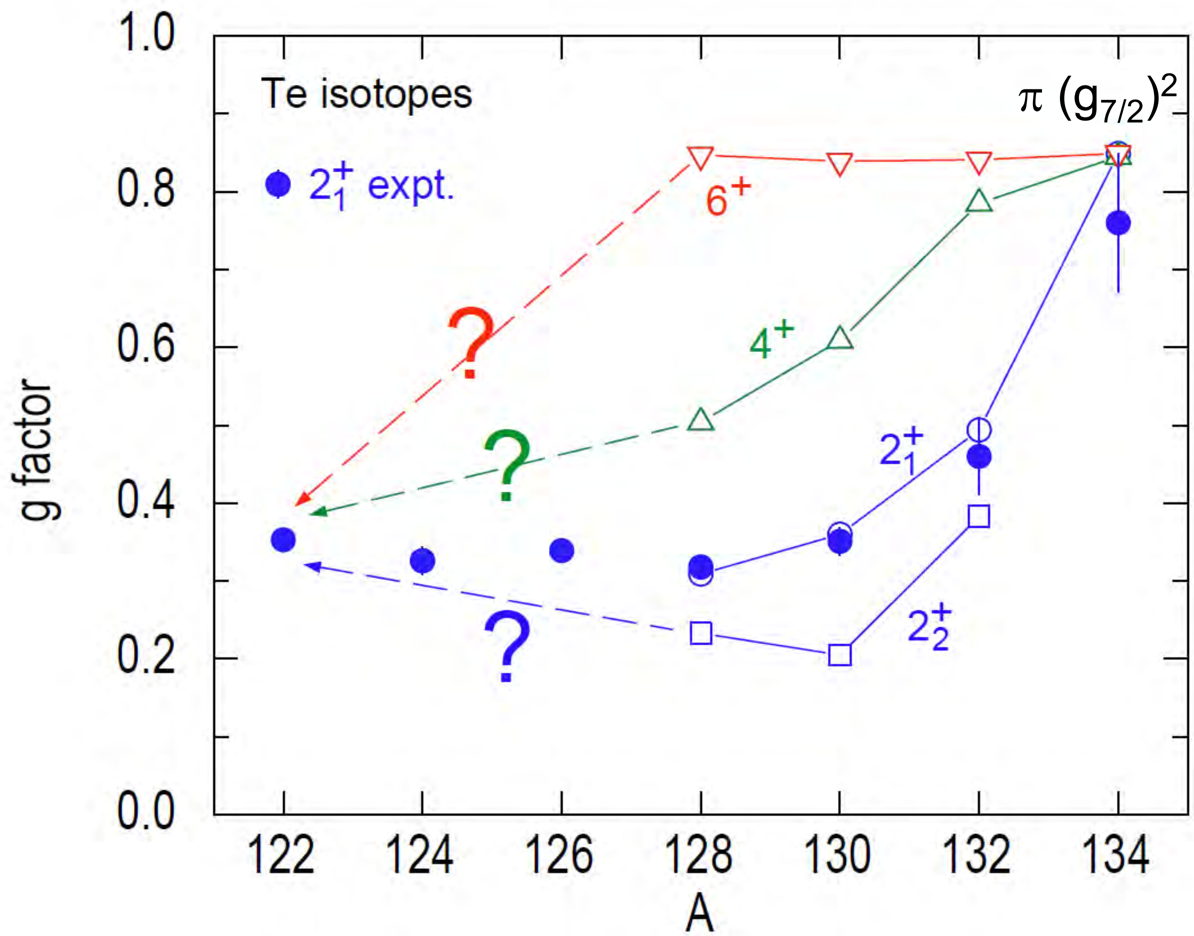
Shape coexistence in the even-Hg isotopes:

NOTE characteristic *parabolic energy* trend

Slide from John Wood



g factors & collectivity



Questions

Need data!

E0, M1, E2

e.g. 6^+ g factors
TDPAD → IPAC

Many methods;
Many facilities?

Nushellx with 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)

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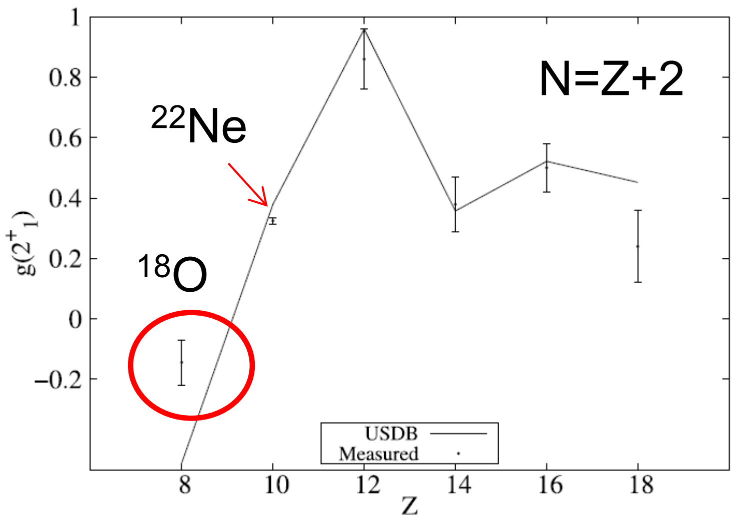
Do we understand the sd shell?

- g.s. moments of odd-A nuclei – sensitive to odd nucleon not the 'core'
- g(2^+) measured mainly in N=Z nuclei where g(2^+) ~ 0.5
- USD shell model can fail for excited states with N $\neq$ Z

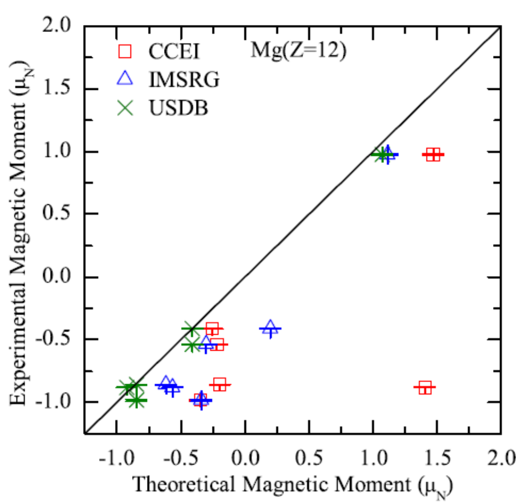


B.P. McCormick et al. PLB 779 (2018) 445

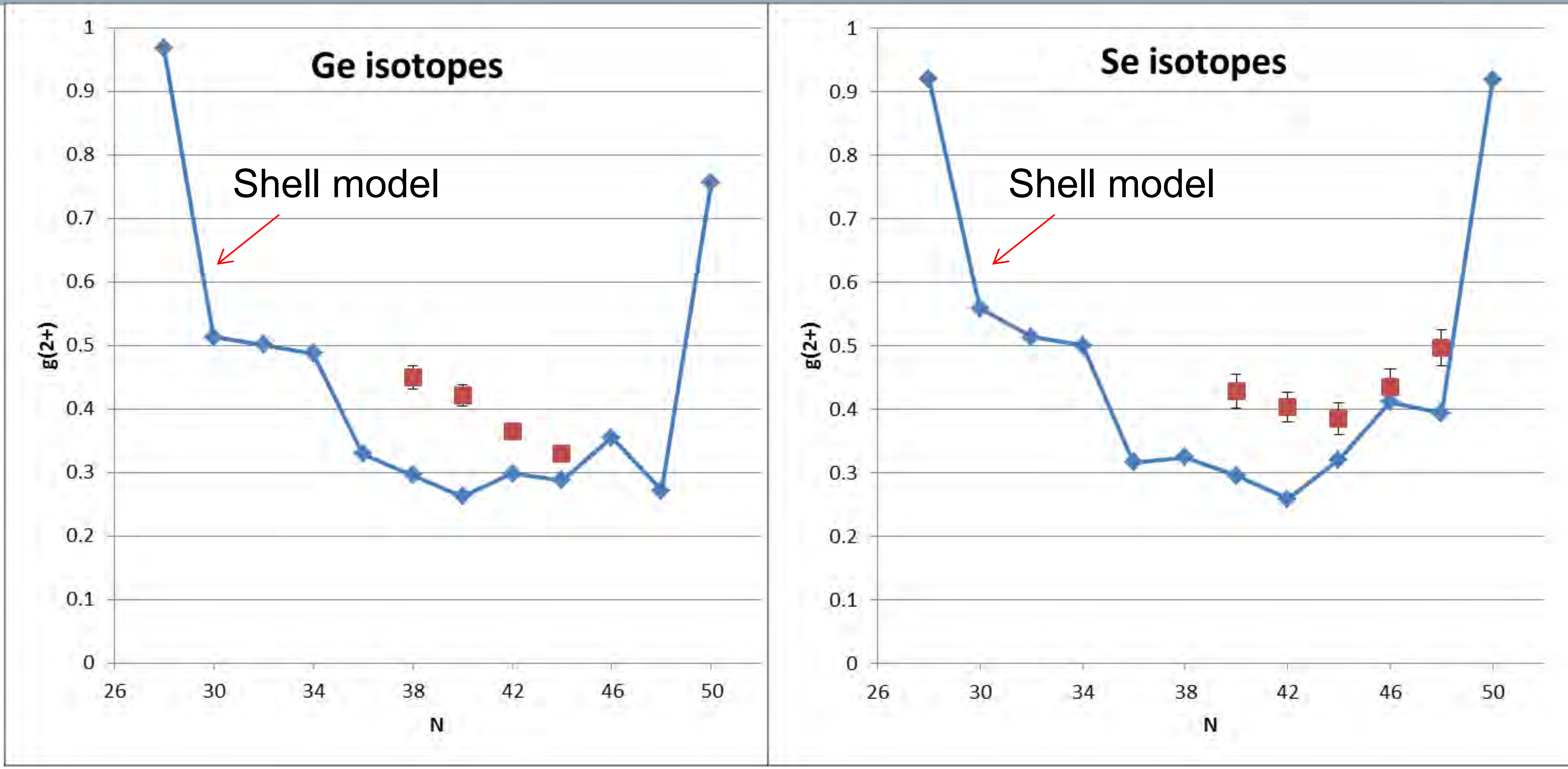
PHYSICAL REVIEW C **96**, 024316 (2017)

First-principles results for electromagnetic properties of *sd* shell nuclei

Archana Saxena* and Praveen C. Srivastava†



Ge and Se isotopes



Shell model: jj44B interaction (Alex brown)

Level schemes: Phys. Scr. 88 (2013) 045201

Ge Data: Gurdal et al PRC 88, 014301(2013); Se Data: Speidel et al PRC 57, 2181(1998)

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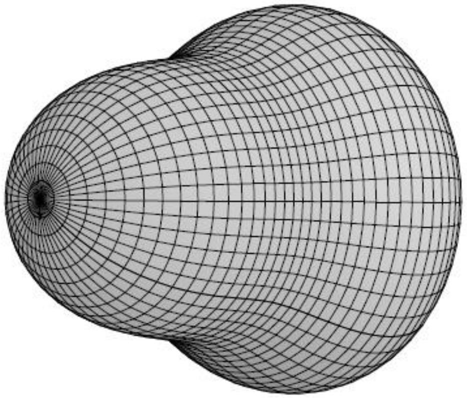
High-spin isomers near ^{208}Pb



Octupole transitions near ^{208}Pb

- Enhanced $\pi i_{13/2} \rightarrow \pi f_{7/2}$ transitions ~20-30 W.u.
- Coupling to 3^- excitation of ^{208}Pb core
  - nominal $\pi i_{13/2}$ state contains $\pi f_{7/2} \otimes 3^-$
  - nominal $\pi f_{7/2}$ state contains $\pi i_{13/2} \otimes 3^-$

Question: How does E3 strength develop as protons and neutrons are added?

- Adding successive $\pi h_{9/2}$ protons and $\nu p_{1/2}$ neutron hole to ^{208}Pb

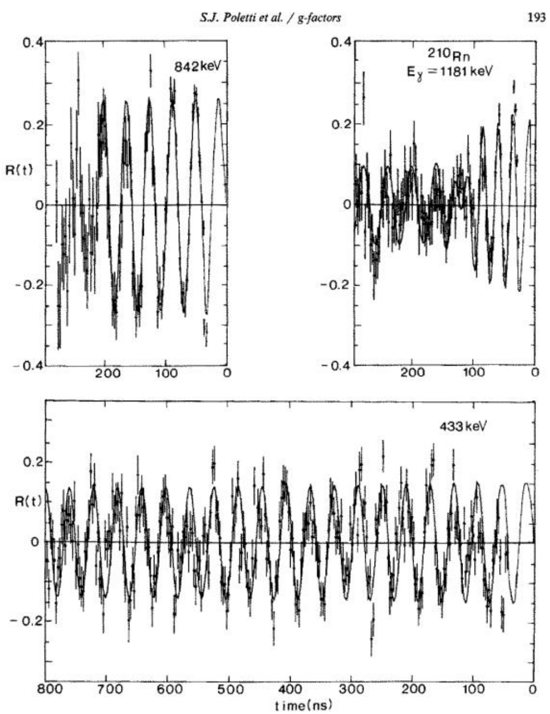
Collective octupole transitions near ^{208}Pb
Talk by Robert Janssens at NS18

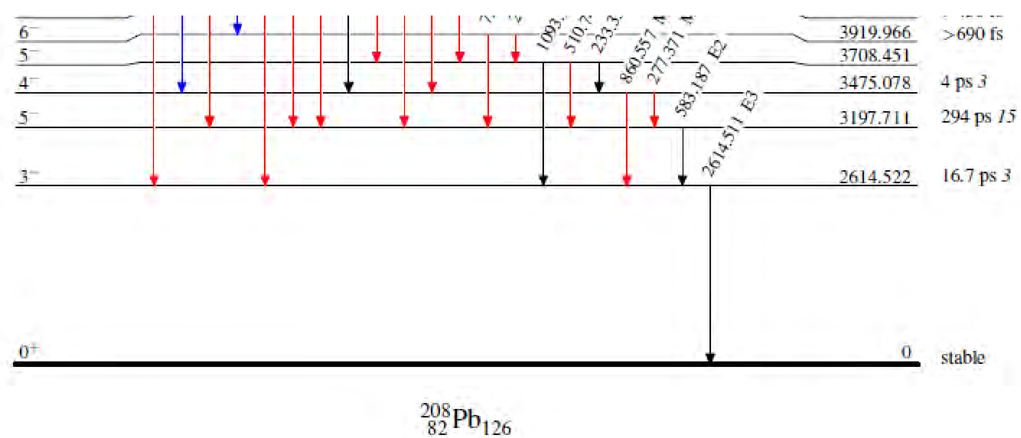
High-spin isomers near ^{208}Pb

Single-particle energies, energy depressions due to octupole coupling and wave functions

Nucleus	Empirical state	Energy [keV]	$\Delta E^{\mathrm{oct\,a)}}$	Wave function$^{\mathrm{b)}}$
^{209}Bi	$\pi\|\tilde{i}_{13/2}\rangle$	1609	410	$0.912\|i_{13/2}\rangle + 0.365\|f_{7/2}\otimes 3^-\rangle + 0.19\|h_{9/2}\otimes 3^-\rangle$
	$\pi\|\tilde{f}_{7/2}\rangle$	897	387	$0.952\|f_{7/2}\rangle + 0.307\|(i_{13/2}\otimes 3^-)_{7/2}\rangle$
	$\pi\|\tilde{h}_{9/2}\rangle$	0	15	$0.998\|h_{9/2}\rangle - 0.061\|(i_{13/2}\otimes 3^-)_{9/2}\rangle$
^{209}Pb	$\nu\|\tilde{g}_{9/2}\rangle$	0	213	$0.977\|g_{9/2}\rangle + 0.214\|(j_{15/2}\otimes 3^-{}_{-9/2})\rangle$
	$\nu\|\tilde{j}_{15/2}\rangle$	1422	426	$0.875\|j_{15/2}\rangle + 0.484\|(g_{9/2}\otimes 3^-)\rangle$

[a]) Energy depression due to particle-octupole vibration coupling.
[b]) The amplitudes were calculated using matrix diagonalisation and the matrix elements of refs. [13,16]).





TDPAD @ ANU mid 1980s!
Rn, Fr, Ra isotopes

NPA 448 (1986) 189

Isomers in Rn isotopes

86) 189

Eigenvectors of related core-excited states in ^{210}Rn, ^{211}Rn, ^{212}Rn

Basis states	Amplitudes				
	$^{211}\text{Rn}, \frac{49}{2}^{+}$ $+(\nu^{-2})_0$	$^{210}\text{Rn}, 25^{-}$ $+(\nu^{-1})_{1/2}$	$^{212}\text{Rn}, 25^{-}$ $+(\nu^{-1})_{1/2}$	$^{211}\text{Rn}, \frac{63}{2}^{-}$ $+(\nu^{-1}\text{i}_{11/2})_7$	$^{212}\text{Rn}, 30^{+}$ $+\nu\text{i}_{11/2}$
$\pi(\text{h}^2\text{i}^2)_{20^+}\nu\text{g}$	0.560	−0.548	0.527	−0.554	−0.606
$\pi(\text{h}^3\text{i})_{17^-}\nu\text{j}$	0.420	−0.462	0.424	−0.512	0.441
$\pi(\text{h}^3\text{i})_{17^-}\nu\text{g})_{43/2^-}\otimes 3^-$	0.249	−0.267	0.257	−0.268	−0.241
$(\pi(\text{h}^3\text{f})_{14}+\nu\text{j})_{43/2^-}\otimes 3^-$	0.192	−0.203	0.201	−0.193	−0.175
$\lvert\psi\rangle_-$	−0.039	0.038	−0.036	0.038	0.043
$\lvert\psi\rangle_+$	0.368	−0.349	0.374	−0.319	−0.339
$\pi(\text{h}^3\text{f})_{14^+}\nu\text{g}\otimes(3^-)^2$	0.128	−0.133	0.137	−0.115	−0.110
$\pi(\text{h}^2(\text{if})_{9^-})_{17^-}\nu\text{j}$	0.415	−0.391	0.433	−0.368	−0.379
$\pi(\text{h}^2\text{f}^2)_{14^+}\nu\text{j}\otimes 3^-$	0.156	−0.146	0.167	−0.120	−0.125
$\pi(\text{h}^2\text{f}^2)_{14^+}\nu\text{g}\otimes(3^-)^2$	0.130	−0.123	0.137	−0.098	−0.106
$\lvert\chi\rangle_-$	−0.005	0.004	−0.009	0.001	−0.002
$\lvert\chi\rangle_+$	0.204	−0.194	0.195	−0.205	−0.217
$\pi\text{h}^2((\text{if})_{10^-}\nu\text{j}_{15/2})_{33/2}$	0.052	−0.065	0.062	−0.057	−0.058

$$\lvert\psi\rangle_\pm = \left(\pi\left(\text{h}^2(\text{if})_{9^-}\right)_{17^-}\nu\text{g}\right)\otimes 3^- \pm \pi\left(\text{h}^2(\text{i}(\text{f}\otimes 3^-)_{13/2})_{12^+}\right)\nu\text{g}\times 1/\sqrt{2(1\pm\delta_1)}, \qquad \delta_1 = 0.84;$$

$$\lvert\chi\rangle_\pm = \left(\pi\left(\text{h}^2(\text{i}^2\otimes 3^-)_{9^-}\nu\text{j}\pm\pi(\text{h}^2\text{i}^2)_{20}+(\nu\text{j}\otimes 3^-)_{9/2}\right)\times 1/\sqrt{2(1\pm\delta_2)}\right. \qquad \delta_2 = 0.69.$$

Octuple collectivity in new regions?

- ^{132}Sn contrast with ^{208}Pb
- Octupole collectivity near ^{146}Gd ?

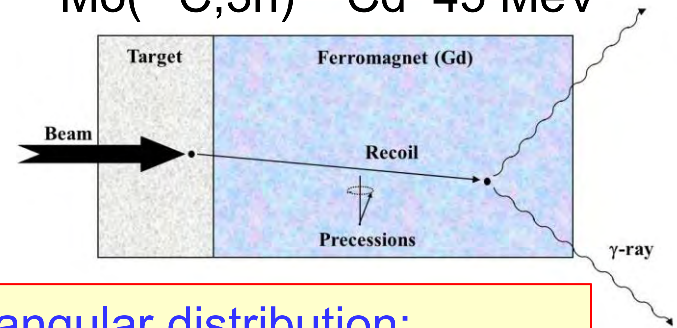
^{110}Cd: g(10+) puzzle

Measurement of the g-factor of the yrast 10^+ state in ^{110}Cd

P.H. Regan [a,b], A.E. Stuchbery [a], S.S. Anderssen [a]

Nucl. Phys. A 591, 533 (1995)

^{100}Mo(^{13}C,3n)^{110}Cd 45 MeV



Measured $g(10^+) = -0.09(3)$ by integral perturbed angular distribution:
$\omega\tau = -g\frac{\mu_N}{\hbar}B\tau$ where $B = 33$ tesla is internal field at site of implanted Cd in *Gd*

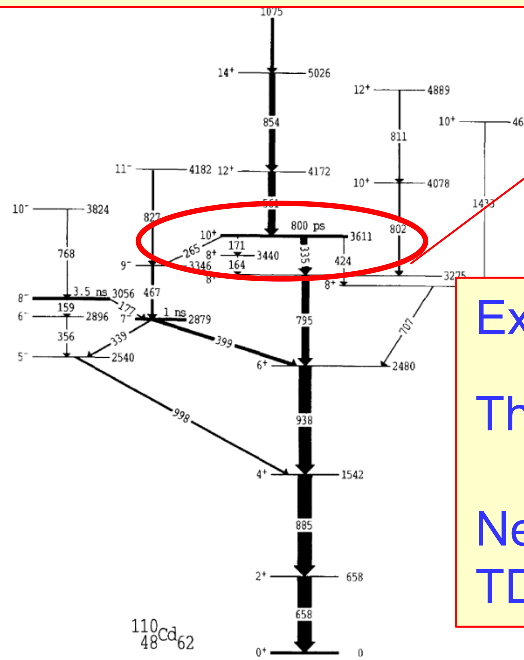


Fig. 1. Partial decay scheme for ^{110}Cd. Mean lives are shown for the longer-lived states of interest.

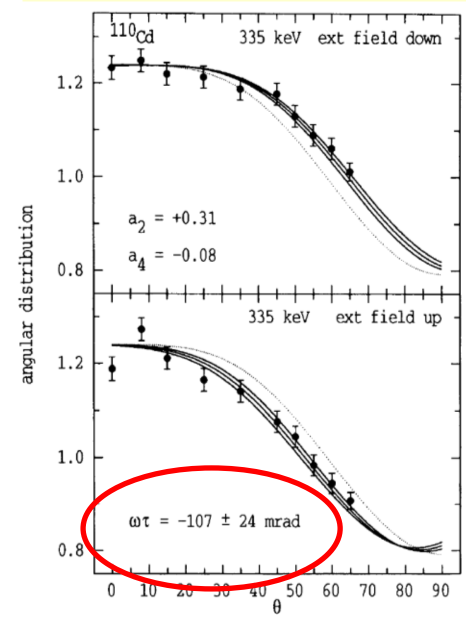
g(10$^+$) = -0.09(3)

Expected $g \sim -0.2$ for $\nu(h_{11/2})^2$

Thus $g \sim -0.1$ looks WRONG!

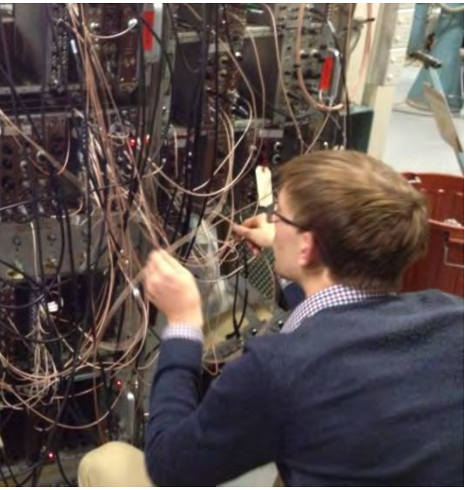
Need to check internal field:
TDPAD with $LaBr_3$ detectors

Robust $\omega\tau$ measured

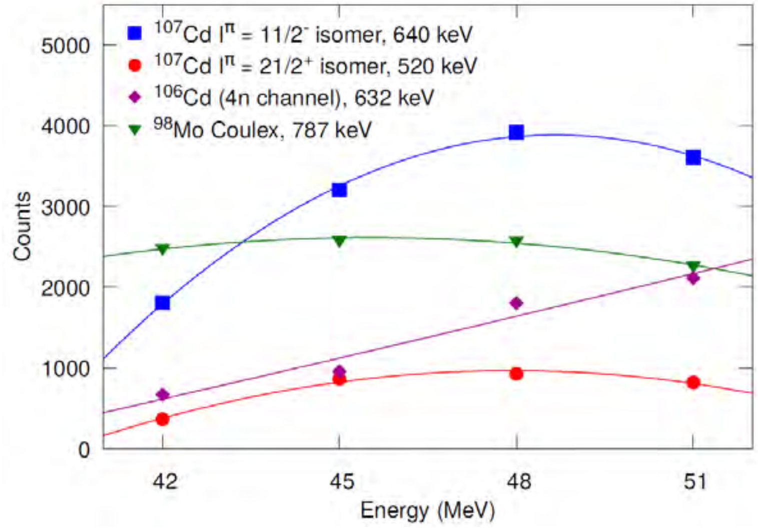


$LaBr_3$ TDPAD

$^{98}Mo(^{12}C, 3n)^{107}Cd$ into Gd
E_γ = 640 keV, $11/2^-$, $T_{1/2}$ = 74 ns; precession period T~12 ns
48 MeV pulsed beam from ANU 4UD Pelletron accelerator
Time Dependent Perturbed Angular Distribution



Tim Gray



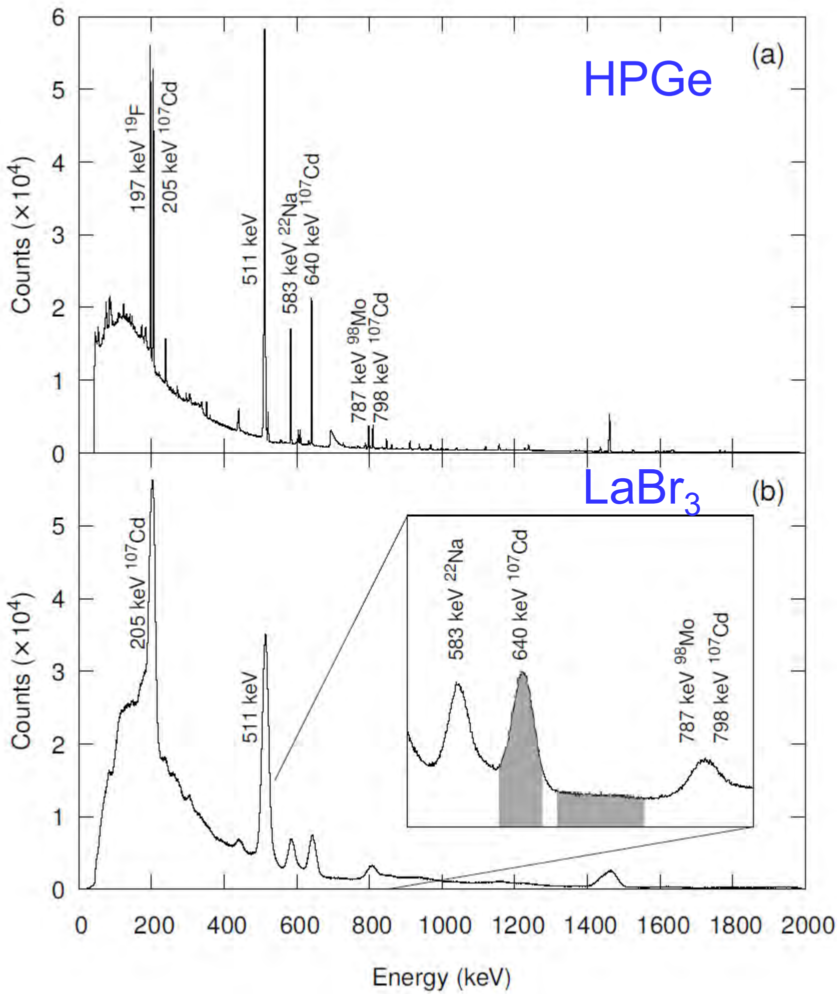
Excitation functions

PHYSICAL REVIEW C **96**, 054332 (2017)

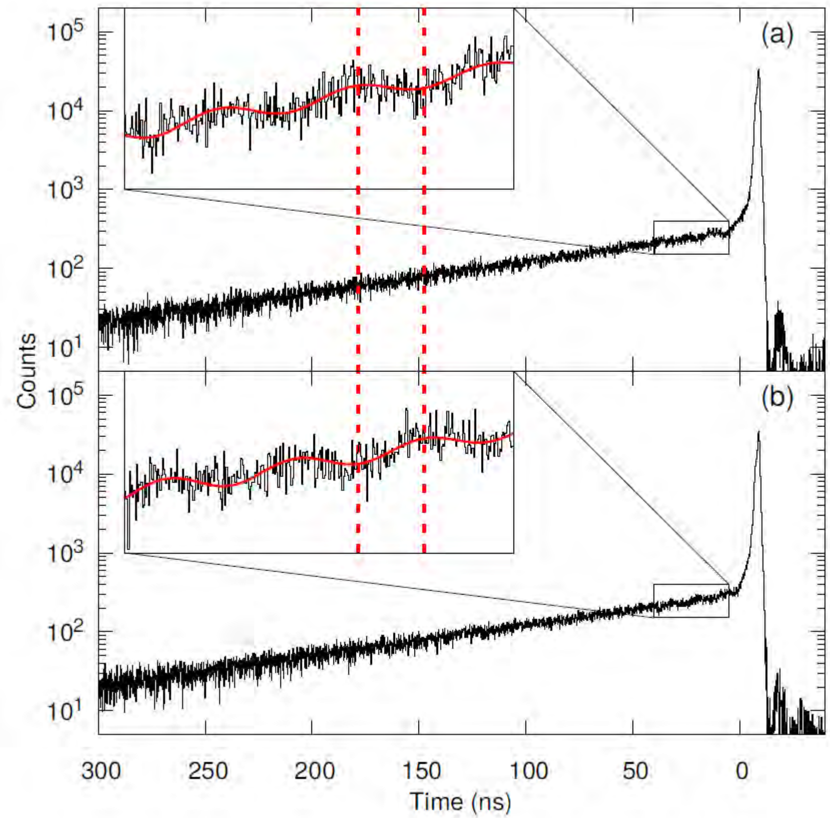
Perturbed angular distributions with $LaBr_3$ detectors: The *g* factor of the first 10^+ state in ^{110}Cd reexamined

T. J. Gray, A. E. Stuchbery, M. W. Reed, A. Akber, B. J. Coombes, J. T. H. Dowie, T. K. Eriksen, M. S. M. Gerathy, T. Kibédi, G. J. Lane, A. J. Mitchell, T. Palazzo, and T. Tornyi

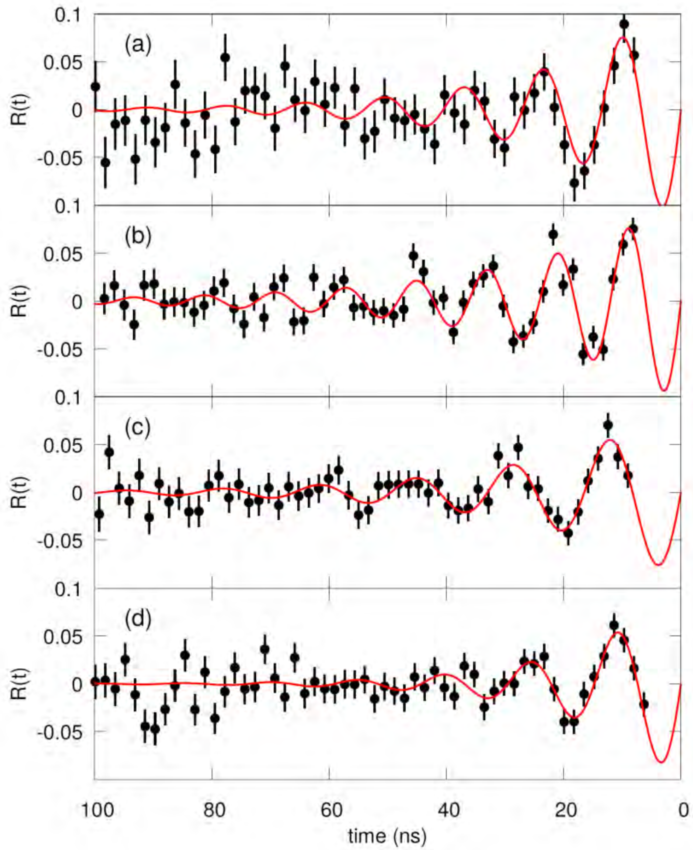
gamma and time spectra

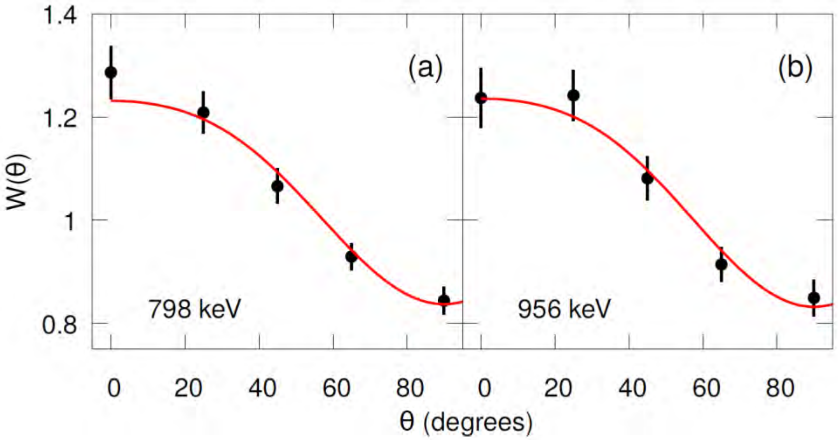


847-keV isomer decay



^{107}Cd in gadolinium





Angular distributions set expected amplitude of R(t)

The period matches that of the expected ~ 33 Tesla field but:

- Decaying amplitude means a distribution of fields
- Low amplitude of R(t) implies low-field sites
- Accumulating radiation damage

Outcomes

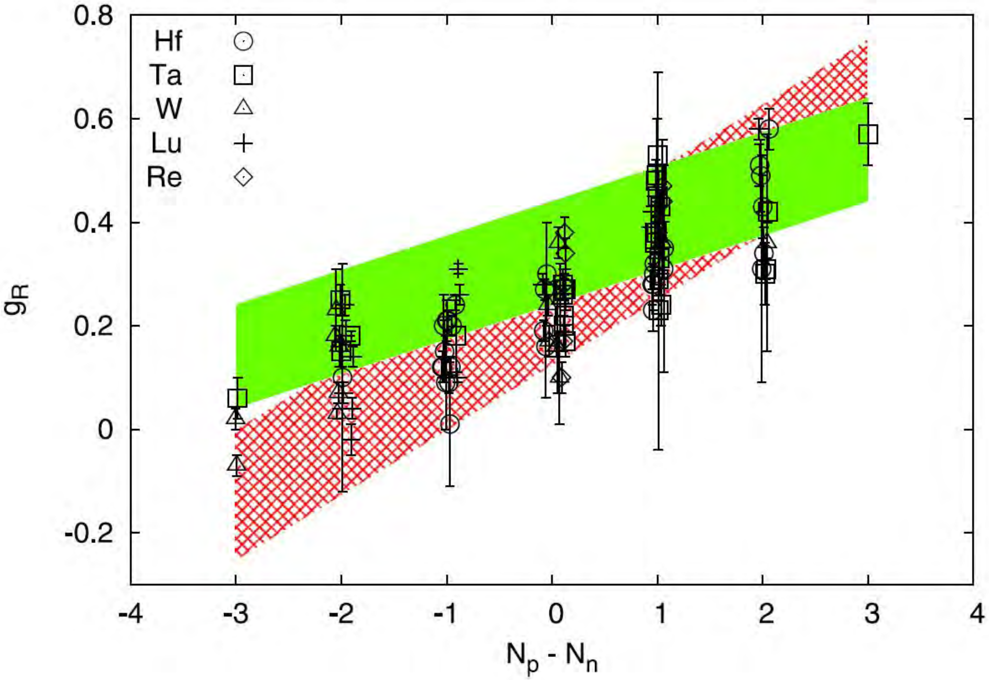
- Successful application of LaBr3 detectors to the in-beam TDPAD method
- Gadolinium hosts may be of limited use (complex field distributions; radiation damage)
- 10^+ state in ^{110}Cd g factor consistent with seniority-2 $\nu h_{11/2}$ configuration

K isomers

$$g = g_R + \frac{K^2}{I(I+1)}(g_K - g_R)$$

Multiquasiparticle states:

$K = \sum K_i \qquad K g_K = \sum K_i g_{K_i}$



Quasi-particle and collective magnetism: Rotation, pairing and blocking in high-*K* isomers

N.J. Stone [a,b], J.R. Stone [a,b], P.M. Walker [c], C.R. Bingham [b,d]

Physics Letters B 726 (2013) 675

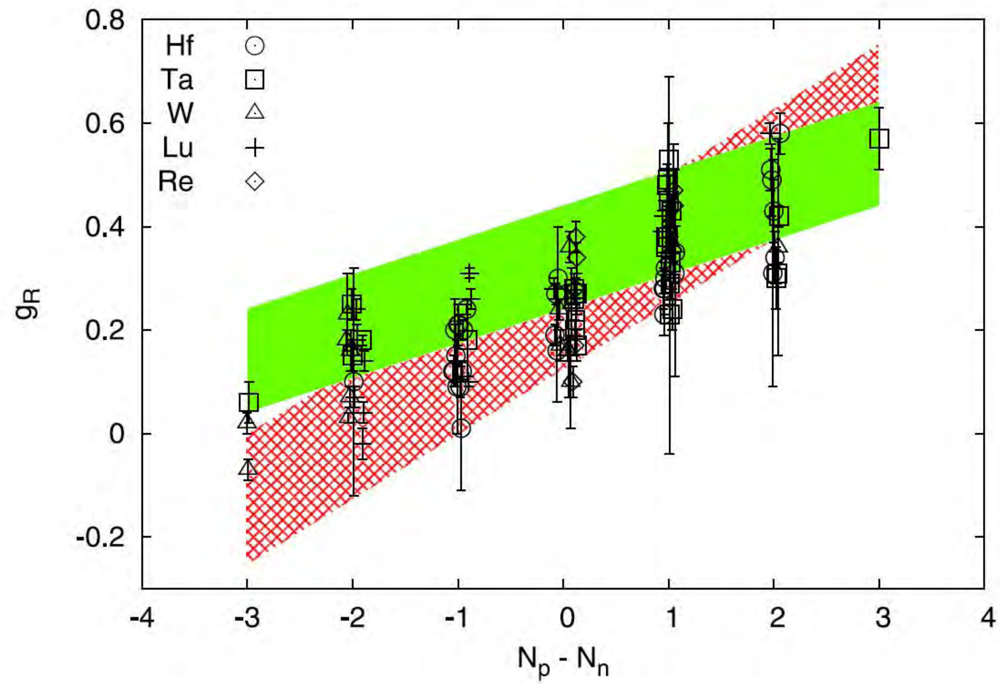
K isomers

$$g = g_R + \frac{K^2}{I(I+1)}(g_K - g_R)$$

Multiquasiparticle states:

$$K = \sum K_i \qquad K g_K = \sum K_i g_{K_i}$$

Pairing blocked



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

Angular momentum of protons

Total angular momentum

Moment of inertia of protons

Total moment of inertia

Open questions

- What is the relation ship between collective magnetism and pairing?
- How do we understand the high-K g factor data?

NPA 589 (1995) 222

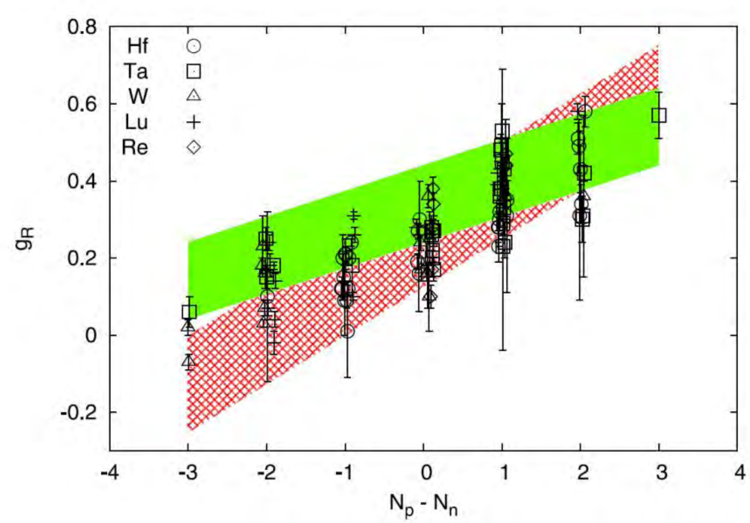
Deformation, pairing and magnetic moments in rare-earth nuclei

Andrew E. Stuchbery

NPA 669 (2000) 27

Magnetic moments in the $1/2^{-}[521]$ ground-state band of ^{171}Yb and Coriolis-induced renormalization of rotational g-factors in odd-A rare-earth nuclei

A.E. Stuchbery [a], S.S. Anderssen [a,1], H.H. Bolotin [b]



… the renormalization of the rotational *g*-factor in the low-*K*, single-quasiparticle bands of odd rare-earth nuclei, compared with their even neighbours, is predominantly due to Coriolis interactions

- High-K isomer moments are interesting!

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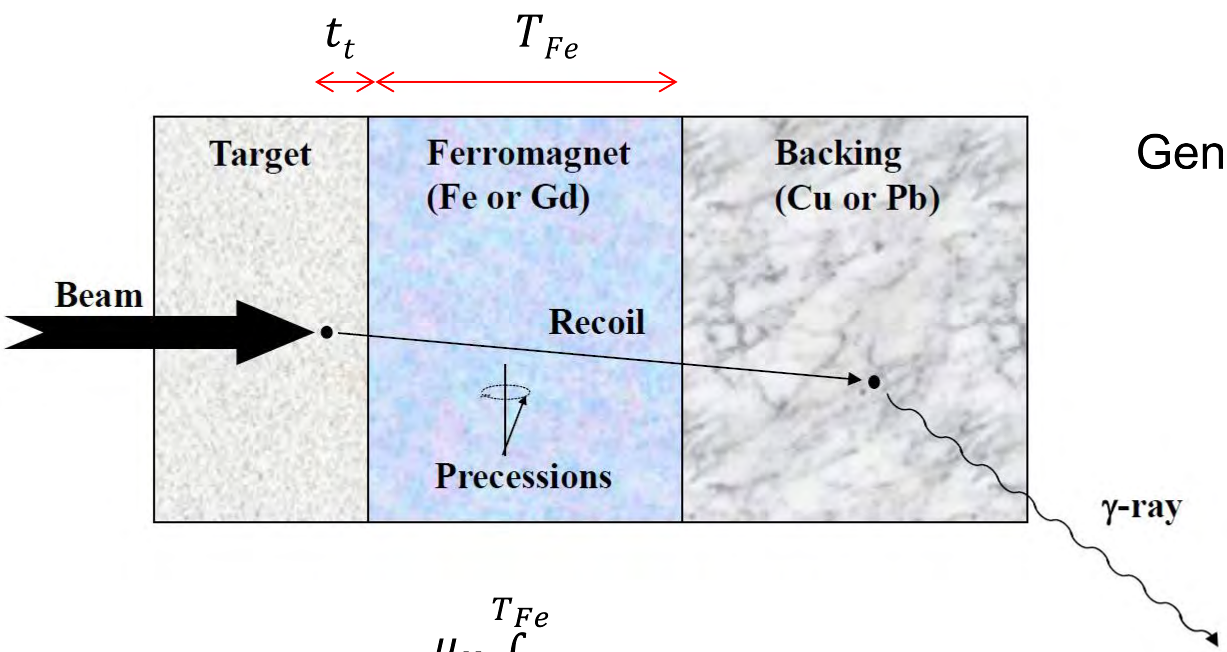
Increasing relevance for FAIR

Transient Fields – 50 years in 2018



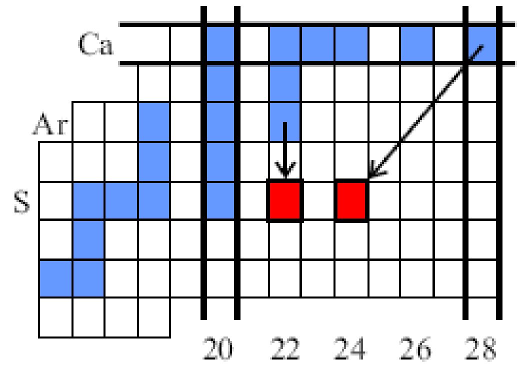
Generally insensitive to lifetime
$\tau \gg TFe \; < 1\,\text{ps}$

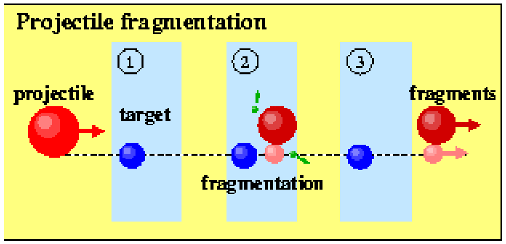
$$\Delta\theta = -g\frac{\mu_N}{\hbar}\int_0^{T_{Fe}} B(v(t))e^{-(t+t_t)/\tau}dt$$

- Good for relative g-factor measurements on picosecond states
  - Conventional and inverse kinematics (target vs beam excitation)
  - Good if calibrate relative to independently known g factor
  - Gives the *sign*

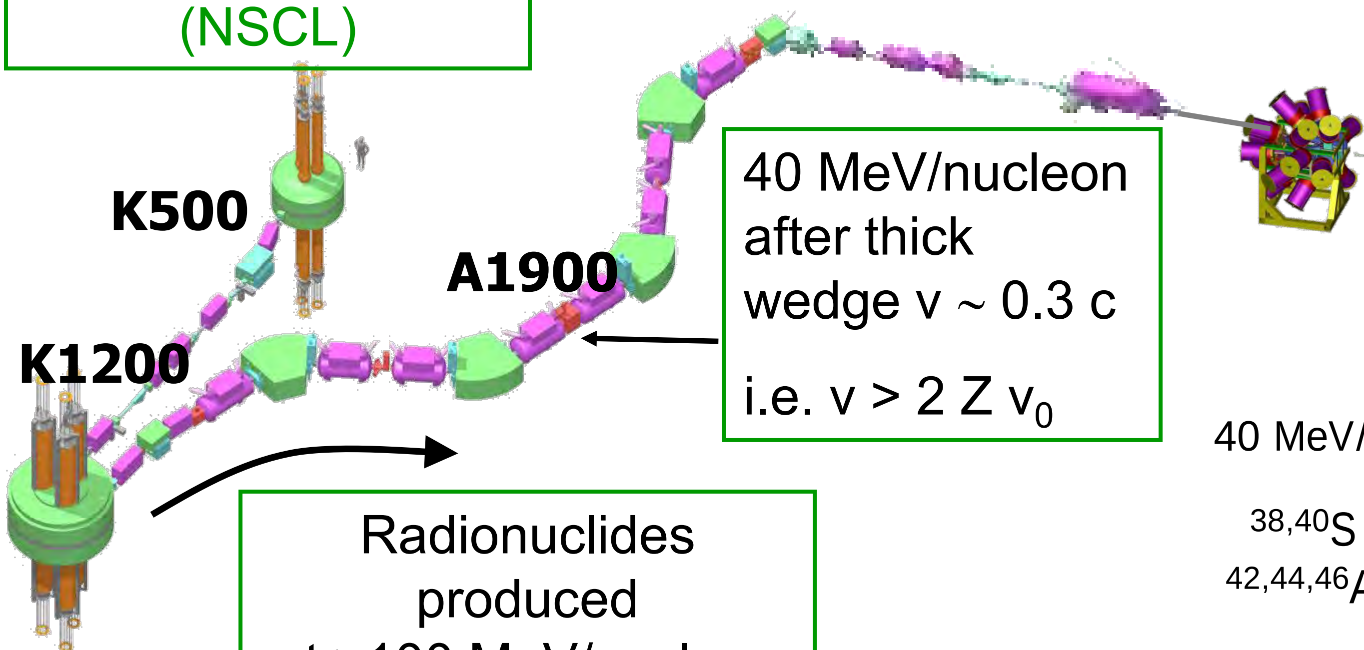
High Velocity Transient Field (HVTF) measurements at NSCL

^{40}Ar → ^{38}S, 10^5 pps
^{48}Ca → ^{40}S, 10^4 pps
^{48}Ca → ^{42,44,46}Ar, 10^5 pps





Coupled Cyclotrons (NSCL)

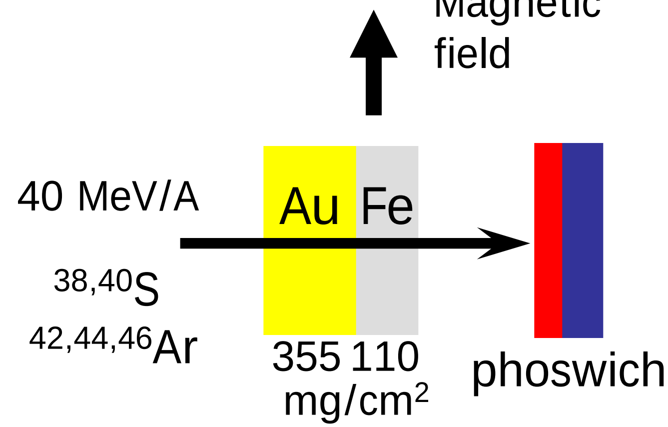


40 MeV/nucleon after thick wedge v ~ 0.3 c

i.e. v > 2 Z v_0

Experimental endstation (SeGA)

Radionuclides produced at >100 MeV/nucleon



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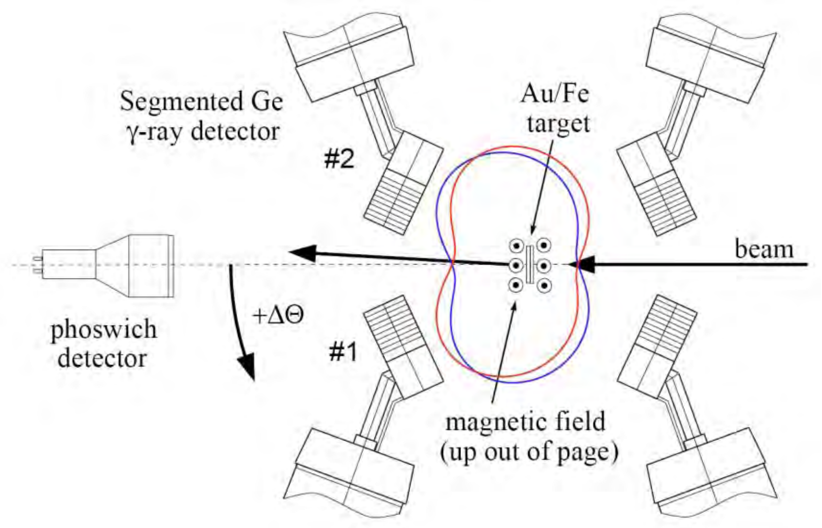
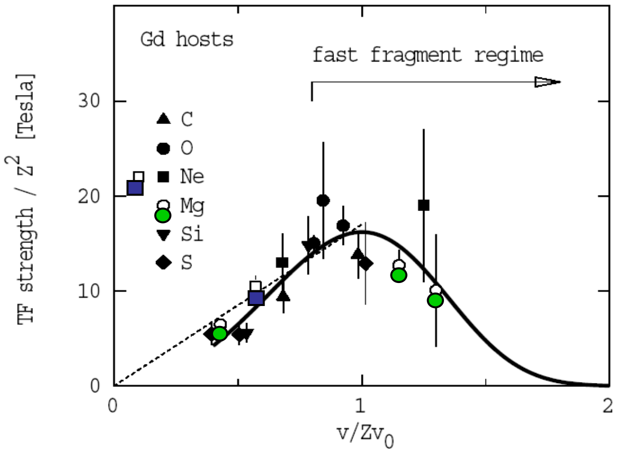
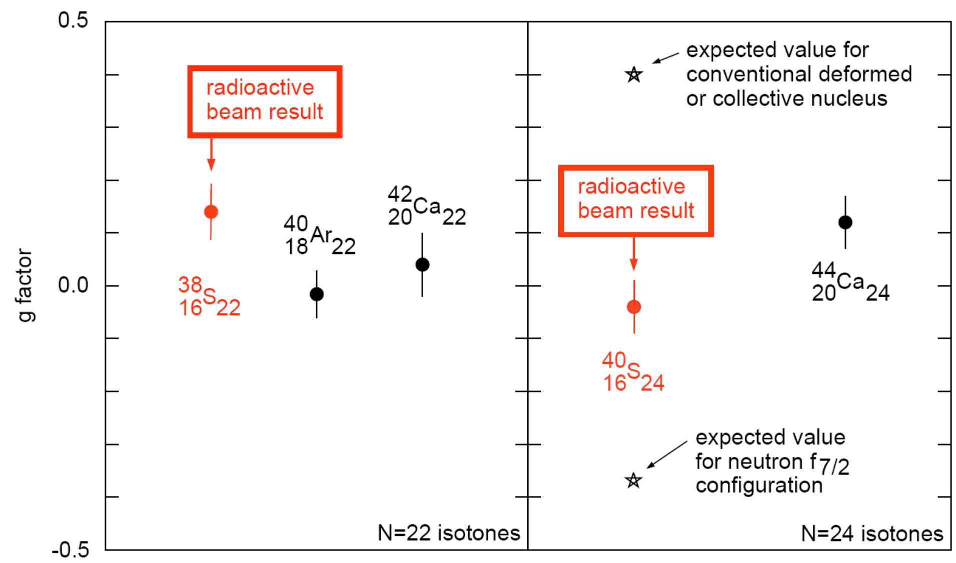
HVTF measurements on ^{38,40}S





TF strength vs ion velocity



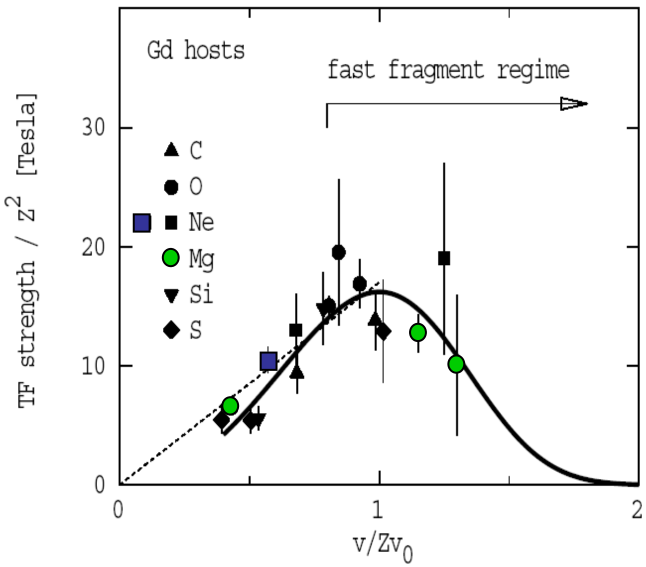
High velocities ⇒Large fields
Experimental uncertainties rival stable-beam measurements

PRL **96**, 112503 (2006)
PRC **74**, 054307 (2006)

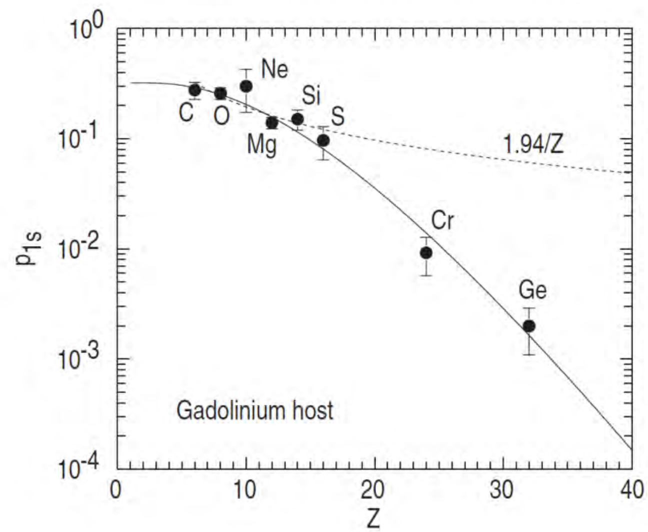
Stable-beam data: Rutgers: Phys Rev C **72**, 014309; Bonn: Phys Lett B **571**, 29.

Limitations of HVTF

TF versus velocity – low-Z



Polarization vs Z



- HVTF – "competitive" up to Z ~ 30 but still need ~10^4 events
- Must slow ions to $v \sim Zv_0$
- τ > 10 ps best for HVTF

PRC 85, 034334 (2012)

PHYSICAL REVIEW C **85**, 034334 (2012)

First $g(2^+)$ measurement on neutron-rich ^{72}Zn, and the high-velocity transient field technique for radioactive heavy-ion beams

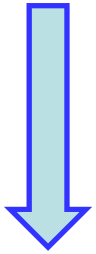
E. Fiori,[1,*] G. Georgiev,[1,†] A. E. Stuchbery,[2] A. Jungclaus,[3] D. L. Balabanski,[4] A. Blazhev,[5] S. Cabaret,[1] E. Clément,[6] M. Danchev,[7] J. M. Daugas,[8] S. Grevy,[6] M. Hass,[9] V. Kumar,[9] J. Leske,[10] R. Lozeva,[1,‡] S. Lukyanov,[11] T. J. Mertzimekis,[12] V. Modamio,[3,§] B. Mouginot,[13] F. Nowacki,[14,15] Yu. E. Penionzhkevich,[11] L. Perrot,[13] N. Pietralla,[10] K. Sieja,[14,15] K.-H. Speidel,[16] I. Stefan,[13] C. Stodel,[6] J. C. Thomas,[6] J. Walker,[3] and K. O. Zell[5]

Australian National University

Outline

- Some physics of moments
  - ✓ Nuclear collectivity
  - ✓ Emerging collectivity
  - ✓ Shell model applications
  - ✓ Isomers – High-spin and K-isomers

- Experimental methods – opportunities and challenges
  - ✓ Transient fields
  - ✓ Recoil in vacuum (including TDRIV)
  - ✓ Decay spectroscopy IPAC method
  - ✓ TDPAD external (and internal?) fields



Increasing relevance for FAIR

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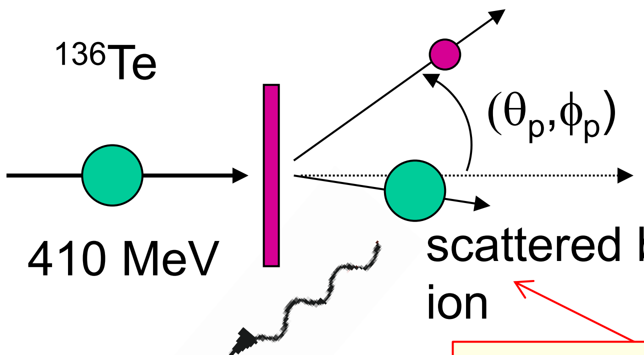
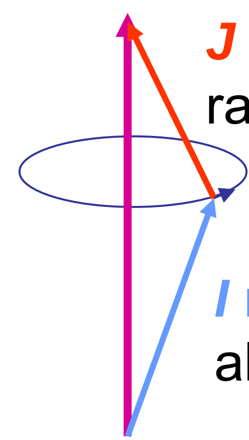
Recoil In Vacuum: ^{136}Te



- *g* factors from B(E2) experiments
- Analyze particle-γ angular correlations

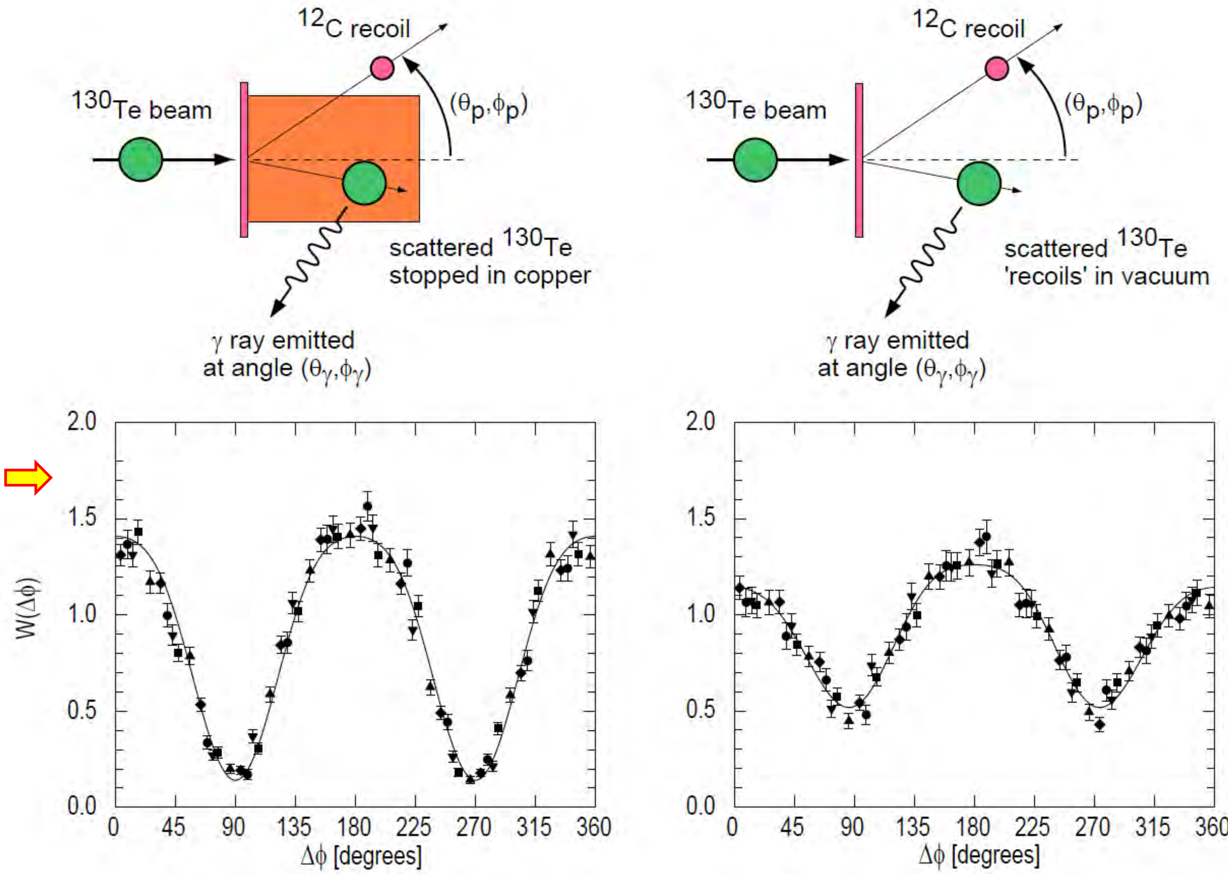
Coulomb excited beam emerges from target as highly charged ion



Attenuation coefficient due to RIV: contains information about the nuclear moment $0 \le G_k \le 1$

$$W(\theta_p, \theta_\gamma) = \sum_{k,q} B_{kq}(\theta_p) G_k F_k Q_k D_{q0}^{k*}(\phi_\gamma - \phi_p, \theta_\gamma, 0)$$

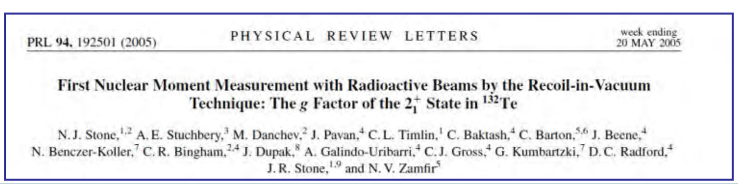
Angular correlations



unperturbed ⇨

⇦ perturbed

$\phi_p - \phi_\gamma$ = angle difference around beam axis



PRL 94, 192501 (2005) PHYSICAL REVIEW LETTERS week ending 20 MAY 2005

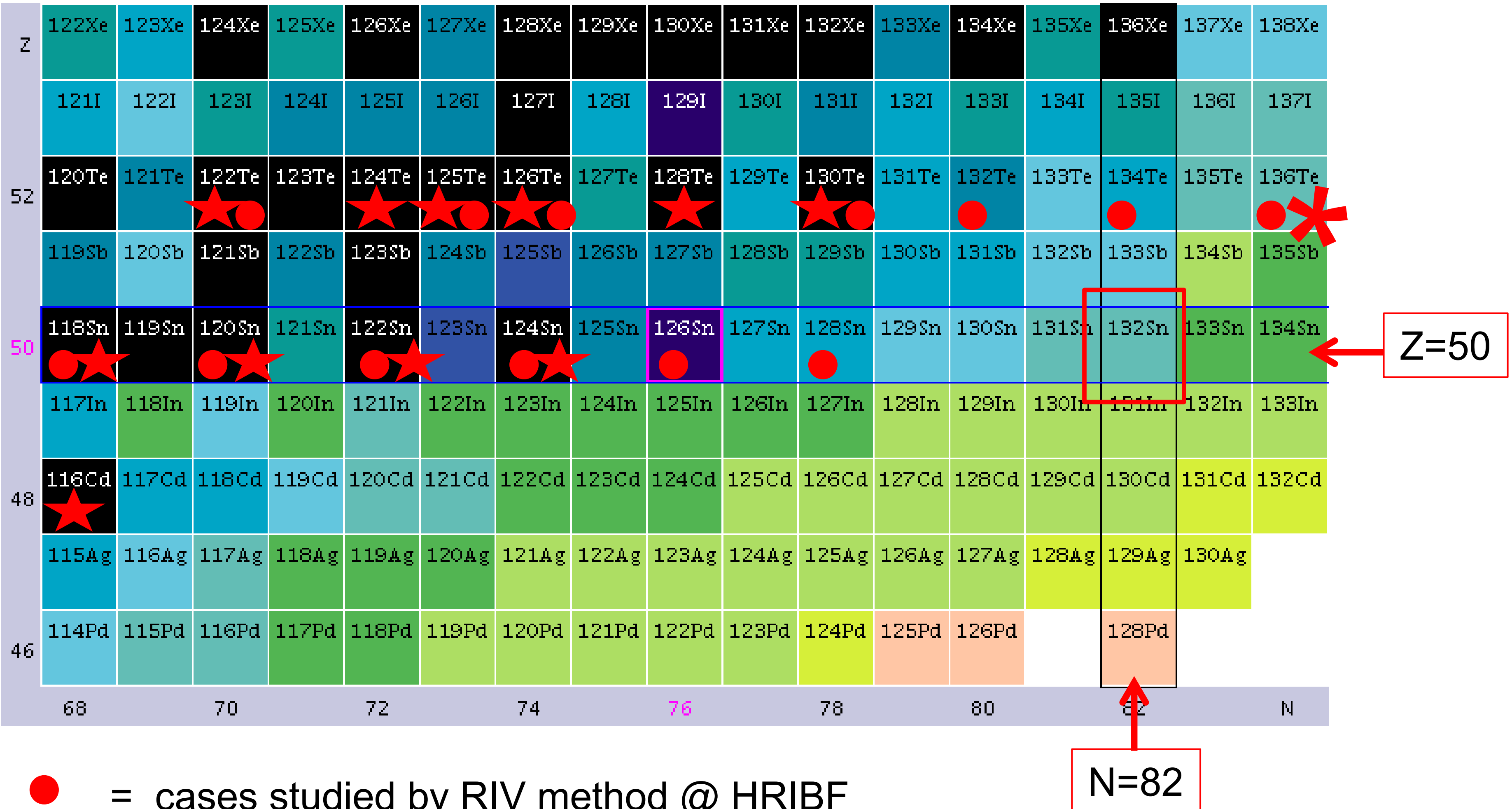
First Nuclear Moment Measurement with Radioactive Beams by the Recoil-in-Vacuum Technique: The g Factor of the 2_1^+ State in ^{132}Te

N. J. Stone,[1,2] A. E. Stuchbery,[3] M. Danchev,[2] J. Pavan,[4] C. L. Timlin,[1] C. Baktash,[4] C. Barton,[5,6] J. Beene,[4] N. Benczer-Koller,[7] C. R. Bingham,[2,4] J. Dupak,[8] A. Galindo-Uribarri,[4] C. J. Gross,[4] G. Kumbartzki,[7] D. C. Radford,[4] J. R. Stone,[1,9] and N. V. Zamfir[5]

Data from PRL 94, 192501 (2005)

Australian National University

^{132}Sn region

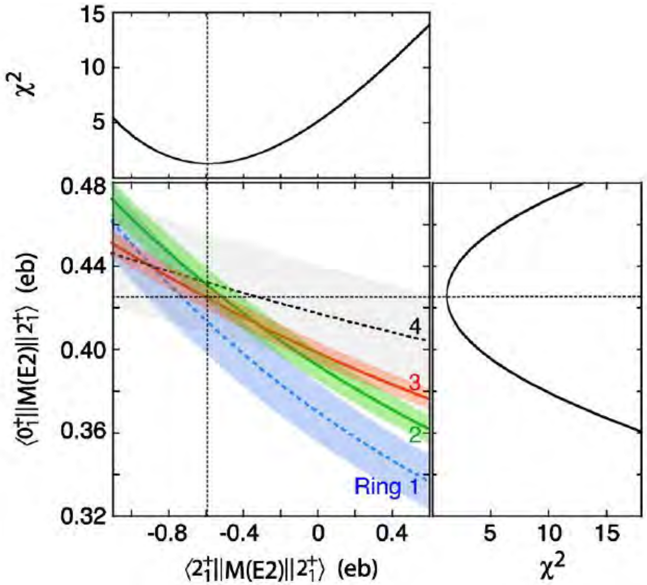


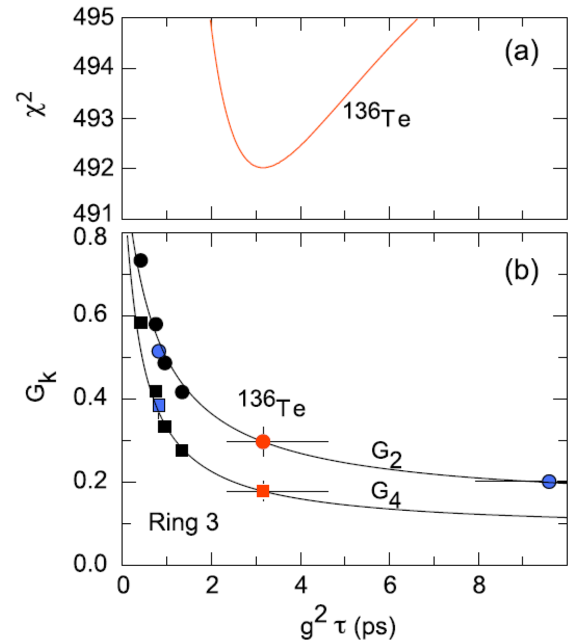
● = cases studied by RIV method @ HRIBF

★ = cases studied by TF method @ ANU

^{136}Te: B(E2), Q(2^+), g(2^+)

Culmination of HRIBF work: $^{112-128}$Sn, $^{132-136}$Te





PRL **118,** 092503 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

Electromagnetic Moments of Radioactive ^{136}Te and the Emergence of Collectivity 2p ⊕ 2n Outside of Double-Magic ^{132}Sn

J. M. Allmond,[1] A. E. Stuchbery,[2] C. Baktash,[1] A. Gargano,[3] A. Galindo-Uribarri,[1,4] D. C. Radford,[1] C. R. Bingham,[1,4] B. A. Brown,[5,6] L. Coraggio,[3] A. Covello,[7] M. Danchev,[4,8] C. J. Gross,[1] P. A. Hausladen,[9] N. Itaco,[3,10] K. Lagergren,[9] E. Padilla-Rodal,[11] J. Pavan,[9] M. A. Riley,[12] N. J. Stone,[4,13] D. W. Stracener,[1] R. L. Varner,[1] and C.-H. Yu[1]

Australian National University

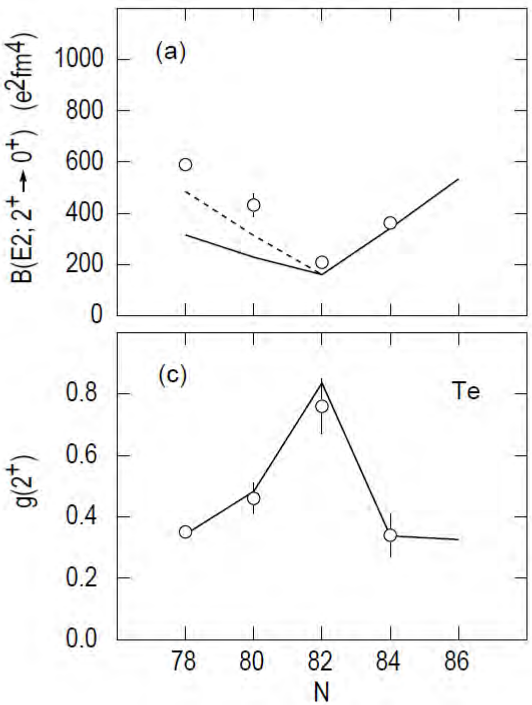
Recoil in Vacuum: ^{136}Te

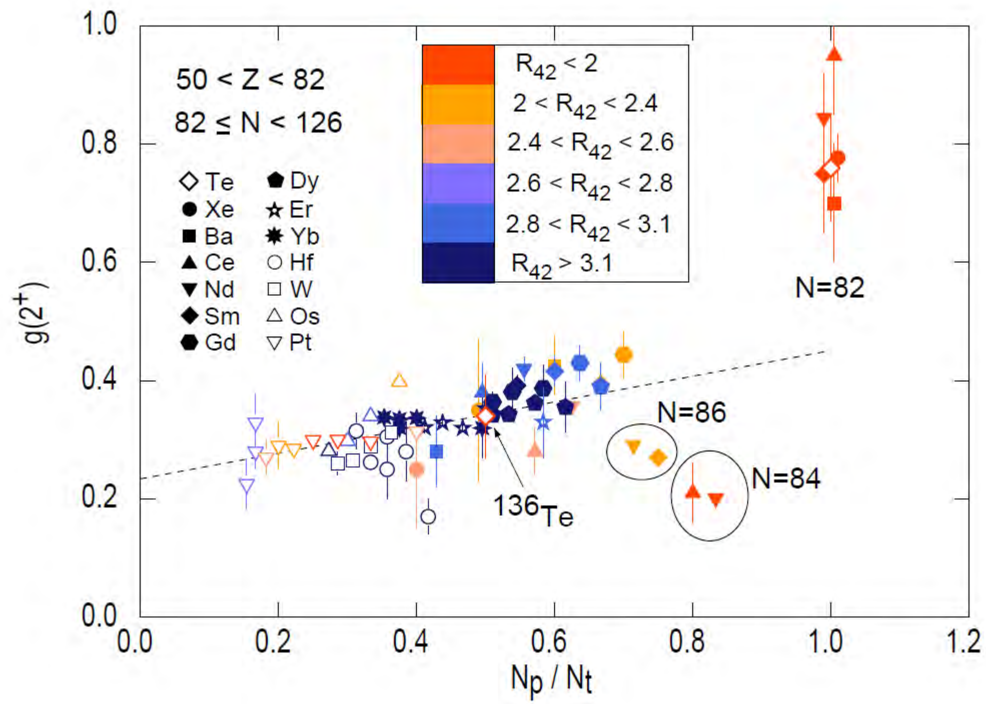
Full PRC paper on RIV (Editor's choice):

PHYSICAL REVIEW C **96**, 014321 (2017)

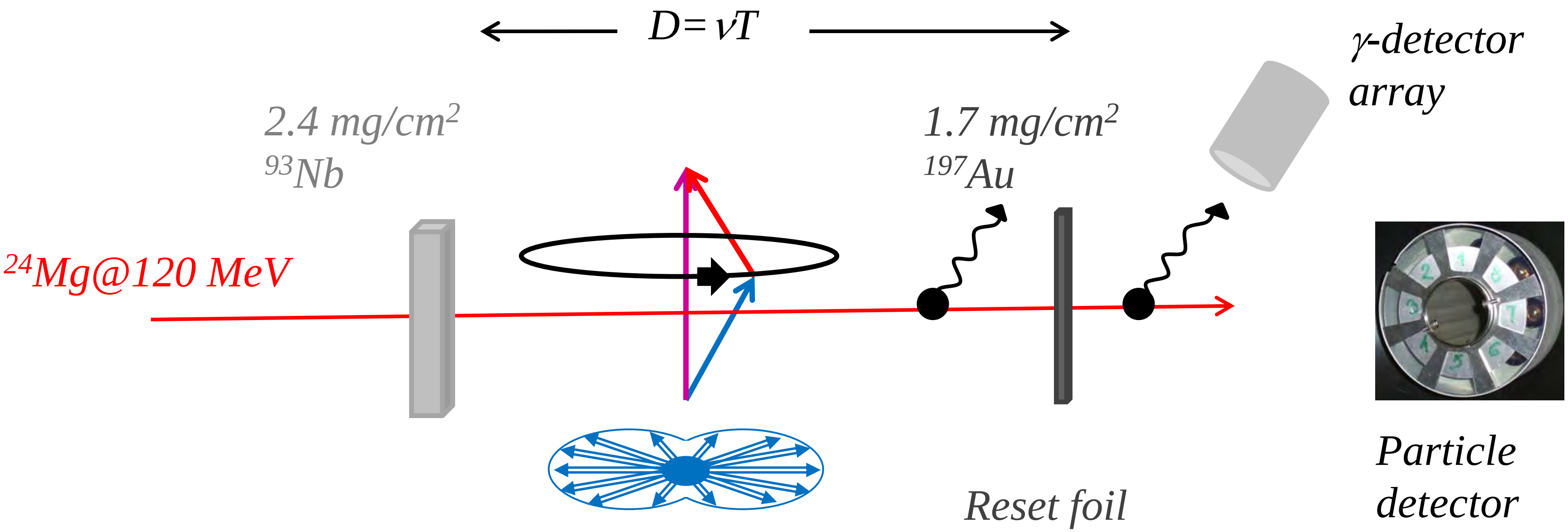
First-excited state *g* factor of ^{136}Te by the recoil in vacuum method

A. E. Stuchbery,[1,*] J. M. Allmond,[2] M. Danchev,[3,4] C. Baktash,[2] C. R. Bingham,[2,4] A. Galindo-Uribarri,[2,4] D. C. Radford,[2] N. J. Stone,[4,5] and C.-H. Yu[2]

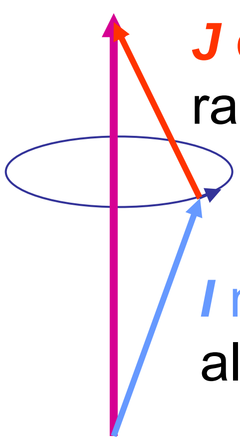




RIV/D or TDRIV Concept



$\mathbf{F} = \mathbf{I} + \mathbf{J}$



J electron spin
randomly oriented

$\omega_{FF'} \propto |g|$

I nuclear spin
aligned by reaction

More than 40% of ions are H-like,
i.e. single 1s electron:

$$B(0) = 16.7 Z^3 \text{ tesla}$$

Precise g factors in sd shell

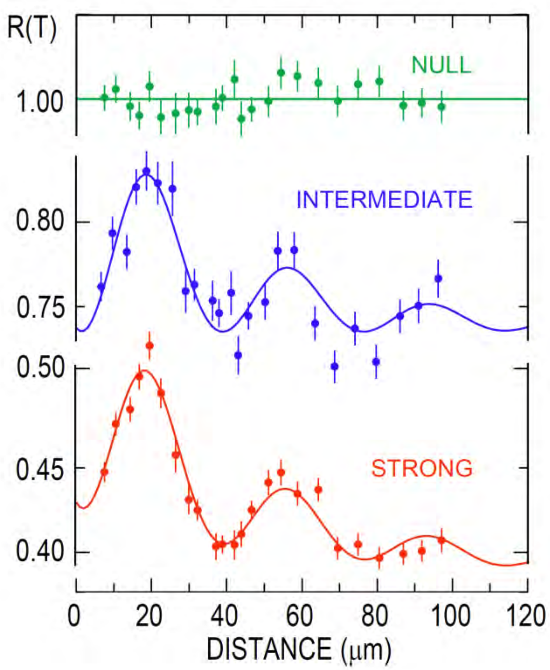
PRL 114, 062501 (2015) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2015

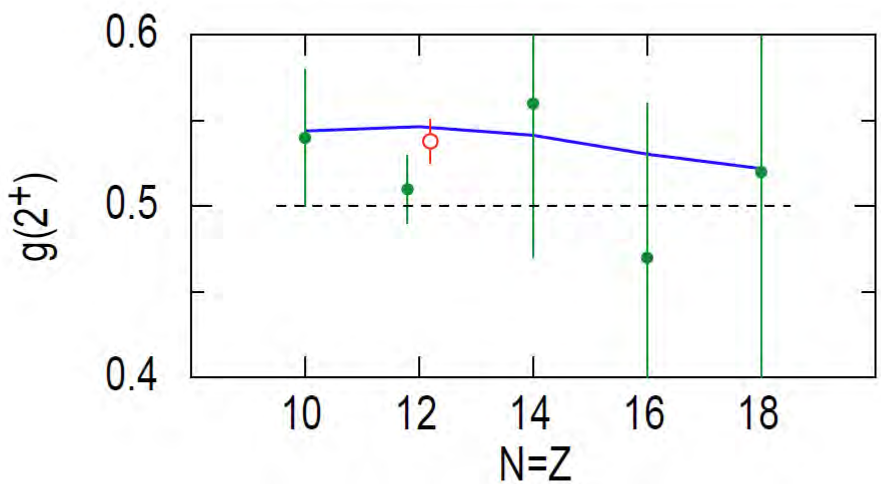
Magnetism of an Excited Self-Conjugate Nucleus: Precise Measurement of the *g* Factor of the 2_1^+ State in ^{24}Mg

A. Kusoglu,[1,2] A. E. Stuchbery,[3,*] G. Georgiev,[1] B. A. Brown,[4,5] A. Goasduff,[1] L. Atanasova,[6,†] D. L. Balabanski,[7] M. Bostan,[2] M. Danchev,[8] P. Detistov,[6] K. A. Gladnishki,[8] J. Ljungvall,[1] I. Matea,[9] D. Radeck,[10] C. Sotty,[1,‡] I. Stefan,[9] D. Verney,[9] and D. T. Yordanov[9,11,12]

PRL 2015

Recoil in vacuum with H-like ions

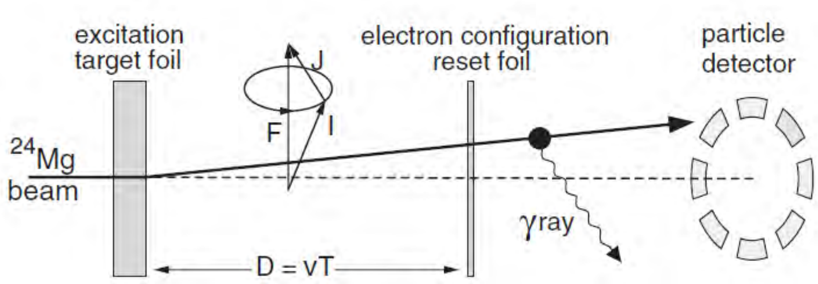




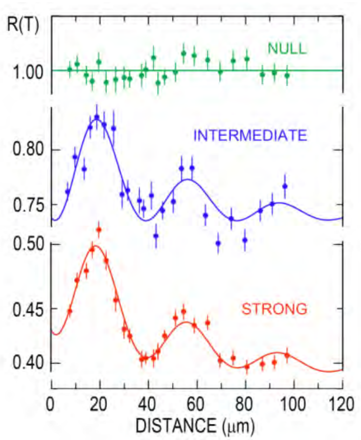
$g(2^+)$ Mg isotopes – toward ^{32}Mg

Australian National University

Time dependent recoil in vacuum: ^{24}Mg

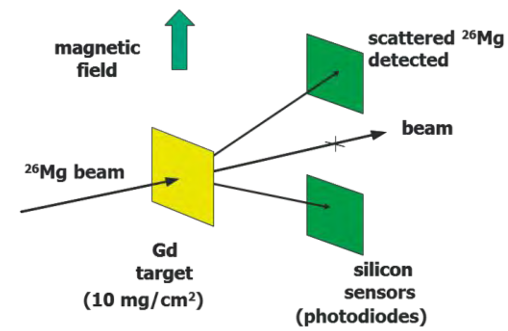


PRL 114, 062501 (2015)

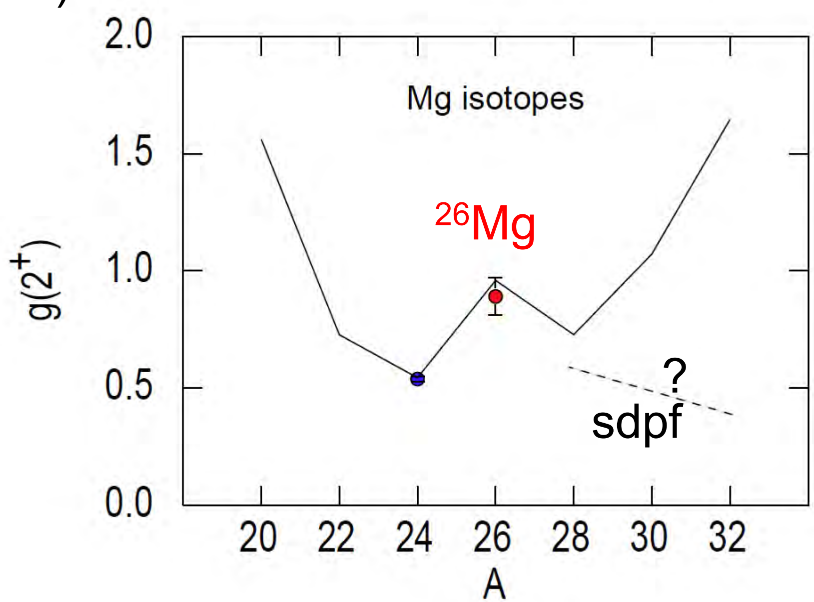


ALTO Orsay

Transient Field Projectile excitation: ^{26}Mg



PLB 779, 445 (2018)

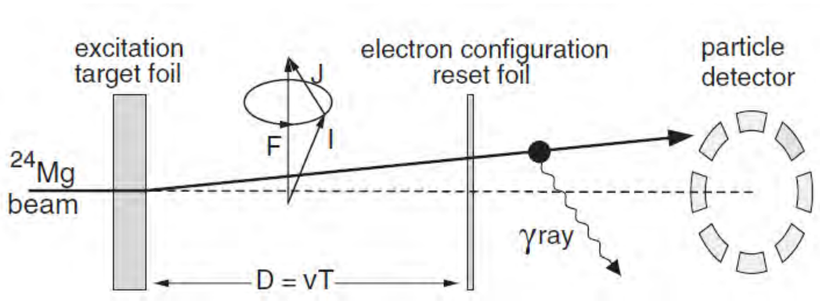


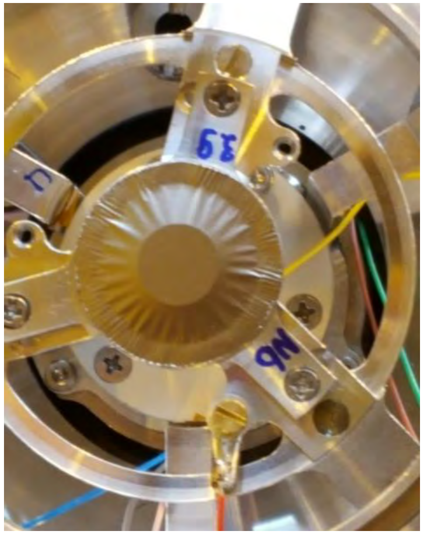
^{26}Mg relative to ^{24}Mg

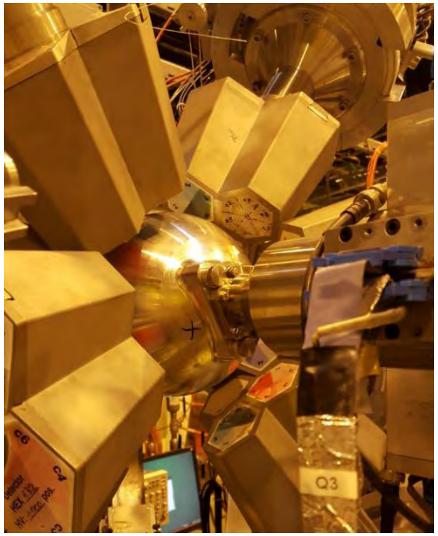
HIAF Canberra

g(2⁺) Mg isotopes – toward ^{32}Mg

Time dependent recoil in vacuum: ^{28}Mg @ ISOLDE
IS628 November 2017 (G. Georgiev, AES et al.)





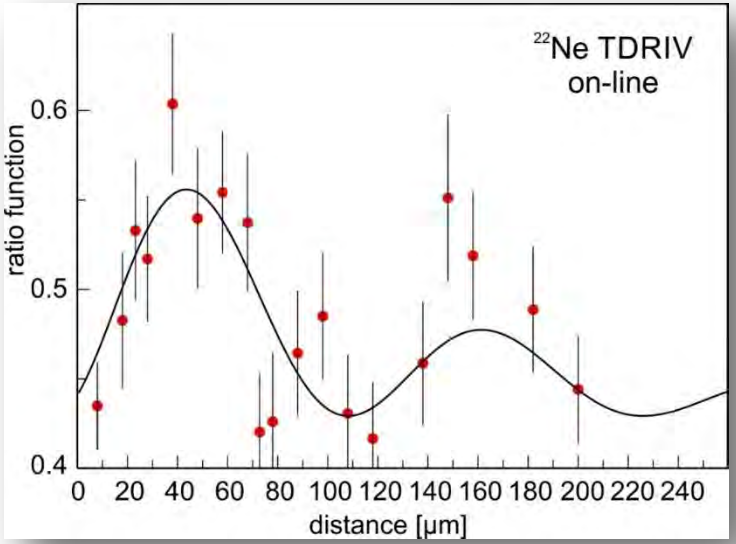


- Miniball detectors at ~90°angles
- ~7% efficiency at 1.4 MeV
- *first use of the Miniball plunger*
- 3.9 mg/cm² Nb target
- 1.1 mg/cm² Ta degrader
- aiming for 20 plunger distances

g(2$^+$) Mg isotopes – toward ^{32}Mg

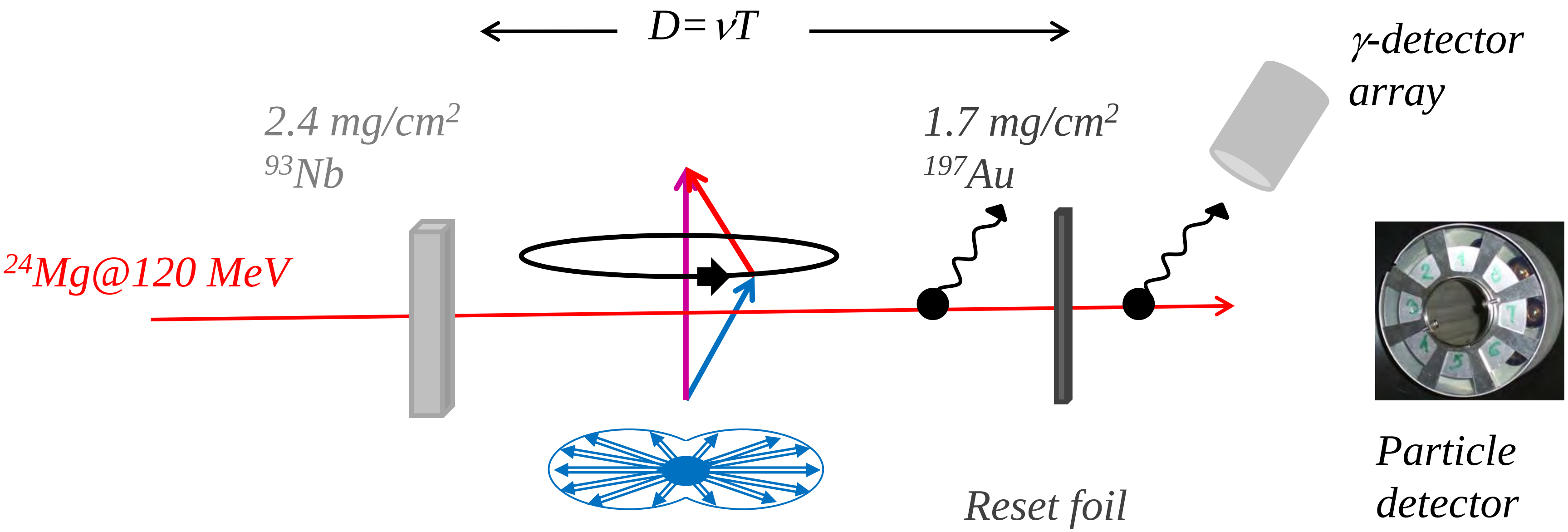
Time dependent recoil in vacuum: ^{28}Mg @ ISOLDE
IS628 November 2017 (G. Georgiev, AES et al.)

- Calibration measurement
  - ^{22}Ne – from EBIS rest gas
  - beam energy - 5.5 MeV/u
  - intensity – 1.5 ppA (limited by the scattering rate in the CD detector)
  - 5 days stable beam

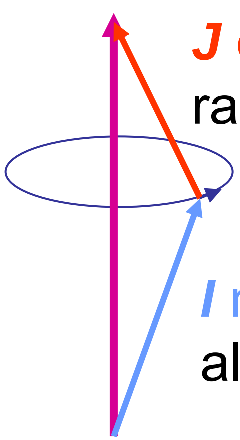


- ^{28}Mg ($t_{1/2}$ = 20.9 h)
  - expected beam intensity: 1x10^6 – 5x10^5 pps
  - **available: + 5x10^6 pps!!**
  - **expected well-pronounced particle – γ angular correlations observed**
  - **10 plunger distances measured**
  - data under analysis in Orsay and Canberra

RIV with higher Z?



F = ***I*** + ***J***



J electron spin
randomly oriented

$\omega_{FF'} \propto |g|$

I nuclear spin
aligned by reaction

More than 40% of ions are H-like, i.e. single 1s electron:

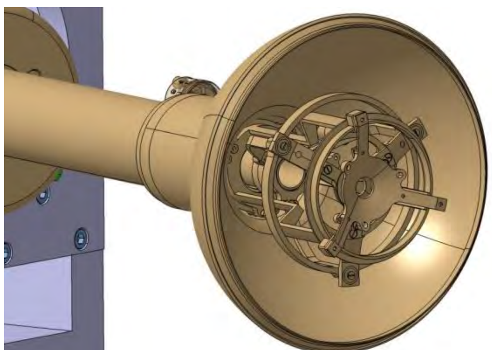
$$B(0) = 16.7 Z^3 \text{ tesla}$$

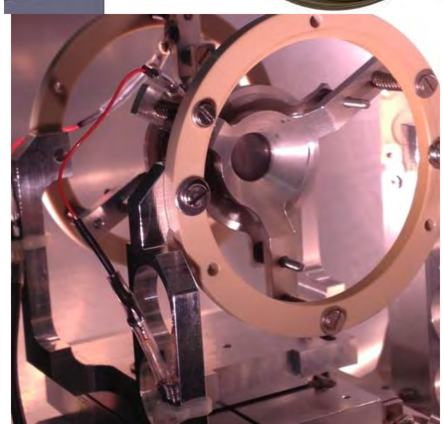
Australian National University

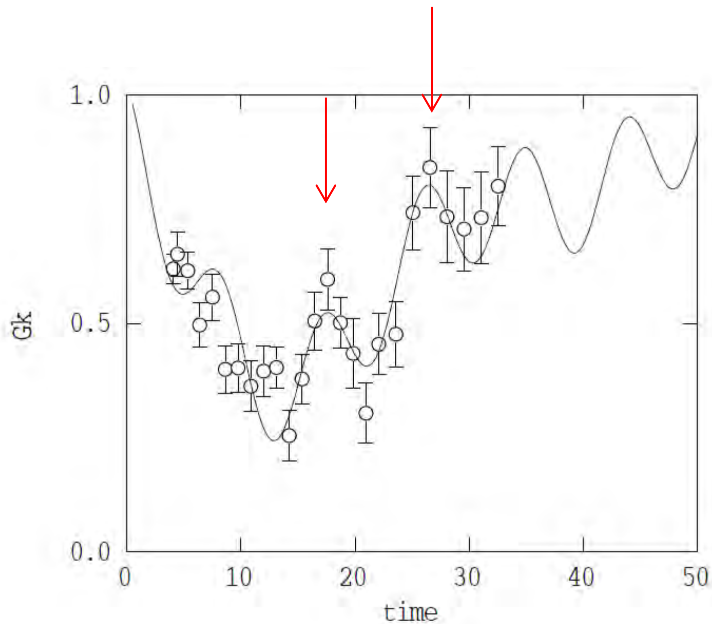
Higher Z with Na-like ions?

$B(0) \propto Z^3$ H-like ions oscillate too fast for Z > ~16. Try Na-like ions for ^{56}Fe.

- ^{56}Fe beam on C+Ni stretched foil
- Orsay Plunger ‘OUPS’ and Miniball @ ALTO
- Reaction kinematics to optimize Na-like ions - based on detailed charge-state distributions from ANU





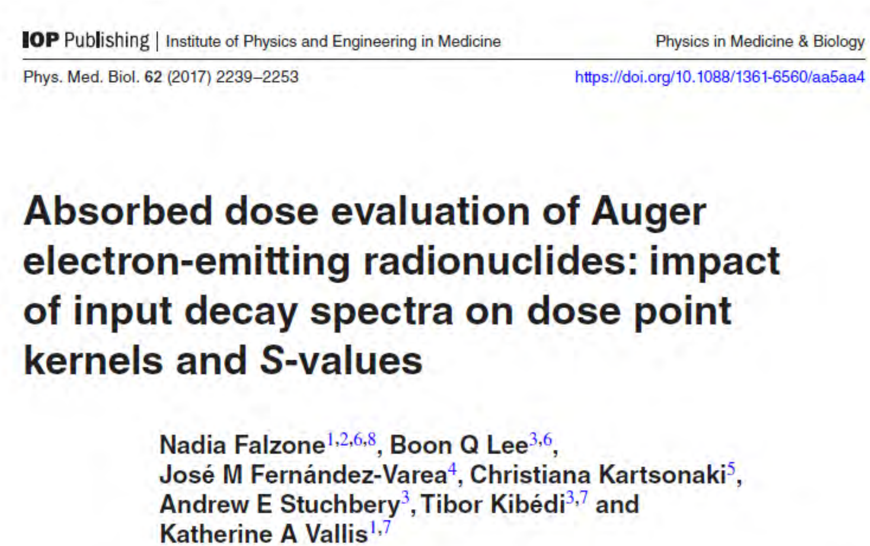


Looks promising – we see correct period among “other stuff”

Modeling RIV

Approach: see Chen et al. PRC 87, 044305 (2013)

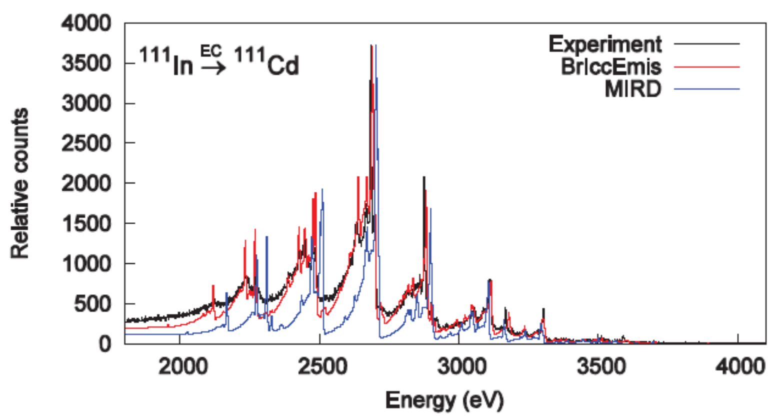
Builds on our work on modeling the Auger cascade for medical radioisotopes

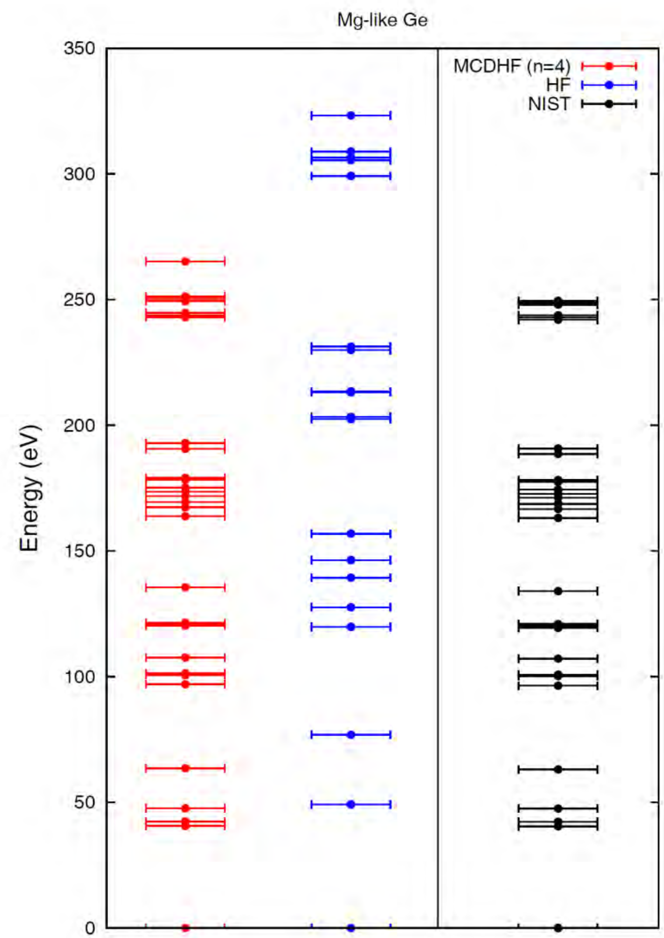

IOP Publishing | Institute of Physics and Engineering in Medicine — Physics in Medicine & Biology

Phys. Med. Biol. 62 (2017) 2239–2253 — https://doi.org/10.1088/1361-6560/aa5aa4

Absorbed dose evaluation of Auger electron-emitting radionuclides: impact of input decay spectra on dose point kernels and *S*-values

Nadia Falzone[1,2,6,8], Boon Q Lee[3,6], José M Fernández-Varea[4], Christiana Kartsonaki[5], Andrew E Stuchbery[3], Tibor Kibédi[3,7] and Katherine A Vallis[1,7]

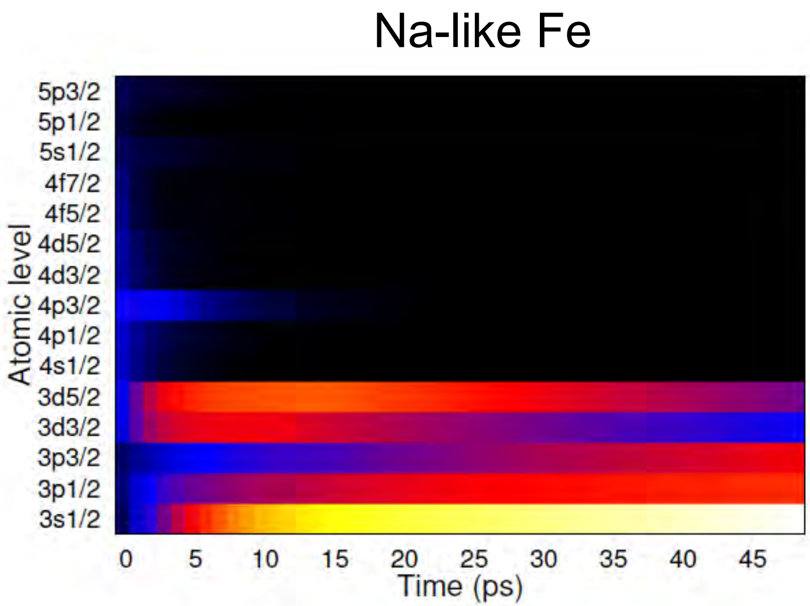


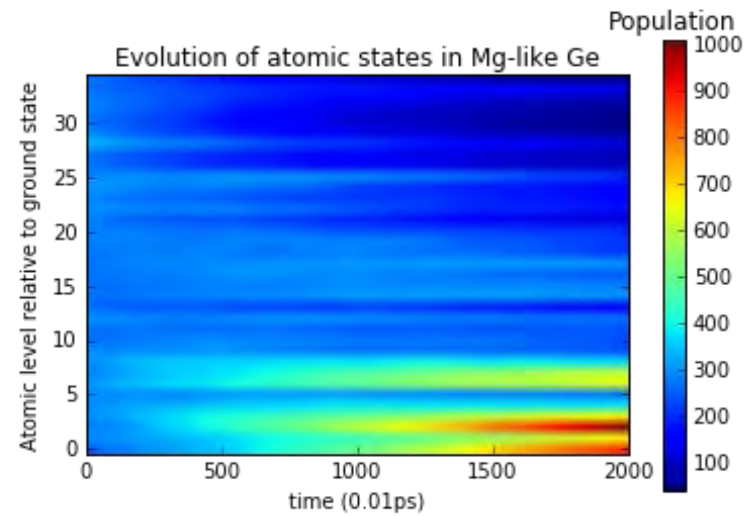


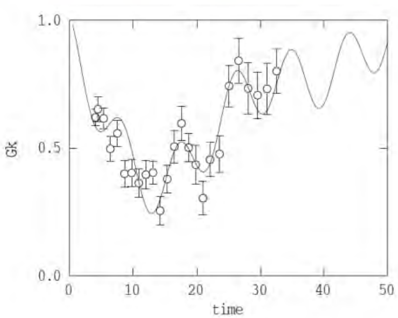
MultiConfiguration Dirac Fock, GRASP2K

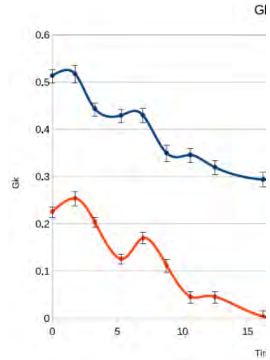
Modeling RIV

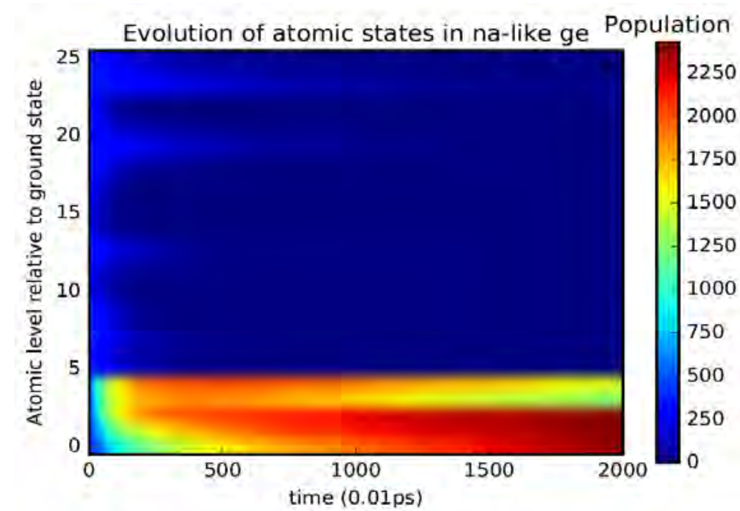
GRASP2K+Monte Carlo
Model atomic decay











RIV @ FAIR

RIV has been very productive and is very promising

BUT…

High energies and large beam spots will be a challenge at FAIR

TDPAD and Decay spectroscopy methods are a more appealing place top start.

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Outline

- Some physics of moments
  - ✓ Nuclear collectivity
  - ✓ Emerging collectivity
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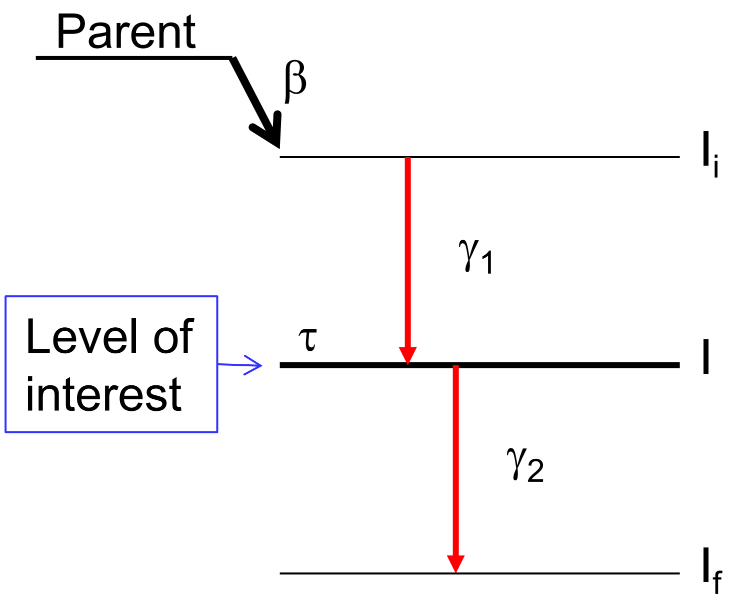
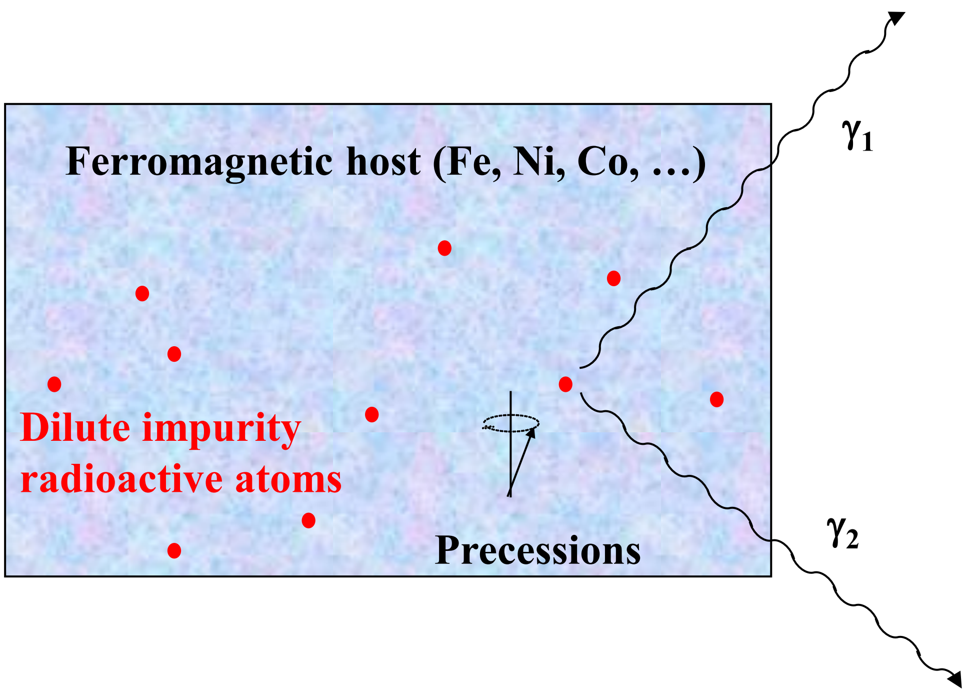
  - ✓ TDPAD external (and internal?) fields

Increasing relevance for FAIR

IPAC/Radioactivity method

Perturbed angular correlation measurements. Observe: $\omega\tau = -g \frac{\mu_N}{\hbar} B \tau$





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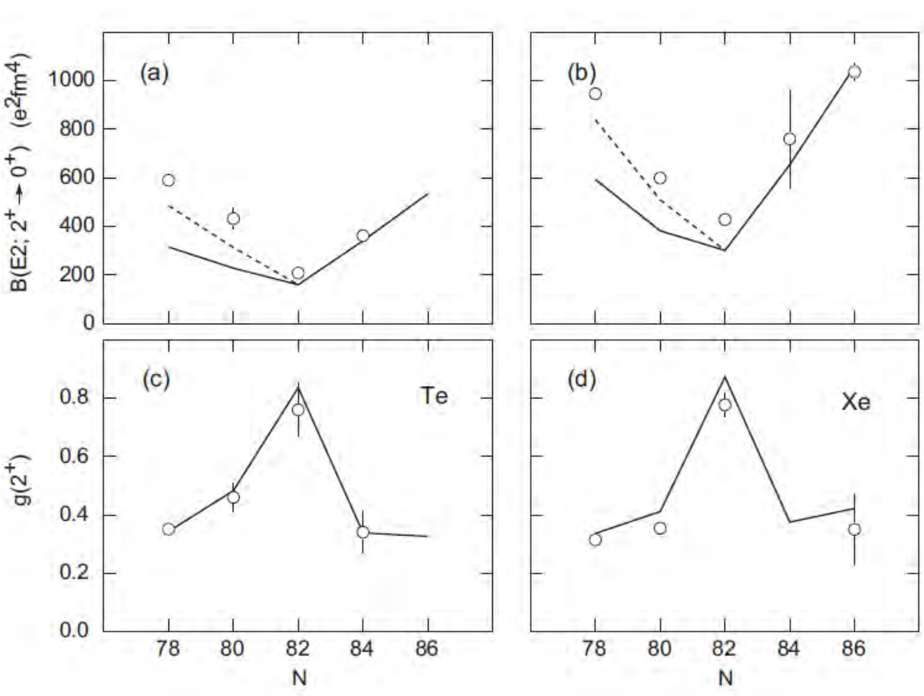
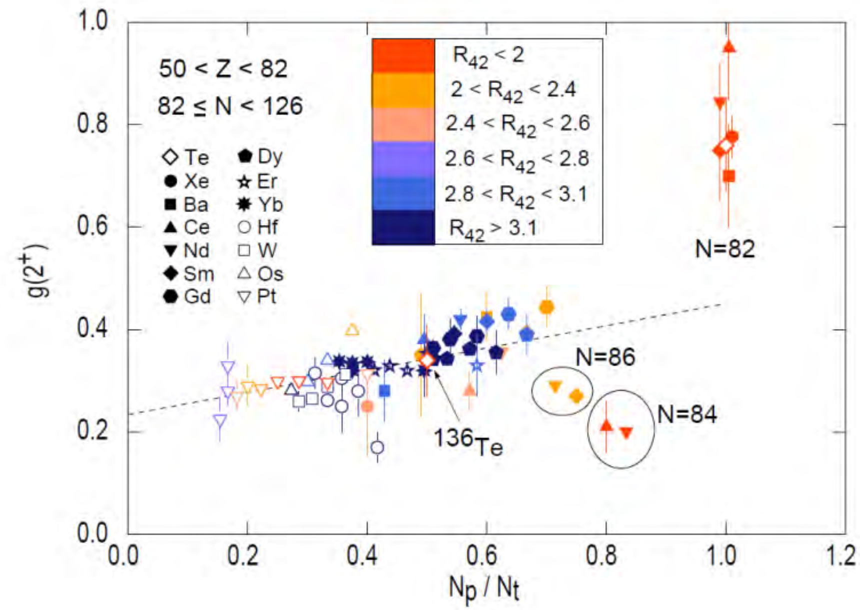
g factors in decay spectroscopy

Example: ^{138}I β decay into N=84 ^{138}Xe (July 2018)

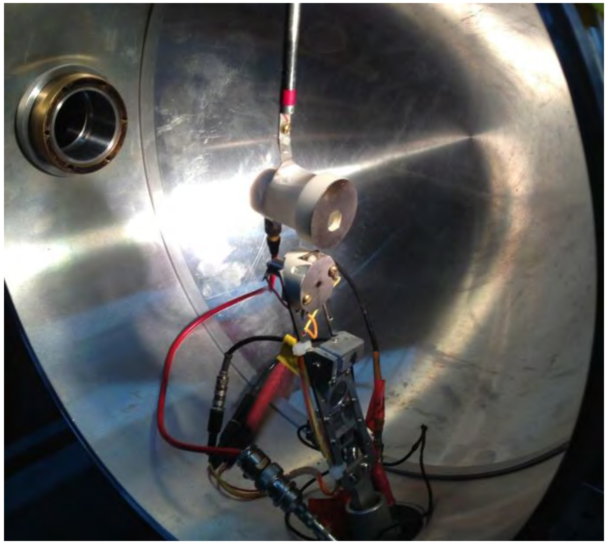




^{138}I from Caribu implanted into iron in Gammasphere

g factors in decay spectroscopy

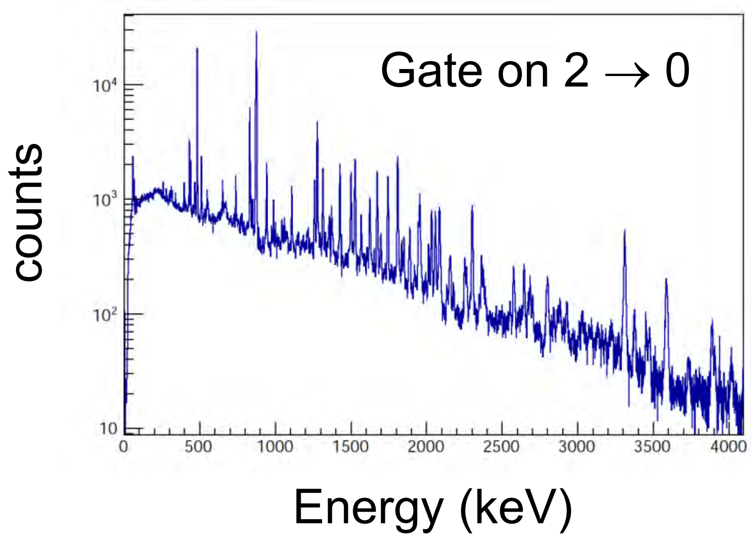
^{138}I from CARIBU implanted into iron in Gammasphere

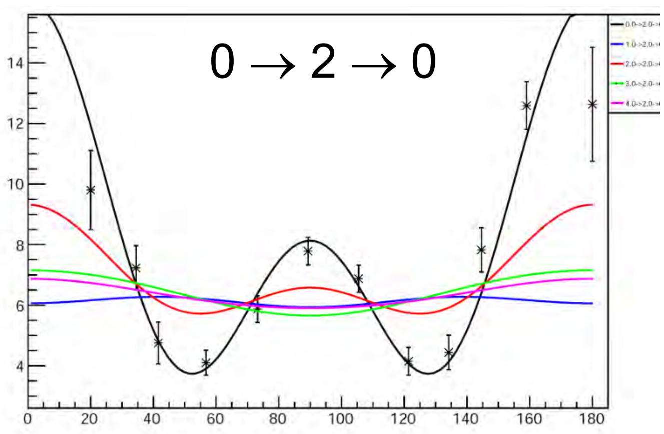


Magnetic field provided by permanent magnets

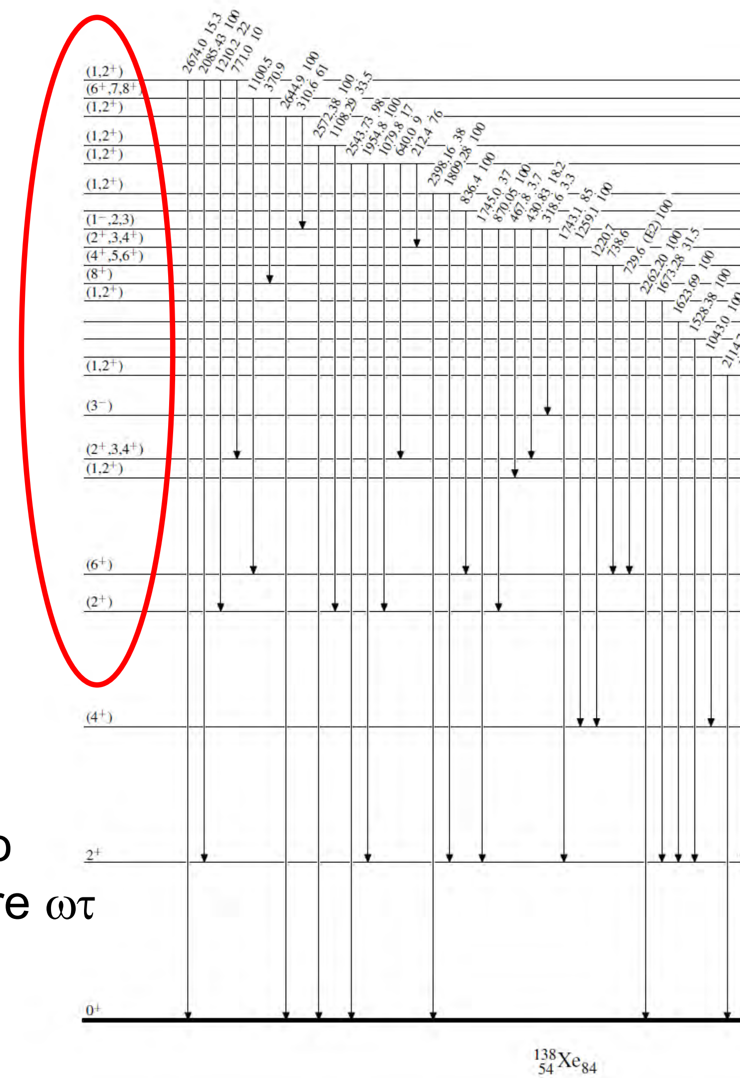
Gammasphere target ladder

g factors in decay spectroscopy





Firm spin assignments



Hope to measure ωτ

Outline

- Some physics of moments
  - ✓ Nuclear collectivity
  - ✓ Emerging collectivity
  - ✓ Shell model applications
  - ✓ Isomers – High-spin and K-isomers

- Experimental methods – opportunities and challenges
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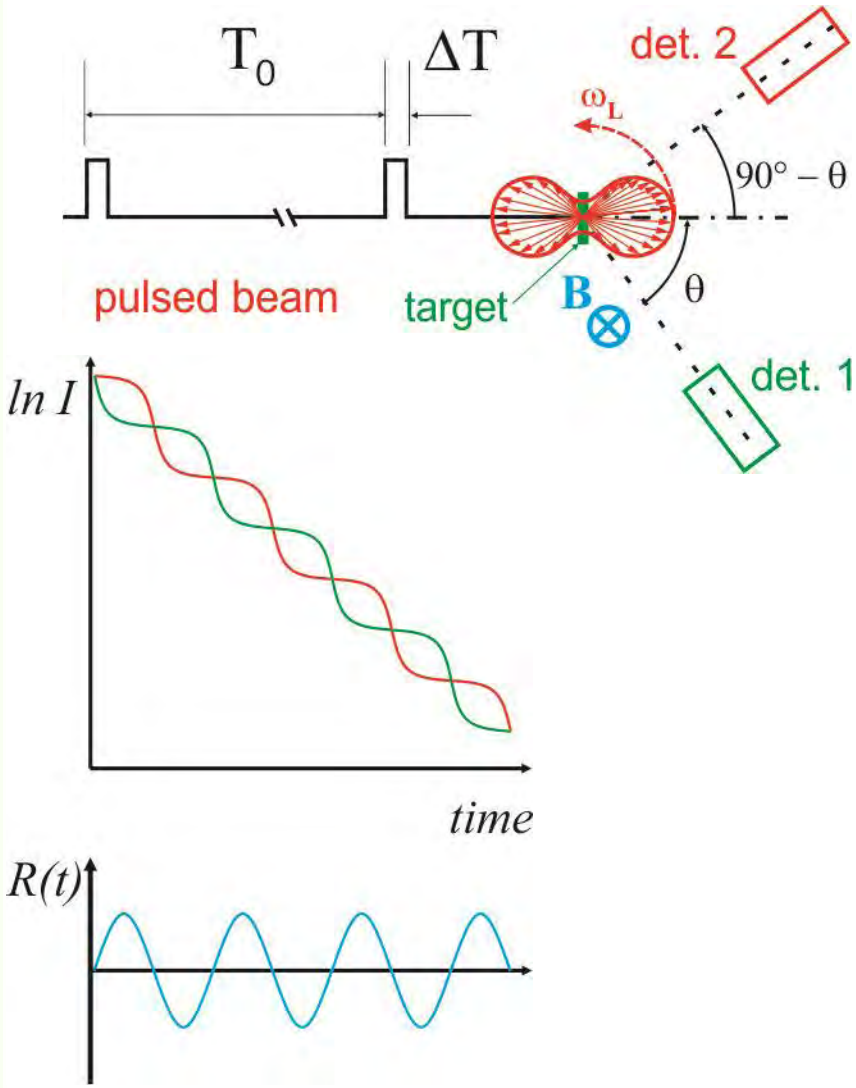
  - ✓ Decay spectroscopy IPAC method
  - ✓ TDPAD external (and internal?) fields

Increasing relevance for FAIR

Time Dependent Perturbed Angular Distributions (TDPAD)

- Isomeric states with lifetimes between "few ns" and "few μs"



- Time reference (t=0) – pulsed beam or ion implantation detector
- Detectors at 90° with respect to each other observing the decay of the state
- **Spin aligned ensemble – how?**
- Perturbation – (external) magnetic field
- Detect the modification of the angular distribution of γ-rays

$$\omega_L = -\frac{g\mu_N B}{\hbar} \rightarrow \textit{Larmor frequency}$$

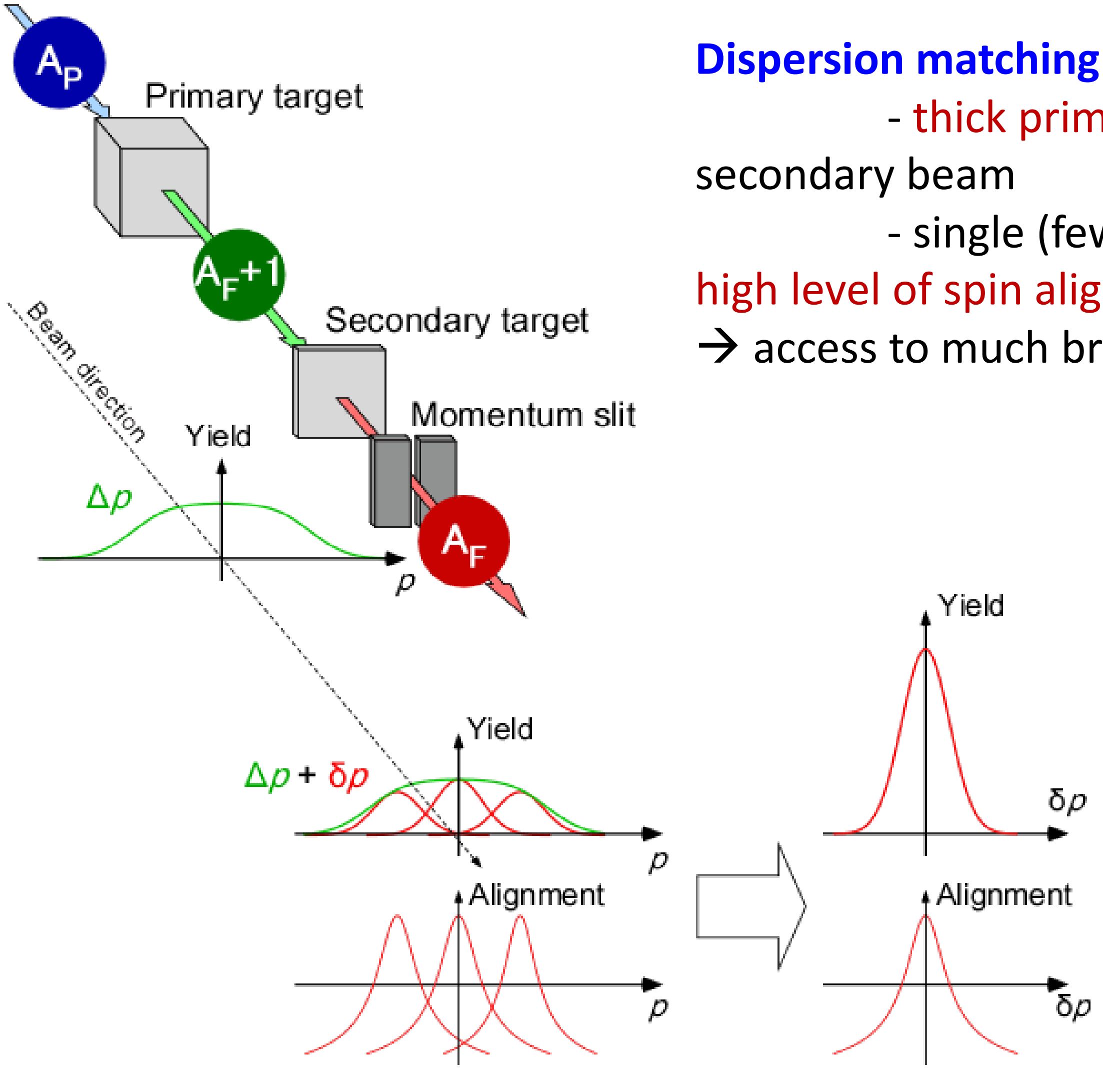
$$R(t) = \frac{I(\theta,t) - \varepsilon I(\theta+90°,t)}{I(\theta,t) + \varepsilon I(\theta+90°,t)} =$$

$$= \frac{3A_2B_2}{4+A_2B_2} cos\{2(\theta - \omega_L t - \alpha)\}$$

TDPAD: isomers near closed shells

- ^{208}Pb region "North East" of ^{208}Pb extensively studied in the past
- ^{132}Sn region currently under study
- ^{68}Ni …^{78}Ni …
- ^{100}Sn region ?
- SE and SW of ^{208}Pb?
- K isomers?

Spin alignment in two-step projectile fragmentation



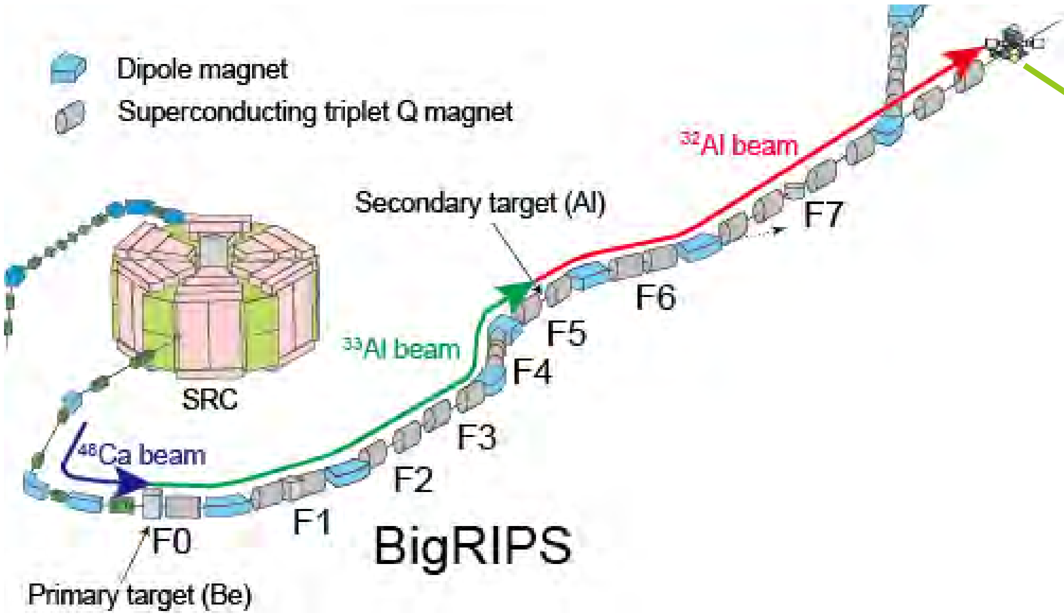
Dispersion matching technique:

- thick primary target → high yield of the secondary beam
- single (few?) nucleon removal reaction → high level of spin alignment

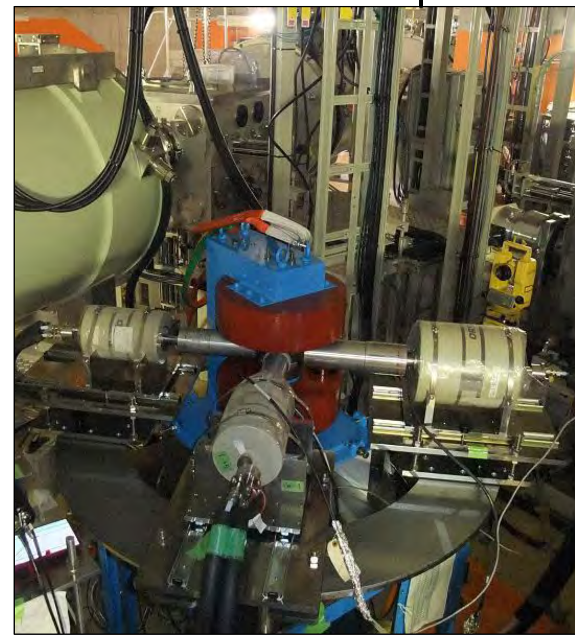
→ access to much broader range of the nuclear chart!

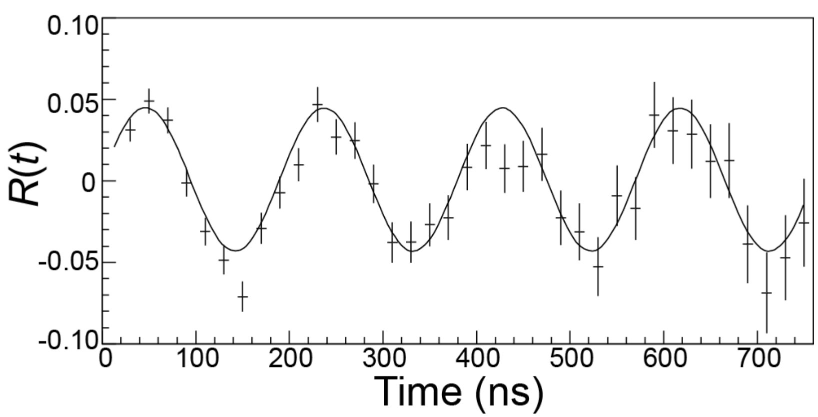
Proof of principle – ^{32}Al (2010)

Production : $^{48}Ca \rightarrow {}^{33}Al \rightarrow {}^{32}Al$



TDPAD setup





- Production of ^{32}Al with 8(1)% alignment
- First measurement of $g(^{32}Al)$=1.32(1)
- FOM improvement >50

ARTICLES

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Production of spin-controlled rare isotope beams

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