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Measurement and evaluation of magnetic moments of short-lived states

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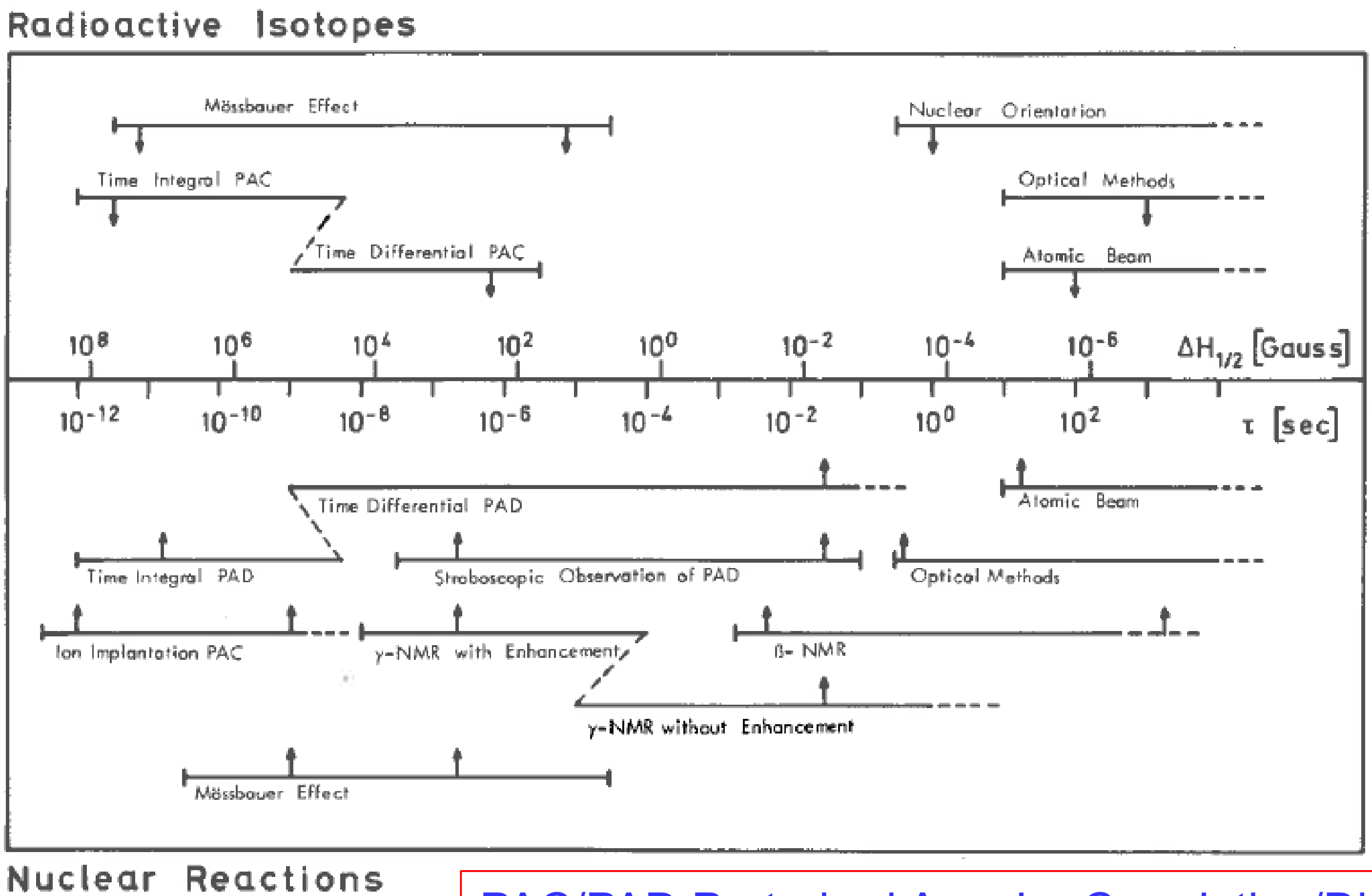
Workshop on Nuclear Moments 2025

Outline

- **Overview of methods – magnetic moments**
- **Recoil In Vacuum**
  - ✓ Time dependent – TDRIV – simple ions
  - ✓ Integral TIV – complex ions
- **Static hyperfine fields**
  - ✓ Moments in radioactive decay
  - ✓ Moments after ion implantation
  - ✓ TDPAD with LaBr3 detectors – shorter lifetimes
- **Transient fields**
  - ✓ Calibration challenges
  - ✓ Solving the calibration challenges with TDRIV
- **Thoughts on data evaluation**

Overview of Methods



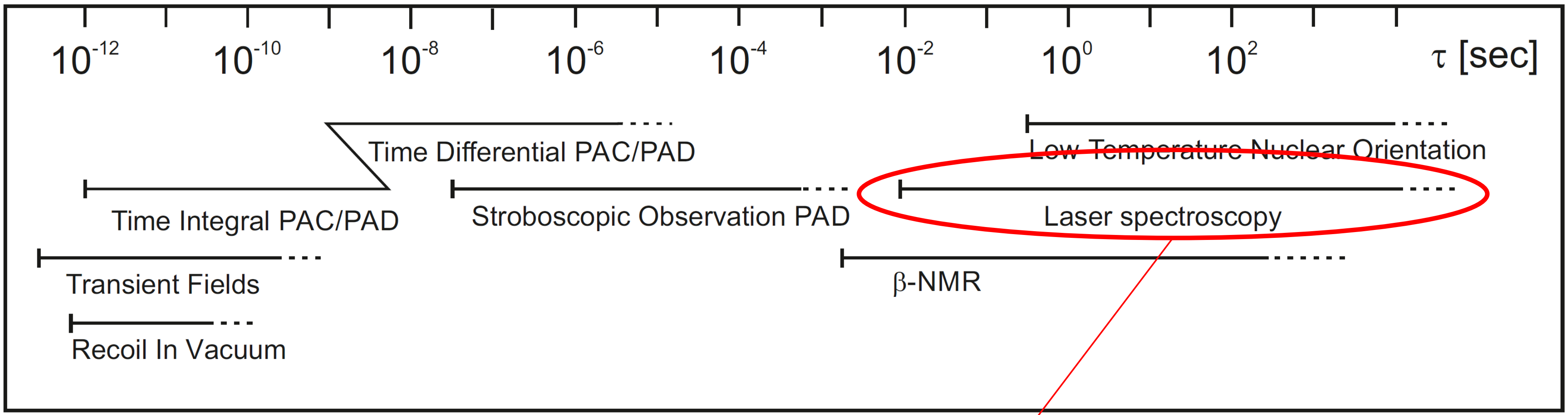
Magnetic dipole moments

PAC/PAD Perturbed Angular Correlation/Distribution Methods

E. Recknagel, in Nuclear Spectroscopy and Reactions, ed. Joseph Cerny, 1974.
- Dated but still useful.

Overview of Methods

Updated and abbreviated (G. Georgiev et al. Review Paper Submitted)



Laser spectroscopy has replaced "atomic beam" and "optical methods" for ground states and long-lived isomers

Overview of Methods

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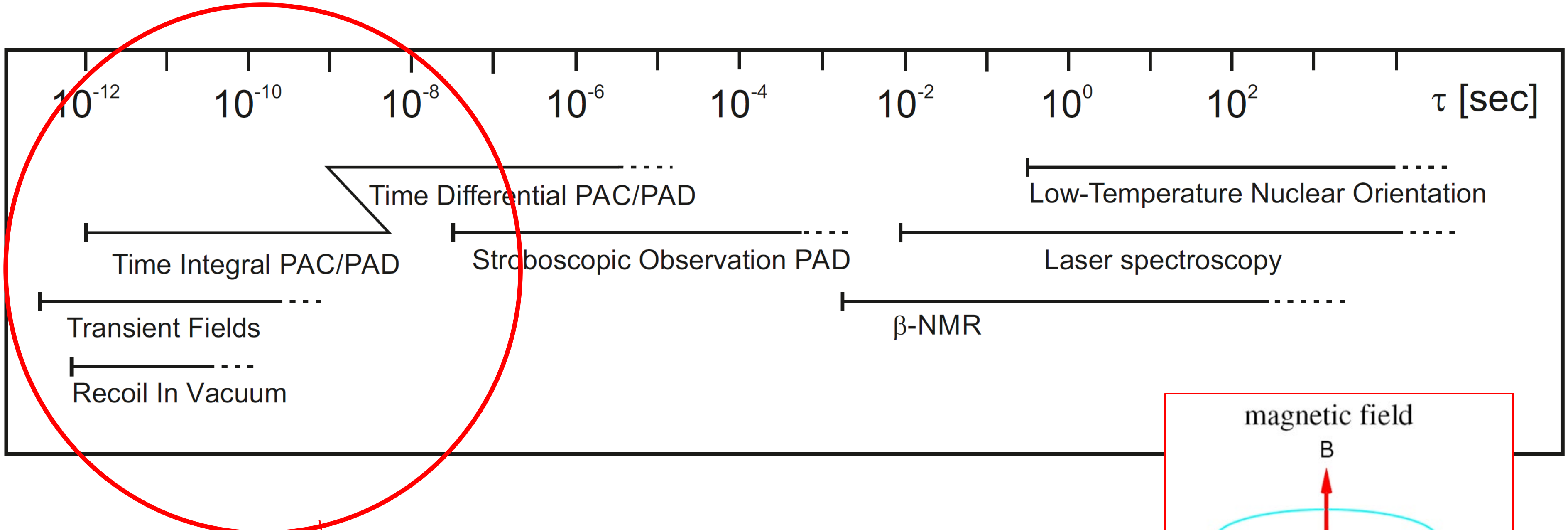
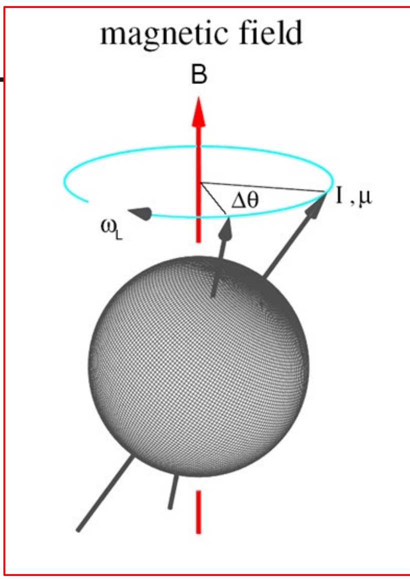
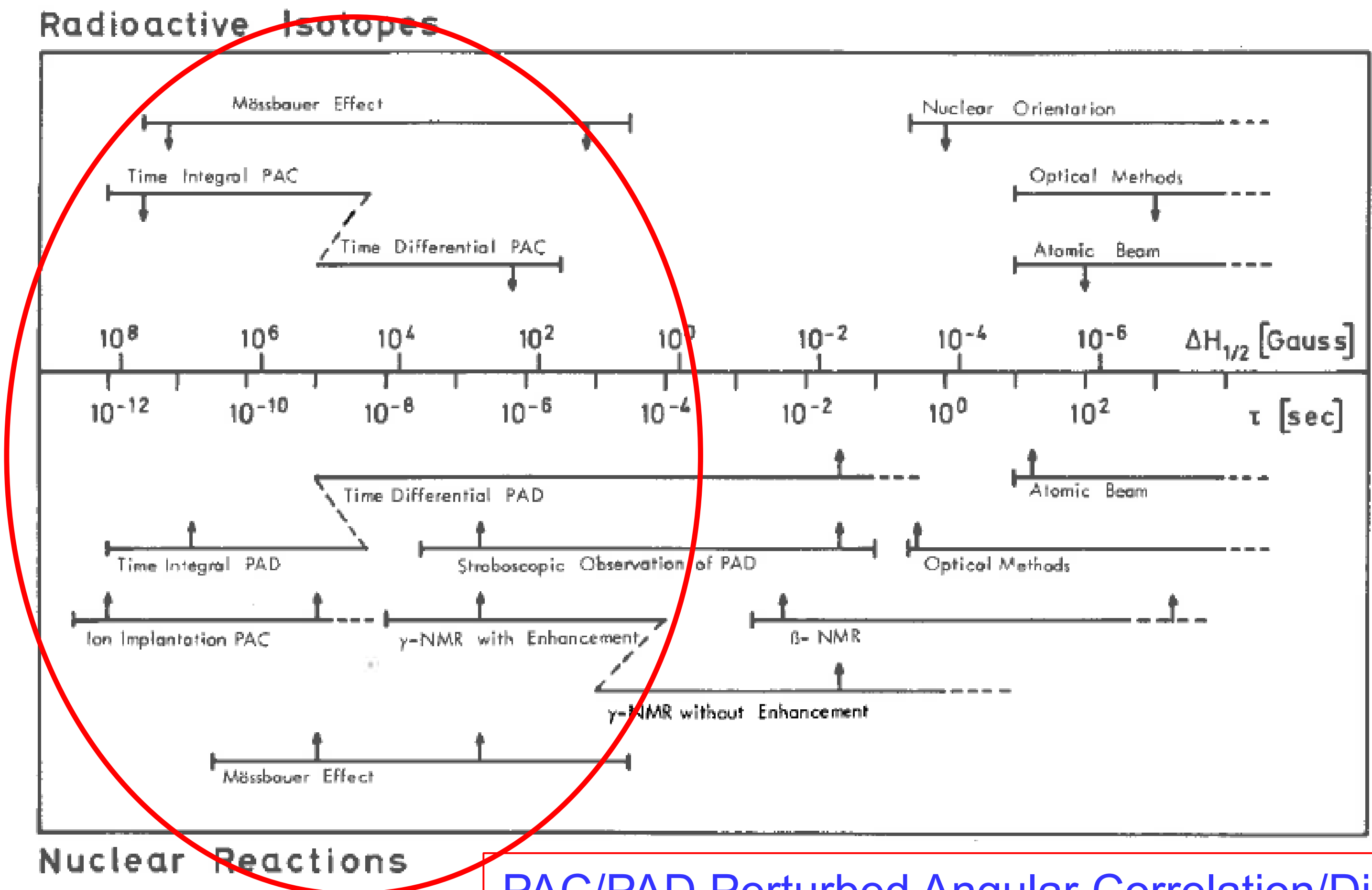




Focus of this talk: shorter-lived excited states

- In-beam and/versus decay spectroscopy

Overview of Methods



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Time-integral/differential

TABLE 1

LIMITING CONDITIONS FOR THE APPLICATION OF METHODS FOR MEASURING NUCLEAR MAGNETIC DIPOLE MOMENTS OF EXCITED STATES OR UNSTABLE GROUND STATES

	Shorter lifetimes		Longer lifetimes	
Method	τ (sec)	Limiting condition	τ (sec)	Limiting condition
Time-integral PAC	10^{-11}	Rotation angle resolution $\omega\tau > 1$ mrad; internal hyperfine field $H \approx 10^6$ G	$\sim 10^{-8}$	Time-differential PAC
Time-differential PAC	10^{-9}	Time resolution $t_1 \lesssim \tau$; Larmor period $1/\omega_L \gtrsim \tau$	10^{-5}	Coincidence condition
Time-integral PAD	10^{-11}	Rotation angle resolution $\omega\tau > 1$ mrad; internal hyperfine field $H \approx 10^6$ G	$\sim 10^{-8}$	Time-differential PAD
Ion implantation PAC	10^{-12}	Rotation angle resolution $\omega\tau > 1$ mrad; internal fluctuating hyperfine field $\bar{H} \approx 10^7$ G	$\sim 10^{-8}$	Time-differential PAD
Time-differential PAD	10^{-9}	Time resolution $t_1 \lesssim \tau$; Larmor period $1/\omega_L \gtrsim \tau$	10^{-2}	Counting rates; relaxation (T_1, T_2)

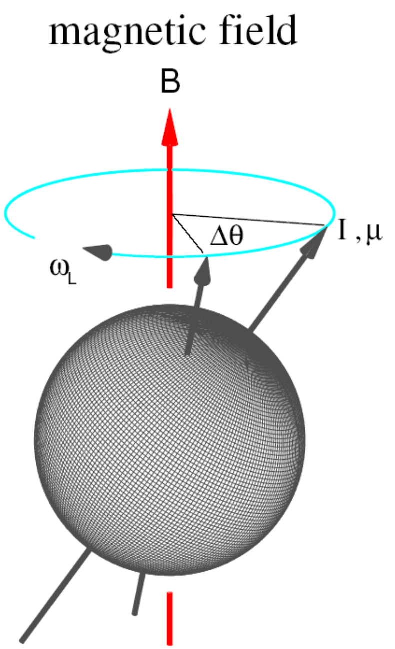
Time Differential PAC/PAD measurements – generally reliable

- Good precision and accuracy – **with exceptions!**
- Examples: TDPAC, TDPAD, TDRIV

Time-Integral measurements – usually only option for picosecond states

- More prone to be problematic
- Examples: IPAC (Radioactivity), IMPAC/IMPAD, Transient-Field
- Static Fields after implantation

Picosecond states



$$\Delta\theta = -g \frac{\mu_N}{\hbar} B \, \Delta t$$

B ~ 10^3 Tesla (hyperfine); Δt ~ few ps

Δθ ~ few degrees (~1 mrad)

Hyperfine fields define the experimental method:

- **Recoil in Vacuum (RIV)**
  - H-like free-ion fields (TDRIV – possible with ps states)
  - Complex free-ion fields (Time Integral RIV)
- **Static internal field in ferromagnetic host**
  - Radioactivity (TDPAC/IPAC)
  - Implantation (IMPAC = online & integral)
- **Transient field in ferromagnetic host**
  - Conventional TF method (v_{ion}/v_0~ 5 or v_{ion}/c ~ 4%)
  - High-Velocity TF method (v_{ion}~Zv_0)

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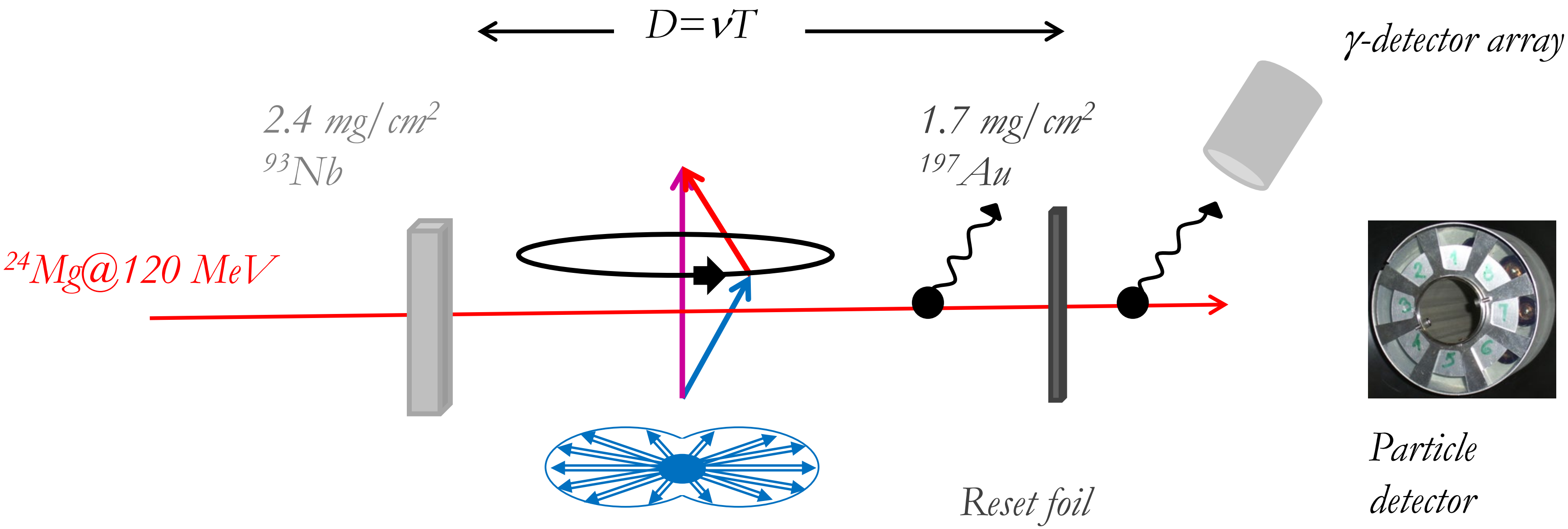
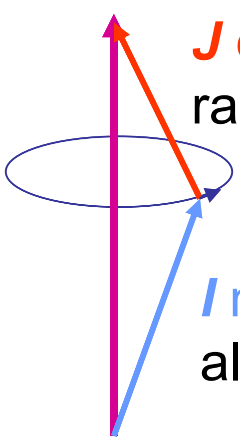
RIV/D or TDRIV Concept



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:

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

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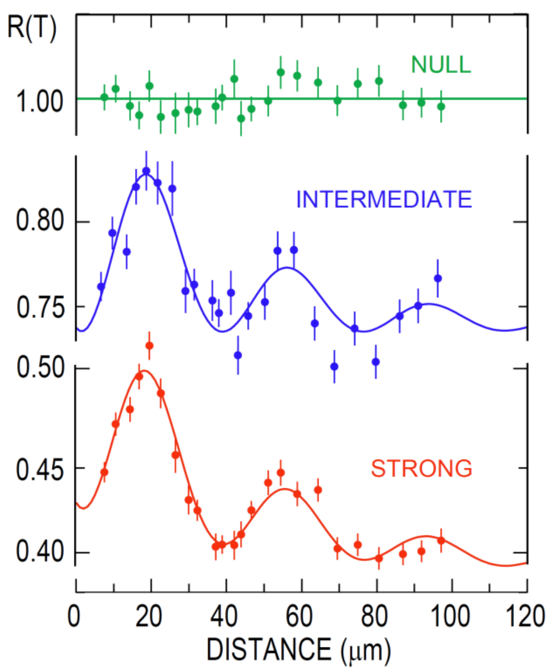
RIV/D or TDRIV Concept

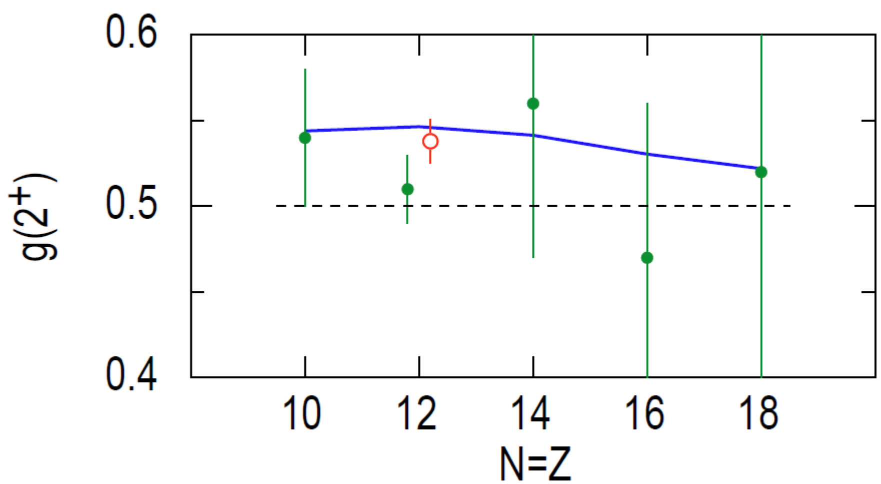
PRL **114,** 062501 (2015) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2015

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

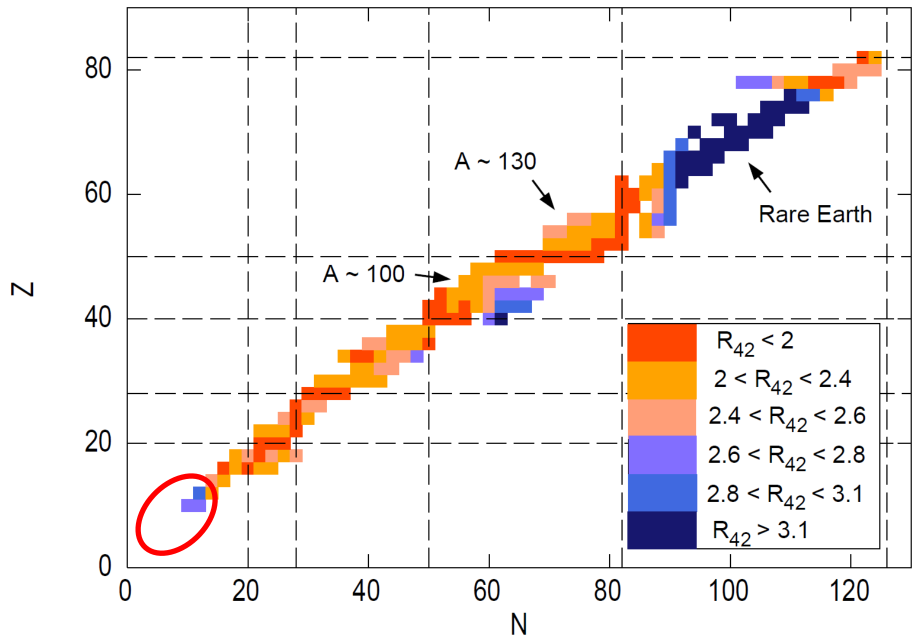




Evaluation of RIV/D

H-like ions

- Hyperfine field well known
- $Z \leq 12$
- Examples:
  - ^{13}C 5/2$^+$ 1981Ru04
  - ^{14}C 3$^-$ 1974Al07
  - ^{15}C 5/2$^+$ 1980As01
  - ^{14}N 2$^-$ 1978Mo27
  - ^{15}N 5/2$^+$ 1983Bi10
  - ^{16}N 3$^-$ 1984Bi03,1989Ra17
  - ^{16}N 1$^-$ 1975As02/1975Fo16
  - ^{15}O 5/2$^+$ 1978Be83
  - ^{16}O 3$^-$ 1984As03
  - ^{18}O 2$^+$ 1976As04
  - ^{20}O 2$^+$ 1980Ru01
  - ^{18}F 3$^+$ 1989Ra17
  - ^{19}F 5/2$^+$ 1984As03
  - ^{19}F 5/2$^-$ 1983Bi03
  - ^{20}Ne 2$^+$ 1975 Ho15
  - ^{21}Ne 5/2$^+$ 1978An30,1977Be30



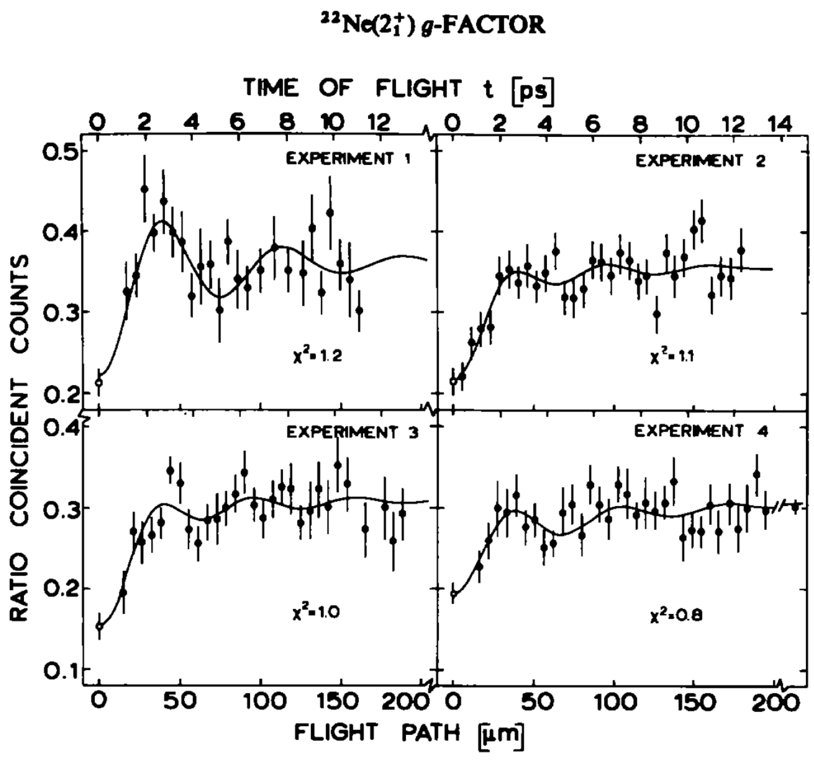
Examples continued:
  - ^{22}Ne 2$^+$ 1977ho01
  - ^{21}Na 5/2$^+$ 1977Be30
  - ^{22}Na 1$^-$ 1976Be06
  - ^{24}Mg 2$^+$ 1975Ho15/AES 2014 PRL

Overall, these TDRIV data can be accepted at face value, particularly if at least one period is observed

TDRIV/D exceptions

Wrong values:

- **^{22}Ne 2^+ 1977ho01**
- ^{21}Na $5/2^+$ 1977Be30



Surprise!

Horstman $|g| = 0.326(12)$ <4% error

TDRIV @ ISOLDE $|g|{\sim}0.4$ 25% higher

ISOLDE result confirmed with improved precision at GANIL

Konstantin STOYCHEV PhD thesis and to be published

The time-zero is important.

TDRIV/D exceptions

Wrong values:

- ^{22}Ne 2$^+$ 1977ho01
- **^{21}Na 5/2$^+$ 1977Be30**

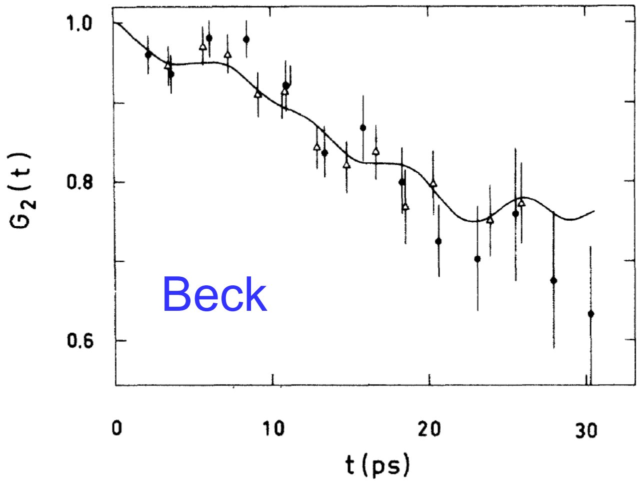


FIG. 5. Measured attenuation coefficient $G_2(t)$ for ^{21}Ne. The circles and triangles correspond to two different runs. The curve represents the best fit to the two sets of experimental data.

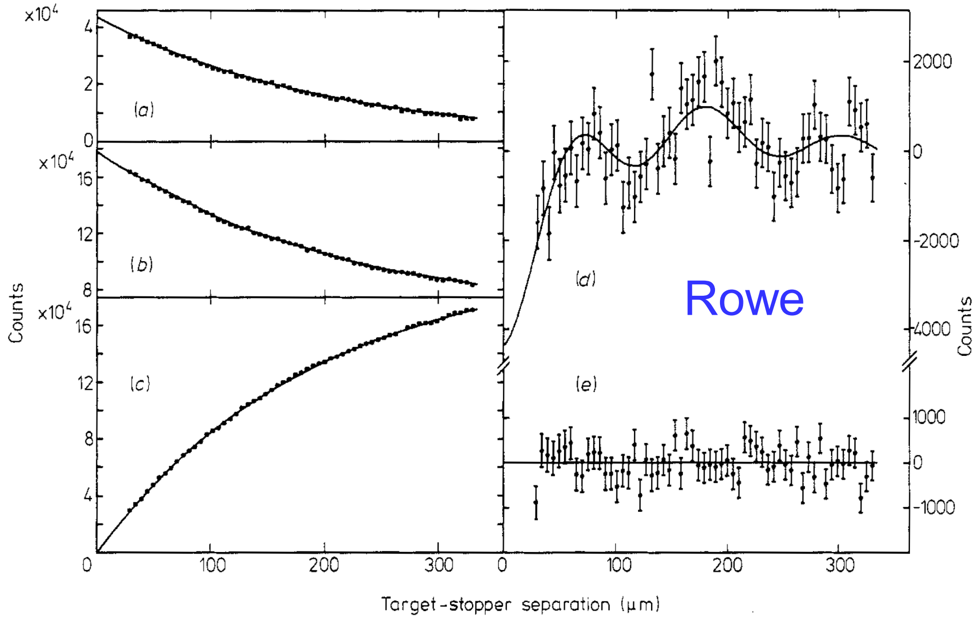


Figure 5. The variations of the intensity with recoil distance of (*a*) the ^{21}Na stopped peak, (*b*) the superimposed ^{21}Na flight peak and ^{21}Ne stopped peak, (*c*) the ^{21}Ne flight peak (indicated in figure 4), (*d*) the ^{21}Ne stopped peak with the exponential component subtracted out, derived from the best-fit parameters from run 4, and (*e*) the ^{21}Na stopped peak with the exponential component similarly removed. This data took 76 h to collect. The maximum target–stopper separation corresponds to a flight time of about 18 ps.

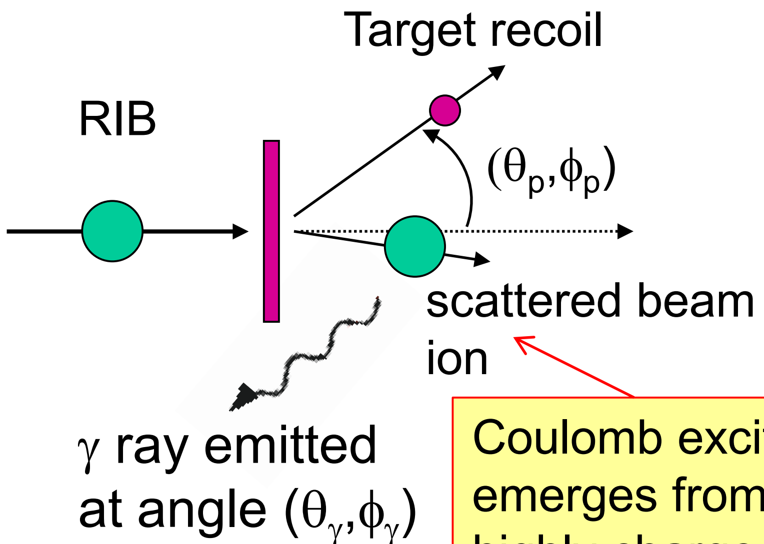
Nuclear electromagnetic moments in the new millennium

The sunset of high-spin physics and the sunrise of exotic nuclear studies

Georgi Georgiev[1*], Dimitar L. Balabanski[2*†], Andrew E. Stuchbery[3*†] and Hideki Ueno[4*†]

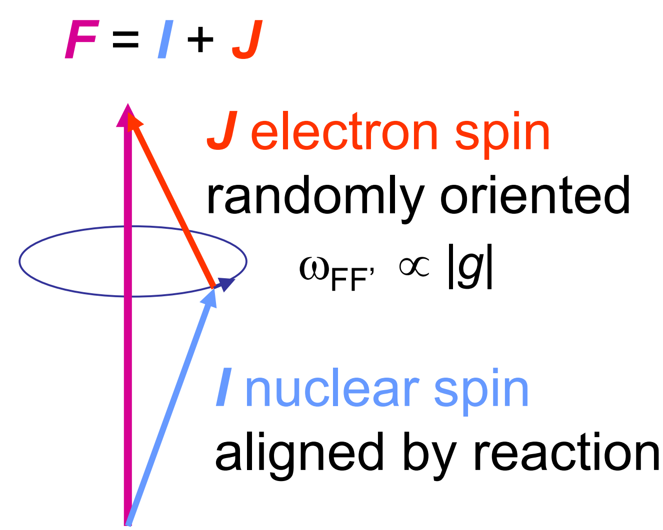
Before coming to the measurement on ^{28}Mg, it is useful to review the three TDRIV measurements of the magnitude of the g factor of the 351-keV $5/2^+$ state in ^{21}Ne published in 1977-78. The results were: $|g| = 0.196(14)$ [545], $|g| = 0.28(3)$ [546], and $|g| = 0.35(8)$ [547]. Of these three measurements, only that of Rowe et al. [545] compellingly observes oscillations (three peaks, two troughs), and yields a g-factor magnitude close to the USDB shell model [27, 378] value of $g = -0.220$. These examples illustrate the quality of the $R(T_f)$ data required to obtain a reliable TDRIV g-factor measurement.

RIV with complex ions



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

Coulomb excited beam emerges from target as highly charged ion

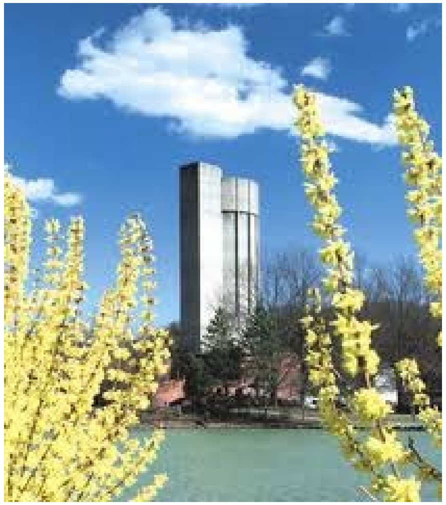


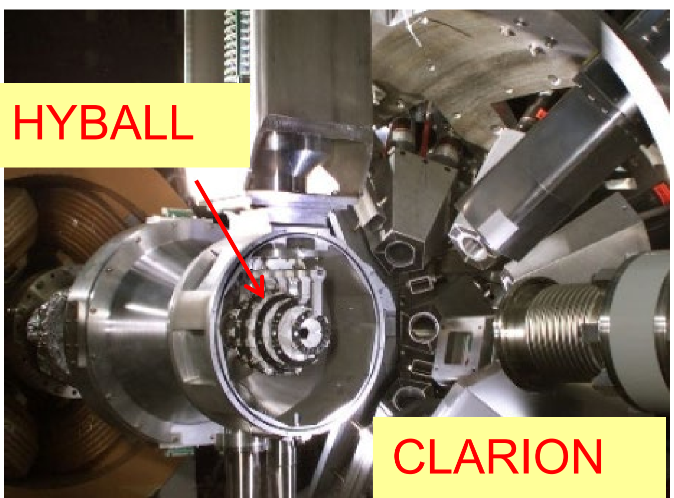
Attenuation coefficient due to RIV: contains information about the nuclear moment $0 \le G_k \le 1$

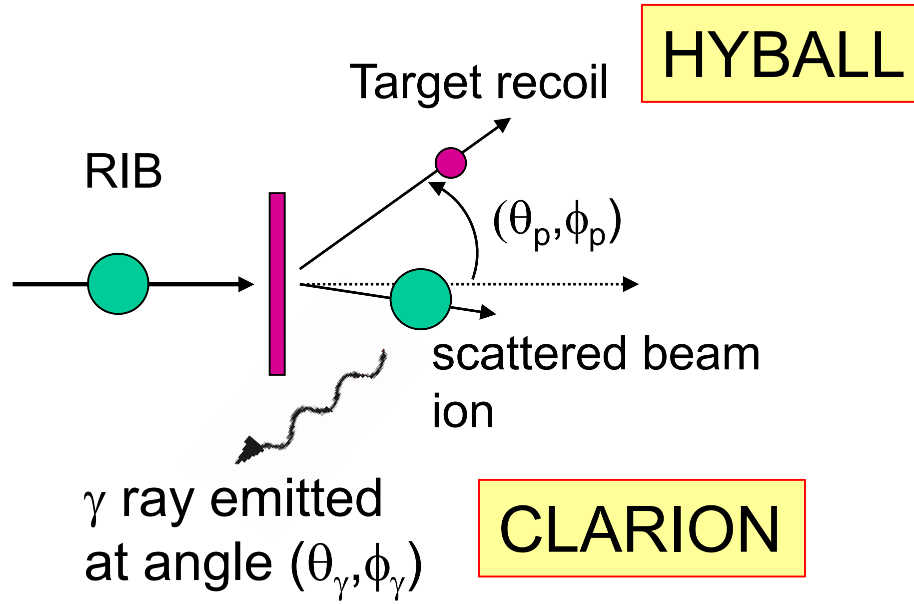
$$W(\theta_p,\theta_\gamma) = \sum_{k,q} \sqrt{2k+1}\,\rho_{kq}(\theta_p) G_k F_k Q_k D_{q0}^{k*}(\phi_\gamma - \phi_p, \theta_\gamma, 0)$$

RIV with complex ions

Mostly recent work from HRIBF, Oak Ridge on Sn and Te isotopes

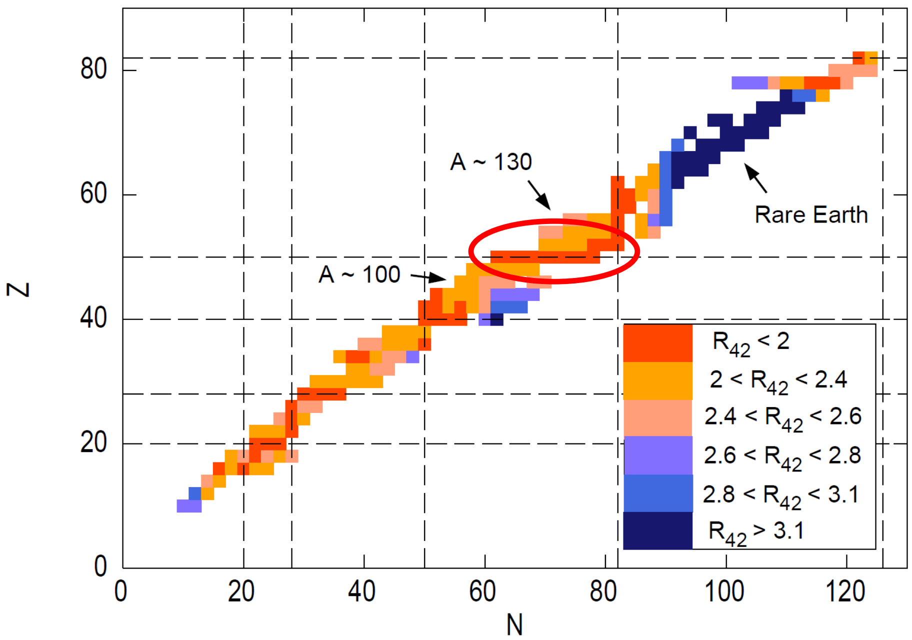


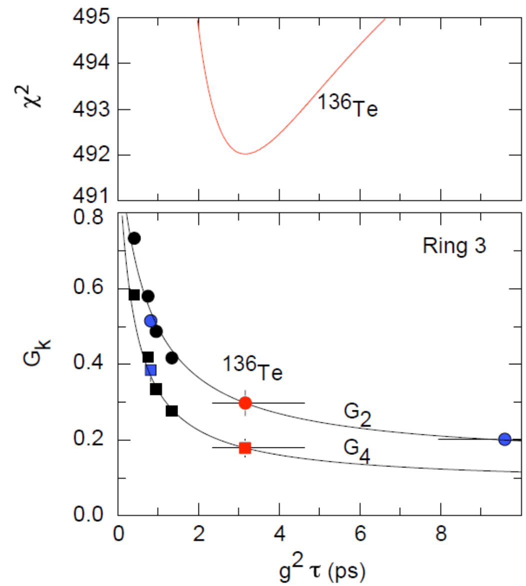




RIV evaluation

Mostly work from HRIBF, Oak Ridge on Sn and Te isotopes





Allmond et al.
PRL **11**, 092503 (2017)
AES et al.
PRC **96**, 014321 (2017)

- Report $g\tau$ or $g^2\tau$. All referenced to radioactivity measurements on the Te isotopes via transient-field measurements
- Evaluation of a change in calibration g factors would require specialist knowledge
- BUT uncertainties in field-calibrations are generally small cf. error on these radioactive beam g-factor measurements

Can be adopted as reported (subject to changes in adopted nuclear lifetimes)

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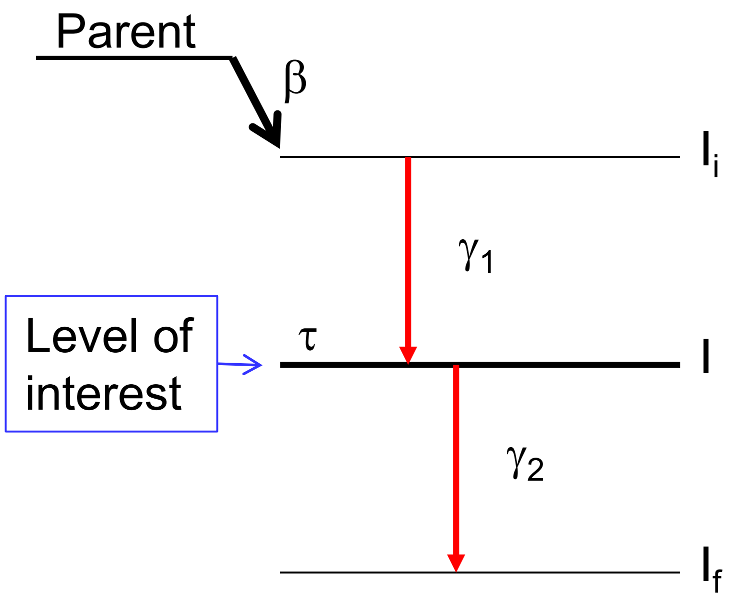
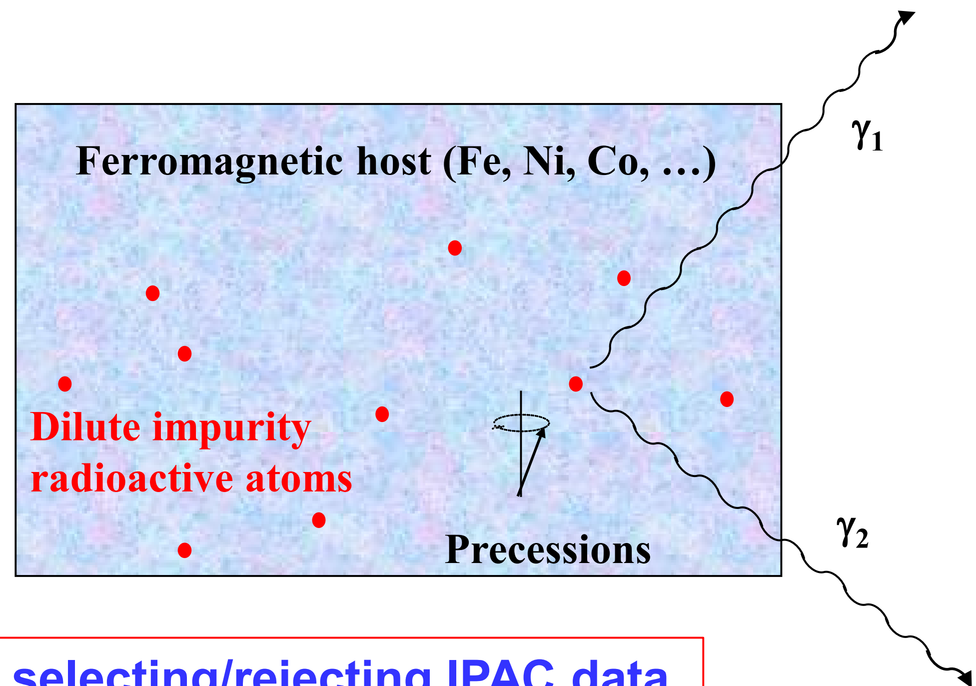
Radioactivity Concept

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

g-factor measurement requires knowledge of field and mean lifetime.
⇒ Adopted value should reflect ‘best’ B and τ values.





Need to discuss and set criteria for selecting/rejecting IPAC data

TDPAC – more likely to be reliable (Georgi)

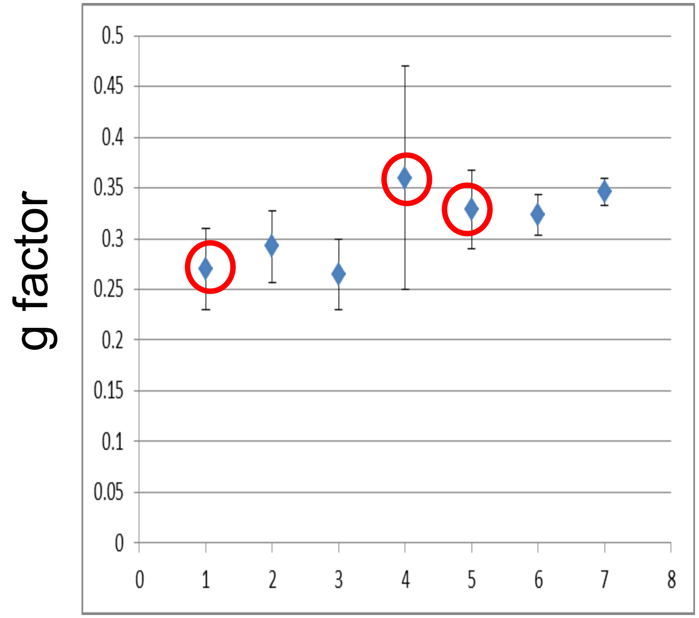
Radioactivity Example

Kawamura, J. Phys. Soc. Japan 50, 1832 (1981)

Table V. Summary of g-factors of 355.7 keV level in ^{196}Pt measured by various methods.

No	g-factor	Method	Reference
1	0.27 ±0.04	CE (O)-γ AD[a)]	15) IMPAC
2	0.292±0.036	γ-γ AC[b)]	16)
3	0.265±0.035	γ-γ AC	17)
4	0.36 ±0.11	CE (O)-γ AD	18)
5	0.329±0.039	CE (O)-γ AD	19)
6	0.323±0.020	e^--γ AC[c)]	20)
7	0.346±0.013	γ-γ AC	This work

a) CE(O)-γ AD: Angular distribution of gamma ray in coincidence with back scattered oxygen in Coulomb excitation.
b) γ-γ AC: Gamma-gamma correlation.
c) e^--γ AC: Electron-gamma correlation.



- Sample preparation
- Annealing
- Impurity concentration
- Impurity sites (alloy formation)
- Polarizing field
- Ge vs NaI detectors

Radioactivity Example

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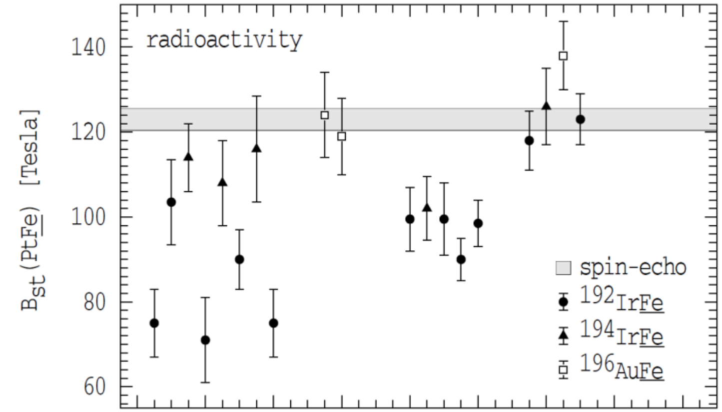
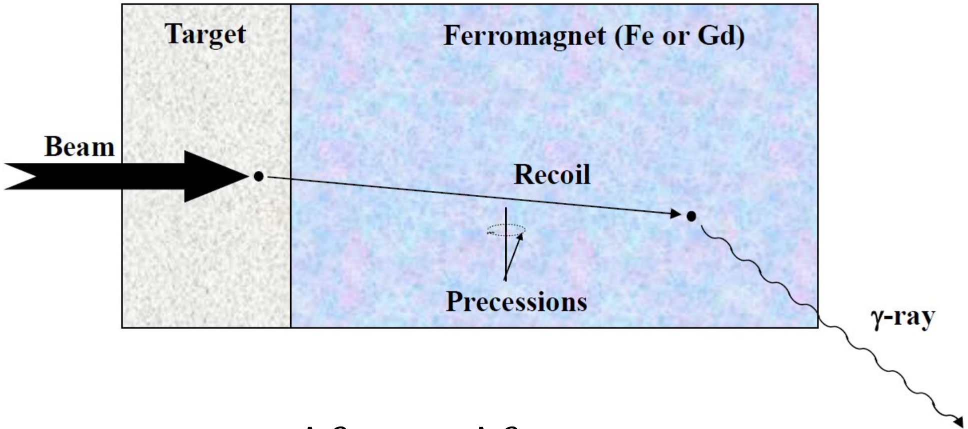
Hyperfine Interact 96, 1 (1995)



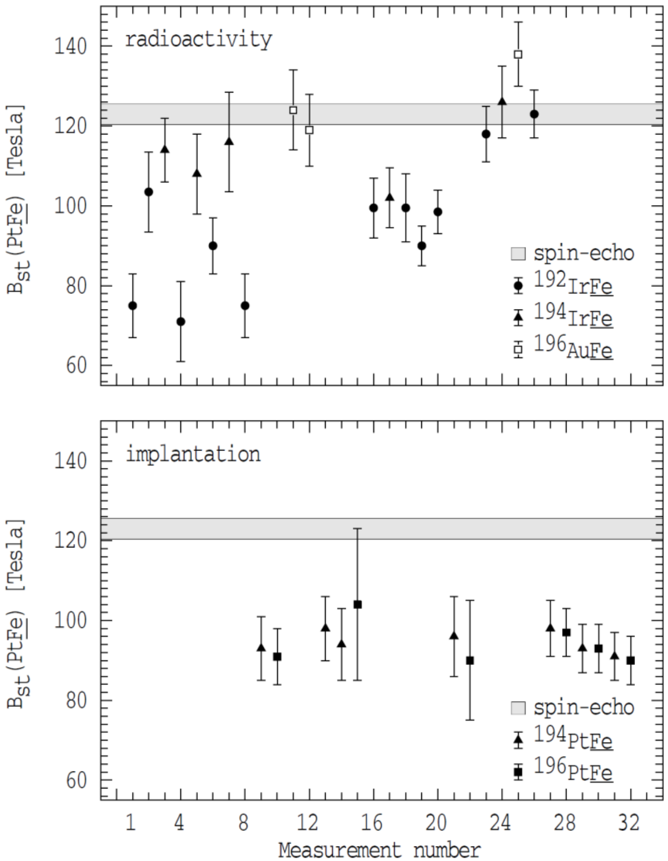
Measurement number

- Sample preparation
- Annealing
- Impurity concentration
- Impurity sites (alloy formation)
- Polarizing field
- Ge vs NaI detectors

Implantation PAC (IMPAC)



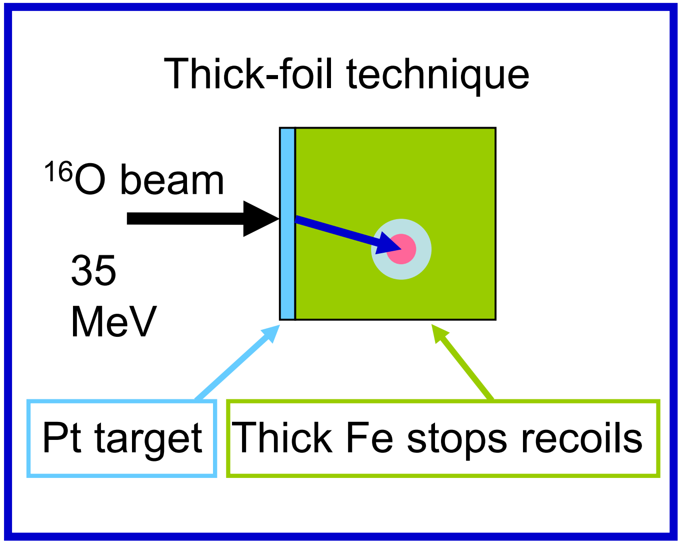
$$\Delta\theta_{obs} = \Delta\theta_{tf} + \omega\tau$$



Combined transient- and static-field precession

- Pre 1975
- Largely superseded by transient-field method
- Must be treated with a high degree of caution
  - Pre-equilibrium effects after implantation
- Should NOT be relied upon for TF calibration

Pre-equilibrium effects



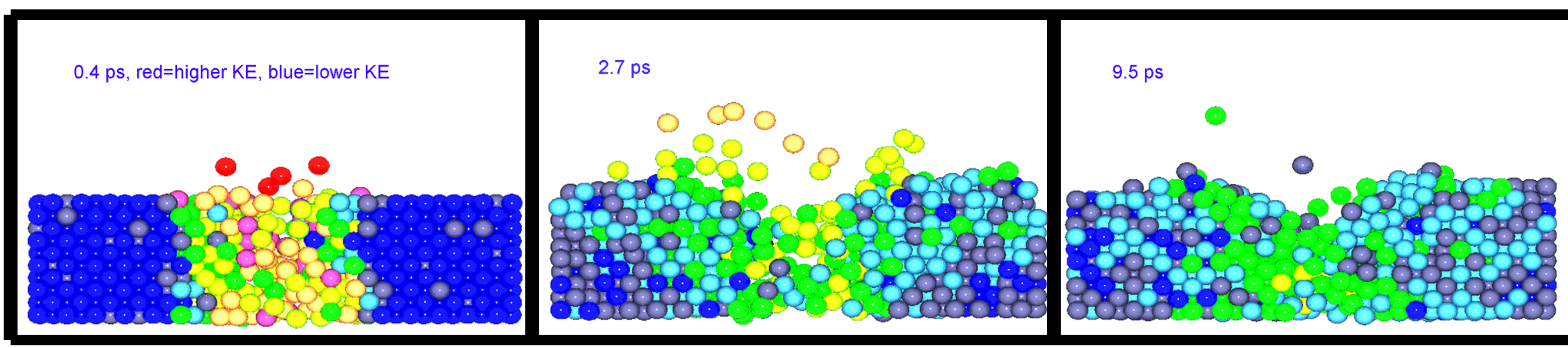
VOLUME 82, NUMBER 18 PHYSICAL REVIEW LETTERS 3 MAY 1999

Thermal-Spike Lifetime from Picosecond-Duration Preequilibrium Effects in Hyperfine Magnetic Fields Following Ion Implantation

Andrew E. Stuchbery and Eva Bezakova
Department of Nuclear Physics, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT 0200, Australia
(Received 15 December 1998)

The effective hyperfine magnetic fields acting on short-lived excited nuclear states ($27 < \tau < 127$ ps) have been measured for ~7.5 MeV Ir and Pt ions immediately after implantation into iron hosts at room temperature. The observed field strengths decrease with the lifetime of the probe state and are consistent with the hyperfine field being absent for about 6 ps after implantation. As the hyperfine field is quenched while the local temperature exceeds the Curie temperature, these results give a direct measurement of the thermal-spike lifetime. [S0031-9007(99)09022-5]

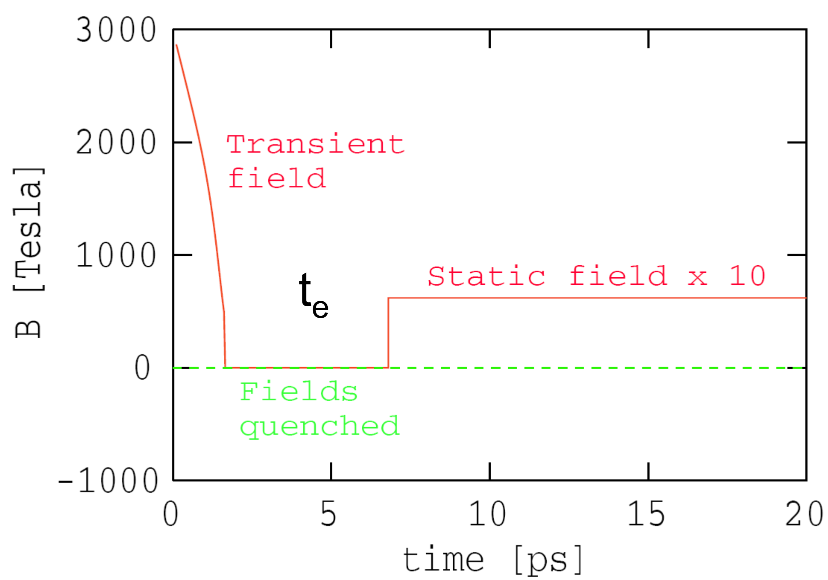
Pre-equilibrium effects due to local disruption after implantation
- cf. the molecular dynamics of sputtering



Quenched static fields

Implantation process is violent in the nuclear stopping regime

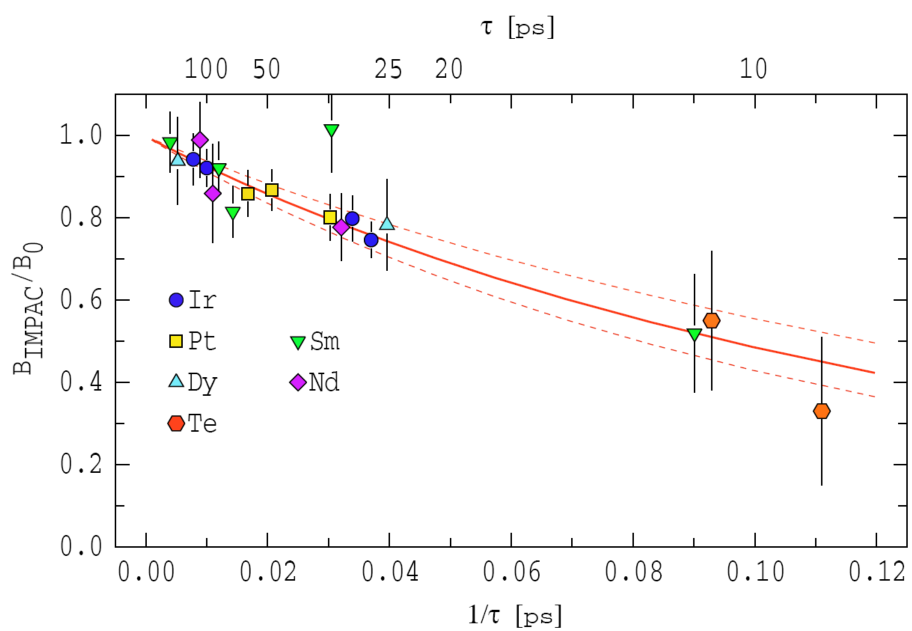
Onset of static field is delayed by an equilibration time $t_e \sim 6$ ps



$$\Delta\theta_{obs} = \Delta\theta_{tf} + \omega\tau \exp(-t_e/\tau)$$

$$\Delta\theta_{obs}/g = \Delta\theta_{tf}/g + \omega\tau \exp(-t_e/\tau)/g$$

$$\Rightarrow B_{IMPAC} / B_0 = \exp(-t_e / \tau)$$

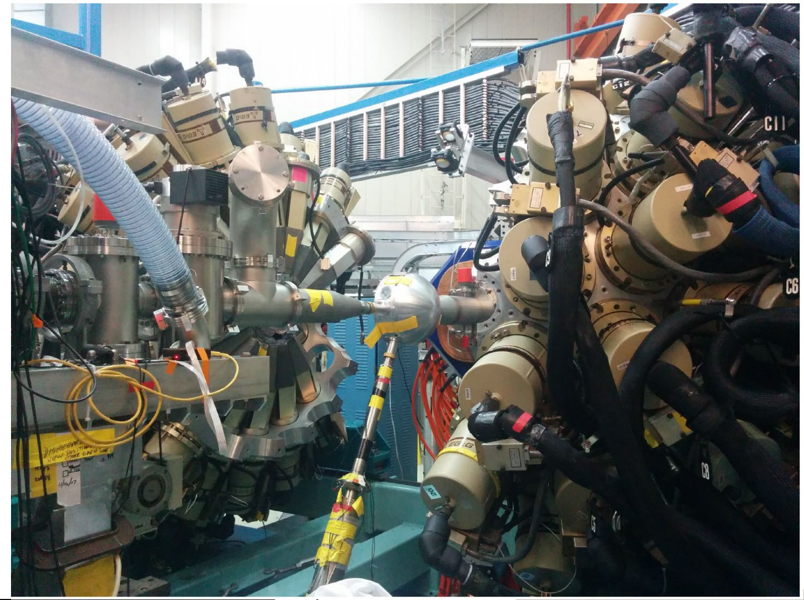


Should evaluate for lower – *Z*

- *Treat IMPAC results with caution*

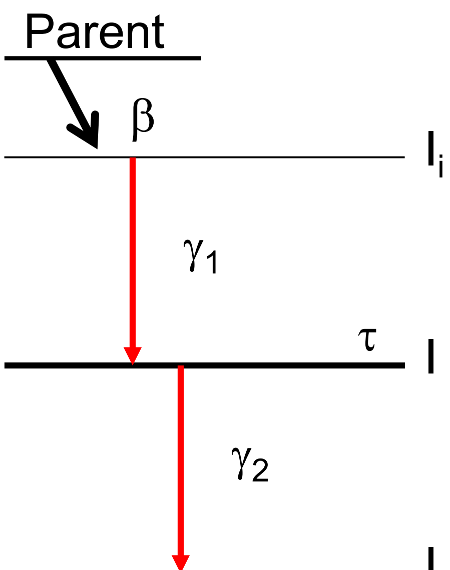
RIB problematic case: ^{138}Xe

CARIBU + Gammasphere experiment

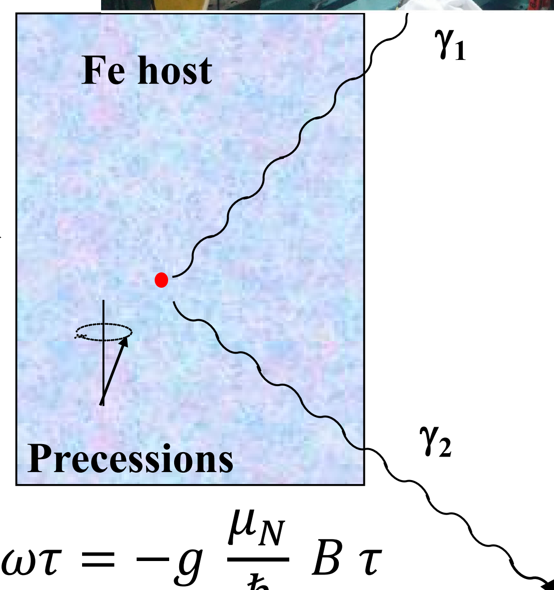


Low excitation spectroscopy and the signs and magnitudes of g factors in the N=84 nuclides ^{136}Te and ^{138}Xe.

A.E. Stuchbery[1], G.J. Lane[1], J.M. Allmond[2], A.D. Ayangeakaa[3], M.P. Carpenter[3], P. Chowdhury[4], J.A. Clark[3], P.A. Copp[4], H.M. David[3], S.S. Hota[1], R.V.F. Janssens[3], T. Kibedi[1], F.G. Kondev[3], T. Lauritsen[3], C.J. Lister[4], A.J. Mitchell[4], M.W. Reed[1], G. Savard[3], D. Seweryniak[3], S. Zhu[3]



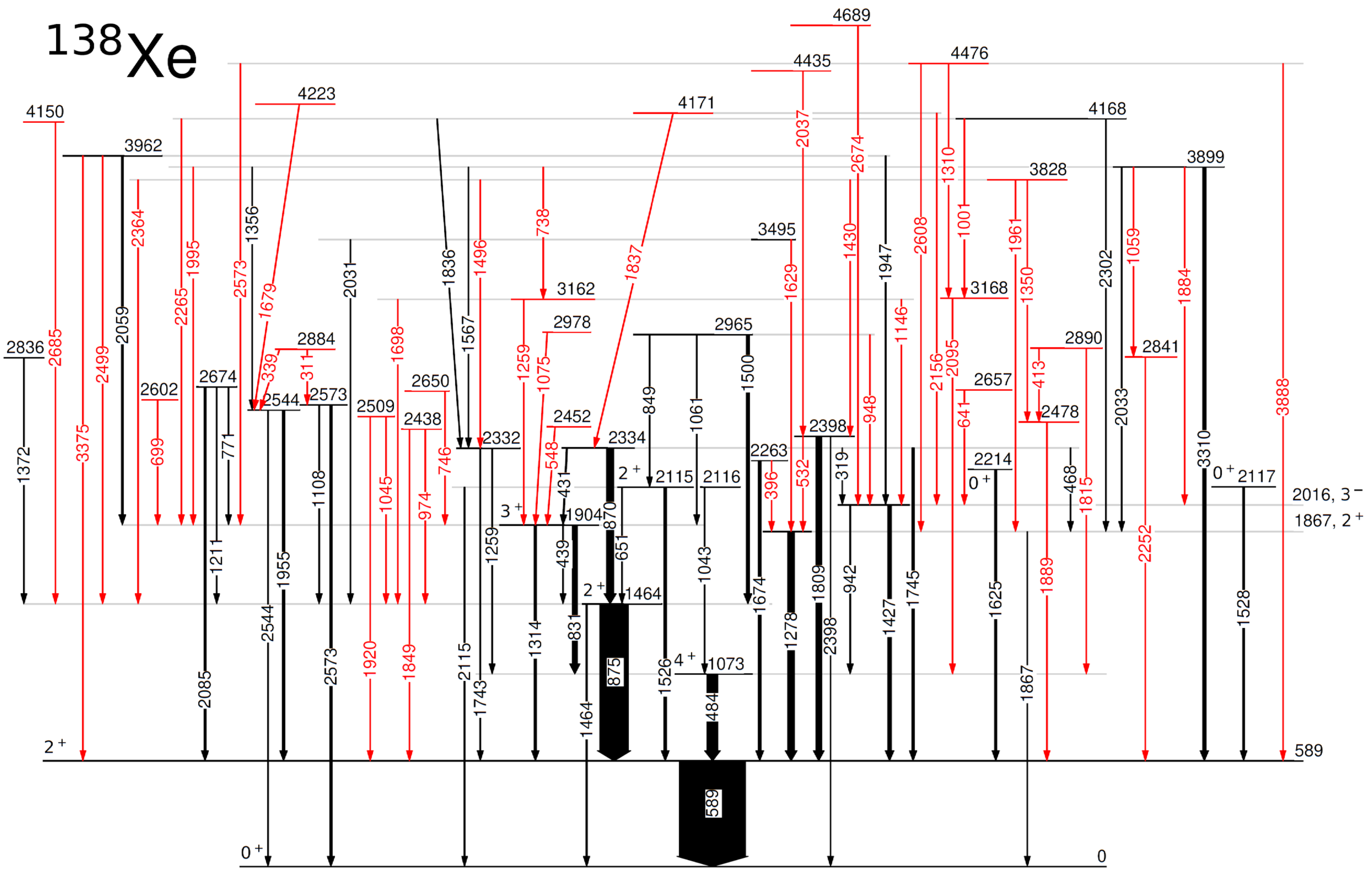
^{136}Sb, ^{138}I beams



$$\omega\tau = -g\,\frac{\mu_N}{\hbar}\,B\,\tau$$

^{138}Xe - outcomes

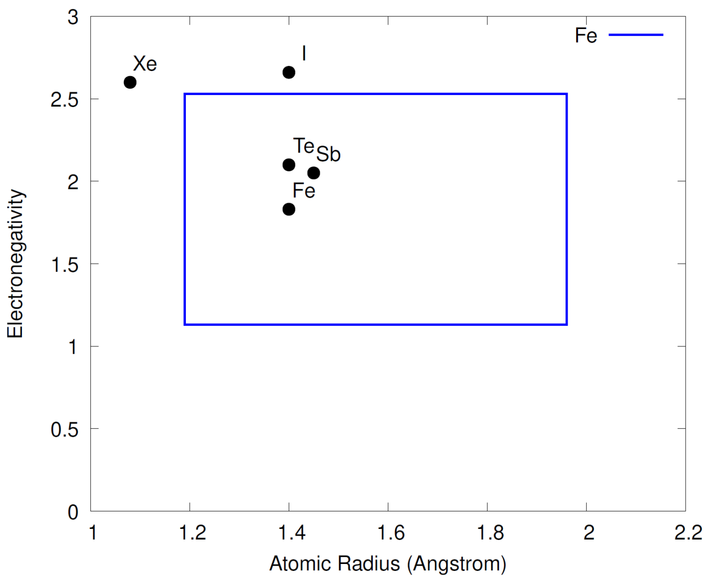
Yielded a wealth of spectroscopic data – Tim Gray PhD Thesis, ANU



^{138}Xe - outcomes

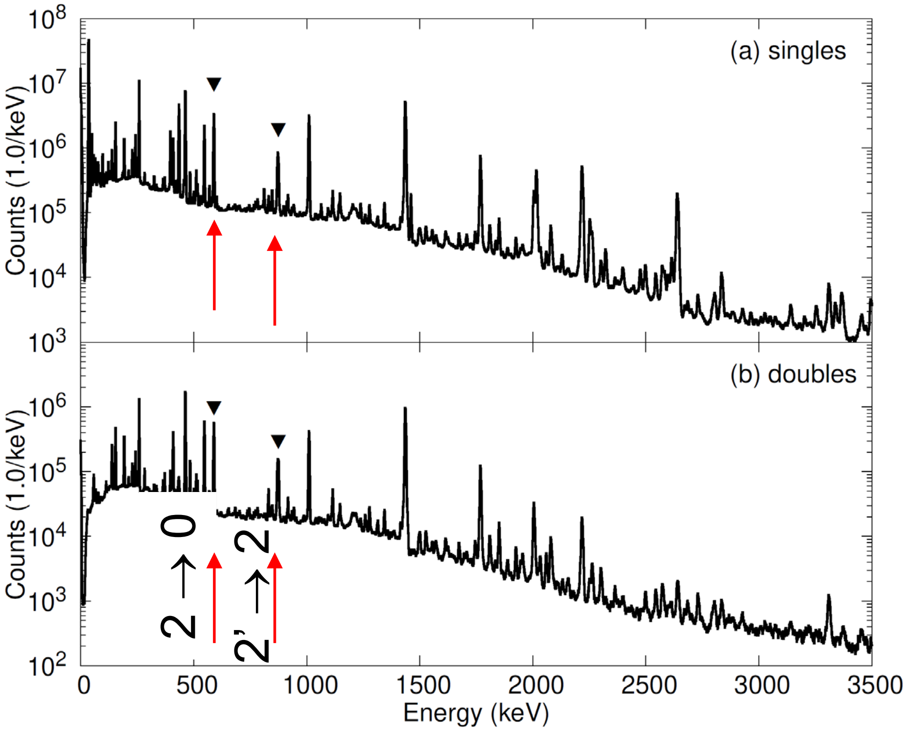
But no g factor – few Xe on good field sites.

Krane has B_{st} =+160.3(52) T. Experiment would have worked if this field were present.



Big misfit between Xe atomic radius and the iron lattice spacing.

Few implanted Xe on “good sites”



Note complexity of spectra

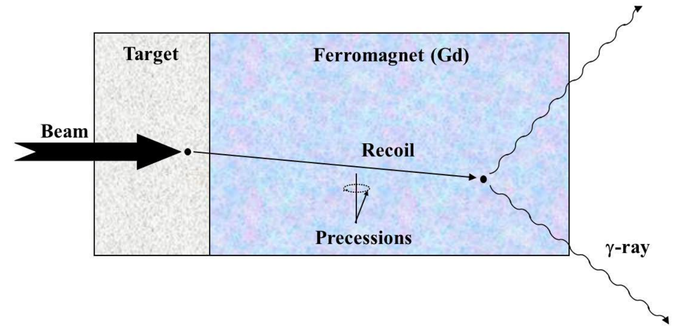
A case I got wrong: ^{110}Cd

ELSEVIER Nuclear Physics A 591 (1995) 533–547

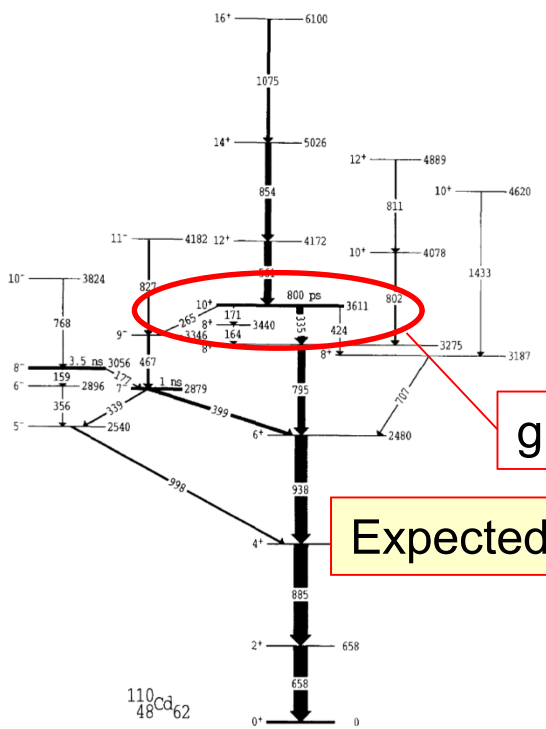
Measurement of the *g*-factor of the yrast 10^+ state in ^{110}Cd

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

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



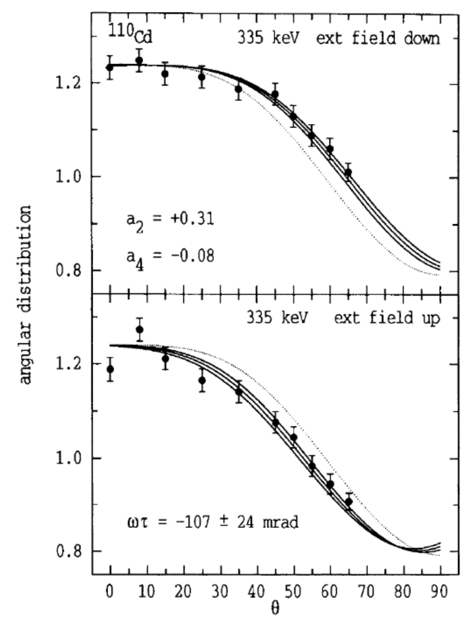
NB: Gadolinium host



g(10⁺) = -0.09(3)

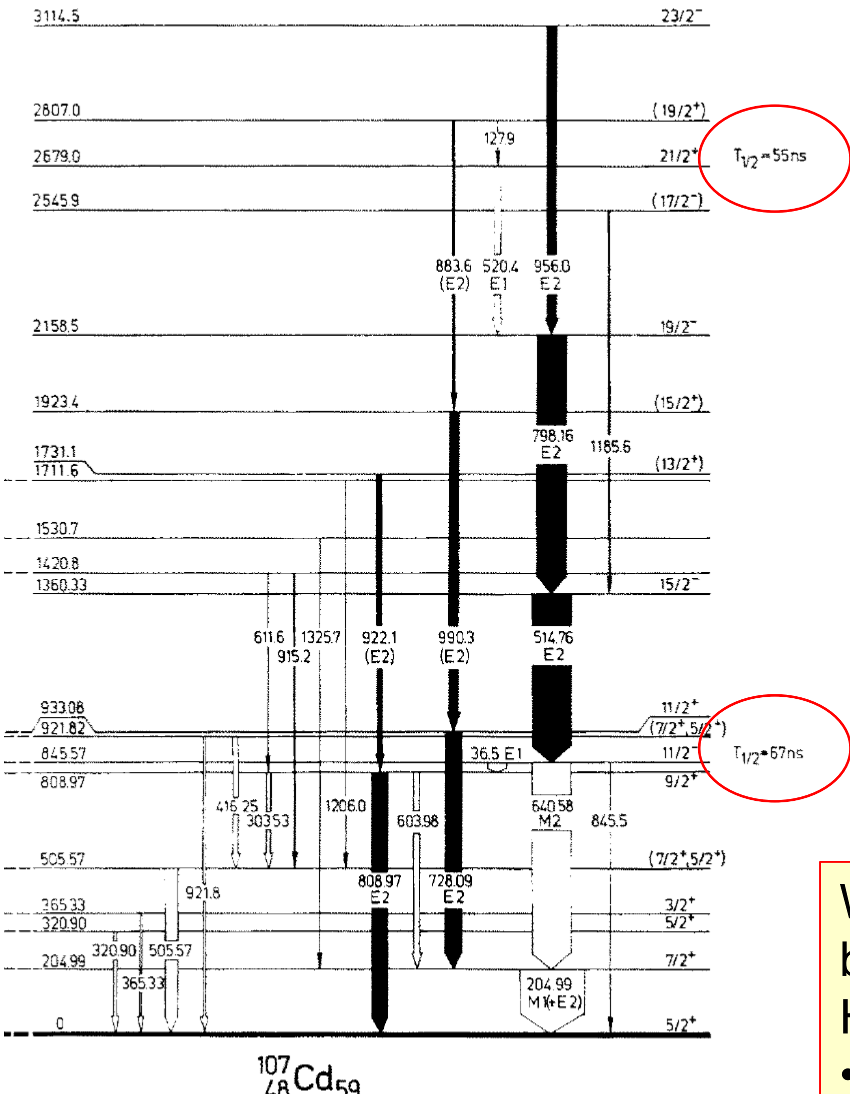
Expected g ~ -0.2 for $\nu(h_{11/2})^2$

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



Integral perturbed angular correlations

^{107}Cd isomers known g

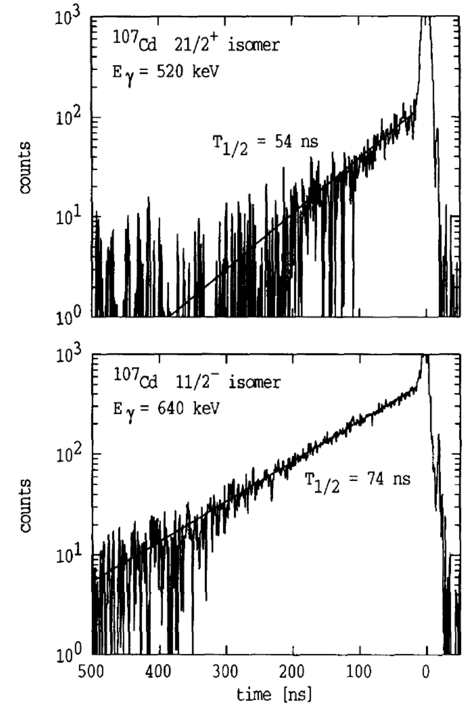


g ~ 0.8

g ~ -0.2

Level scheme from NPA 228, 112

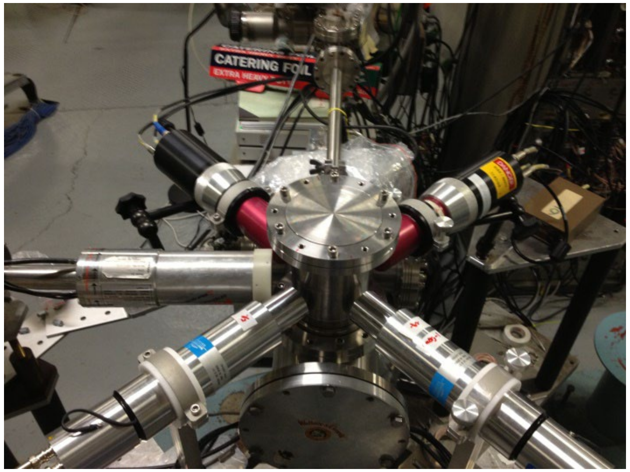
^{100}Mo(^{12}C,5n)^{107}Cd 65 MeV

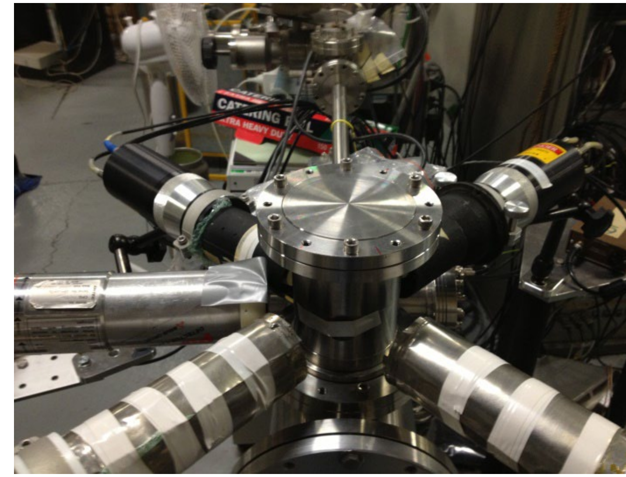


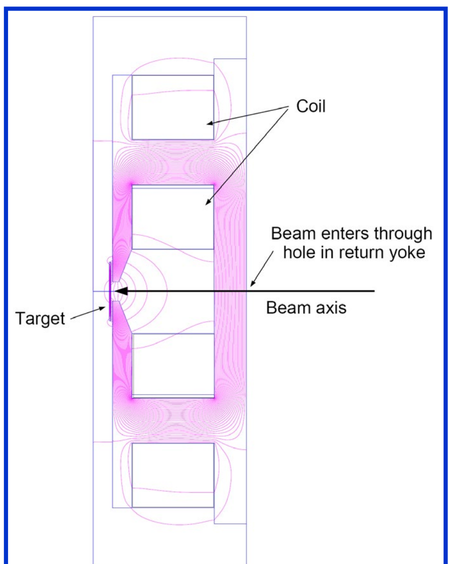
We observed the 11/2$^-$ and 21/2$^+$ isomers but could not resolve spin precessions with HPGe detectors

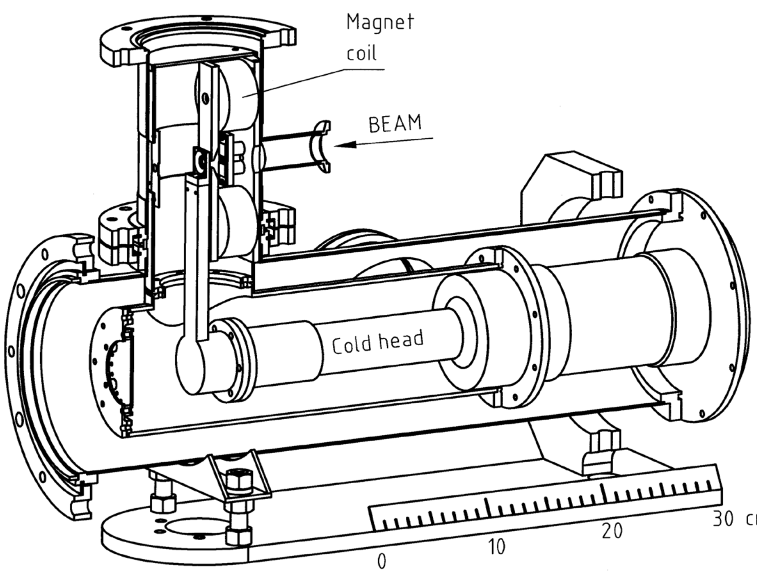
- Can revisit and solve problem with $LaBr_3$
- Use ^{98}Mo(^{12}C,3n)^{107}Cd

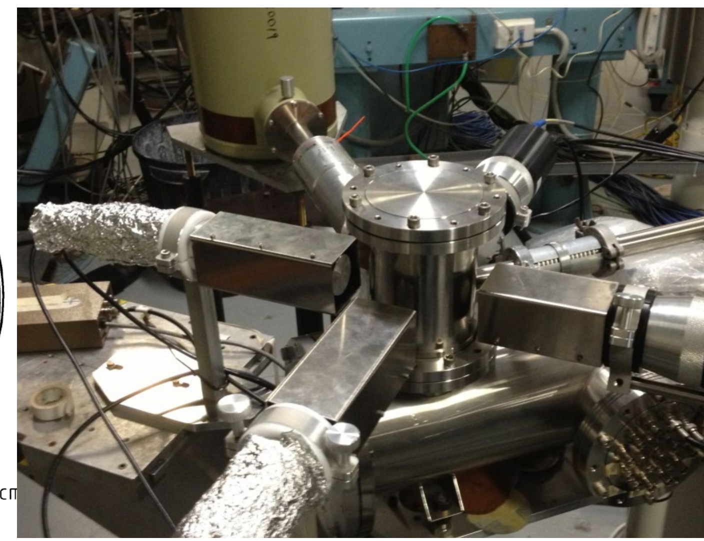
$LaBr_3$ runs mid 2016





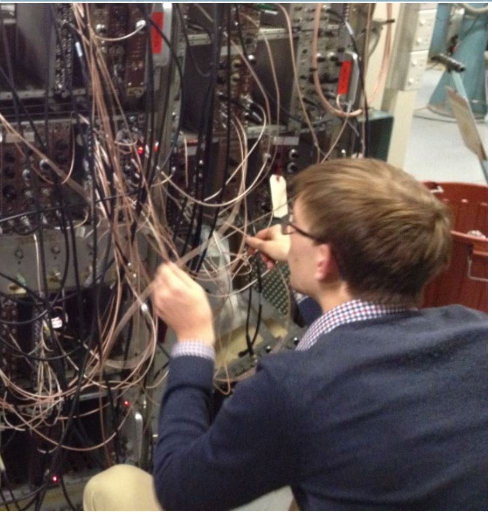






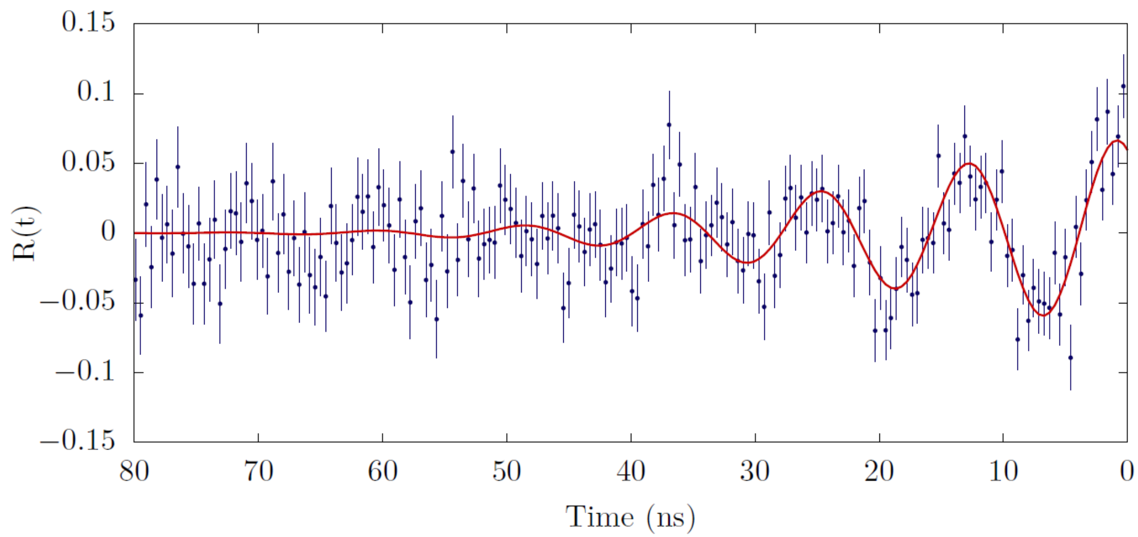
Mu-metal shielding: Steve Battisson.

$LaBr_3$ TDPAD



Tim Gray
ANU Honours Project
2016

$^{98}Mo(^{12}C, 3n)^{107}Cd$ into Gd
$E\gamma$ = 640 keV $11/2^-$ $T_{1/2}$ = 74 ns T~12 ns



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
- IMPAC $g(10^+)$ in ^{110}Cd assumed the wrong effective field
- On-going analysis and method development
  - May yet redeem the IMPAC data

$LaBr_3$ TDPAD

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
Department of Nuclear Physics, Research School of Physics and Engineering, The Australian National University, Canberra, ACT 2601, Australia
(Received 29 September 2017; published 29 November 2017)

PHYSICAL REVIEW C **101**, 054302 (2020)

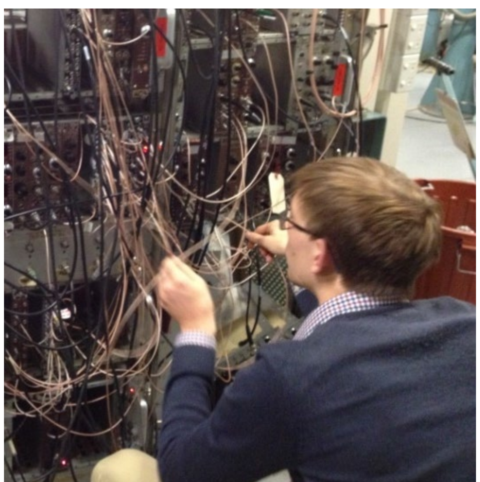
Hyperfine fields at ^{66}Ga, $^{67,69}Ge$ implanted into iron and gadolinium hosts at 6 K, and applications to *g*-factor measurements

T. J. Gray, A. E. Stuchbery, B. J. Coombes, J. T. H. Dowie, M. S. M. Gerathy, T. Kibédi, G. J. Lane, B. P. McCormick, A. J. Mitchell, and M. W. Reed
Department of Nuclear Physics, Research School of Physics, Australian National University, Canberra ACT 2601, Australia

LaBr$_3$ in-beam TDPAD: ^{111}Sn 11/2$^-$ isomer

^{98}Mo(^{16}O,3n)^{111}Sn

Implant into Gd $B_{hf} \approx 30$ tesla

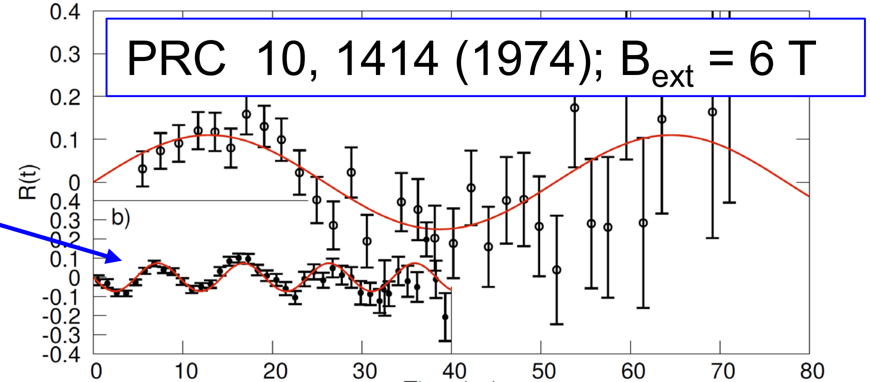


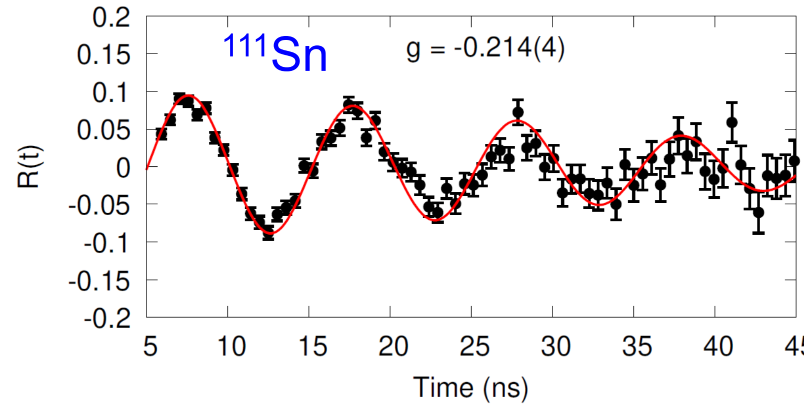
Tim Gray

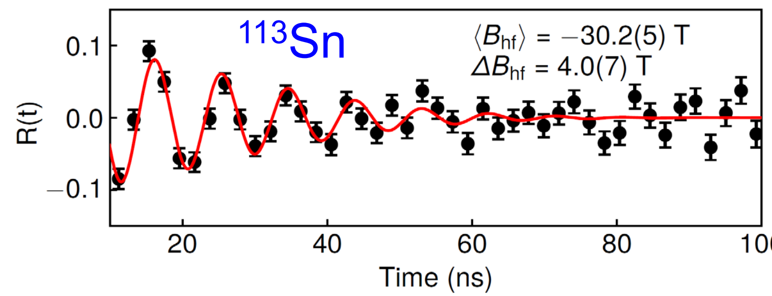
TDPAD =
Time Dependent
Perturbed Angular
Distributions

New result: g=-0.214(4)
- Small error

- Field check used ^{98}Mo(^{18}O,3n)^{113}Sn







LaBr$_3$ in-beam TDPAD: ^{111}Sn 11/2$^-$ isomer

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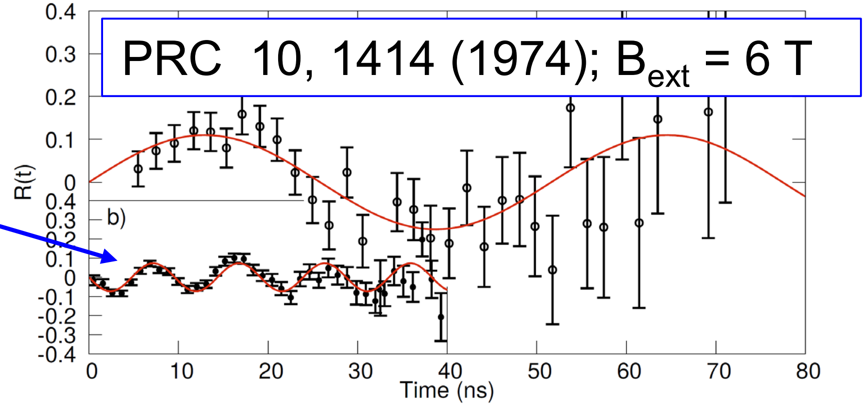
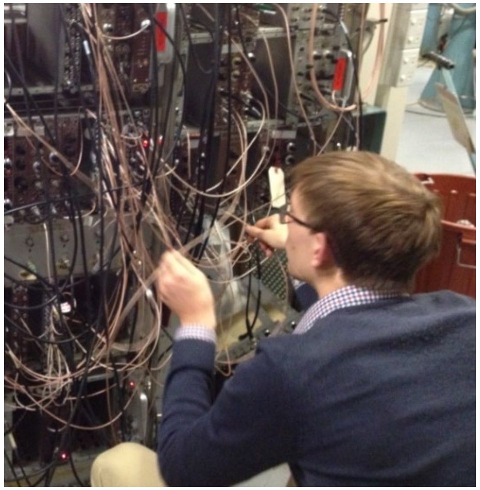
Implant into Gd $B_{hf} \approx 30$ tesla





Tim Gray

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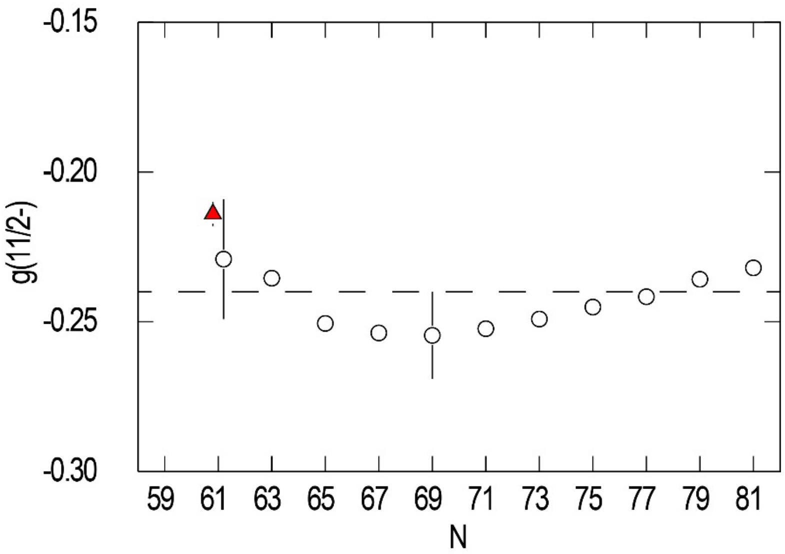
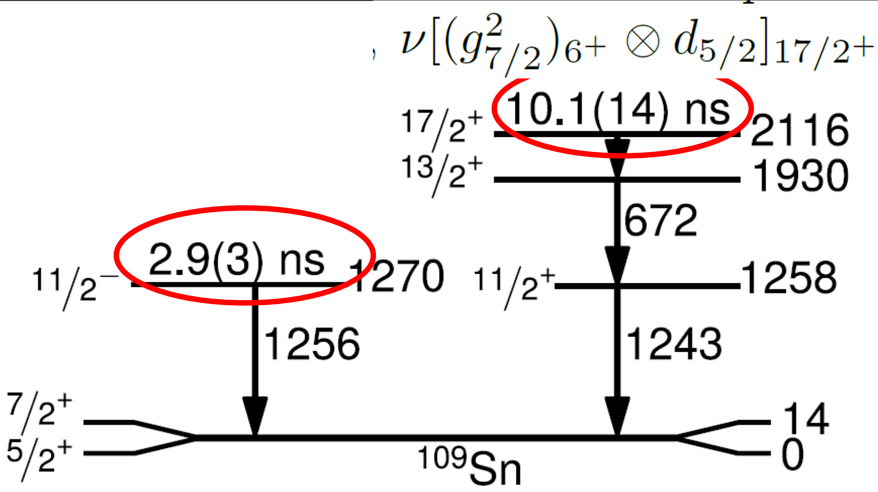
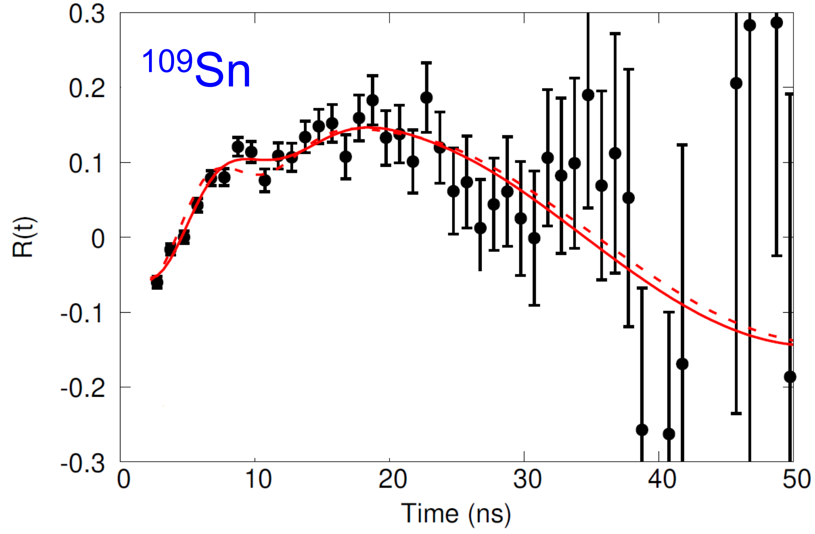
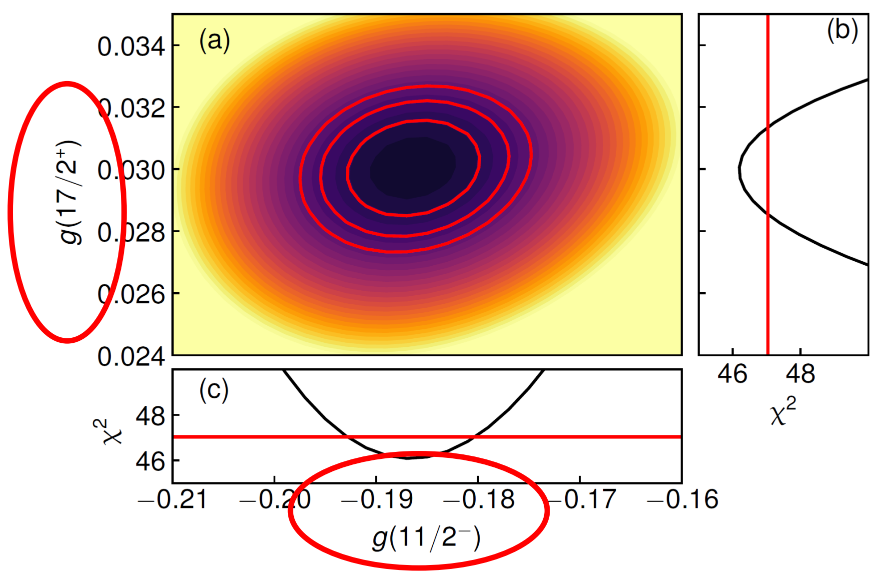


^{109}Sn results





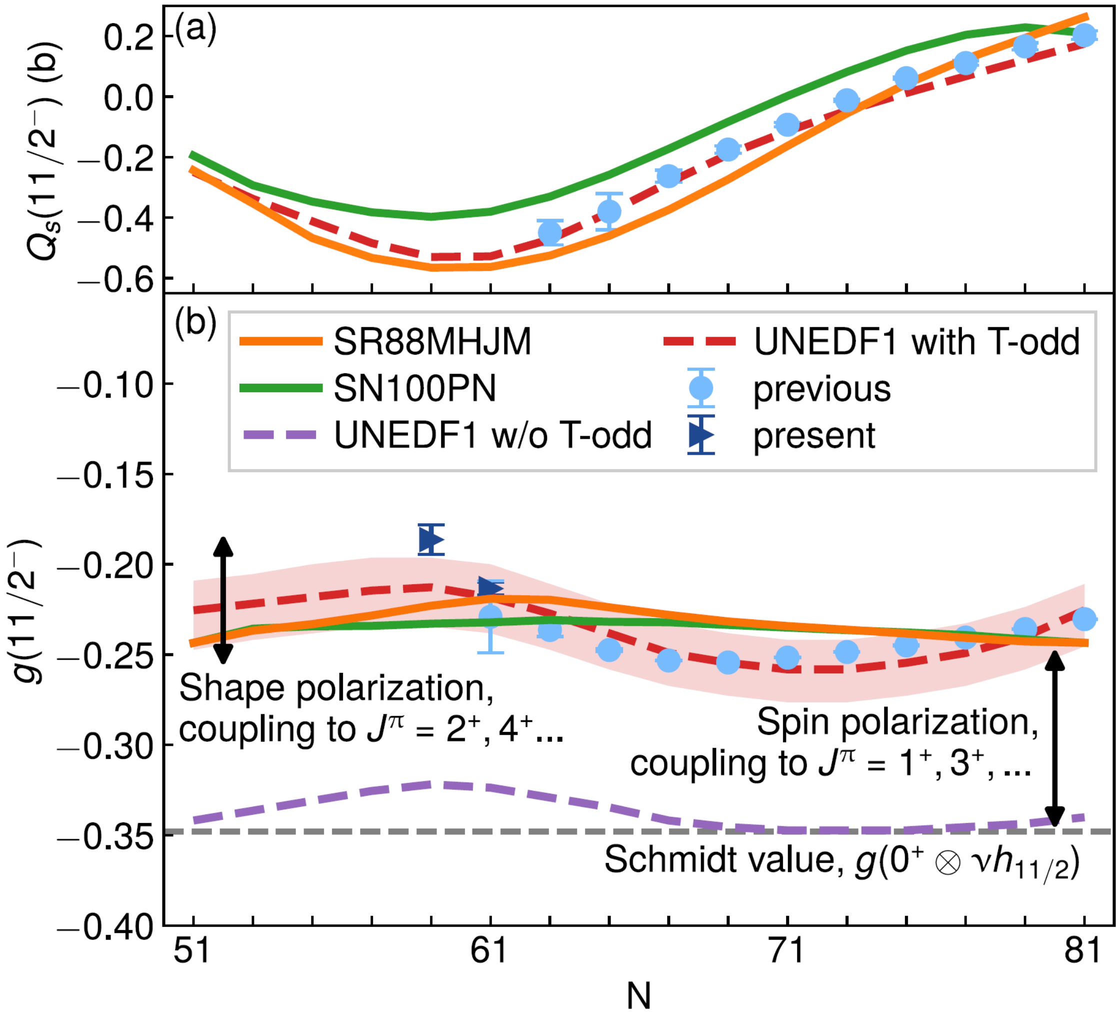
Can't separate 1256 and 1243 in $LaBr_3$



However isomer lifetimes and g factors are so different that they can be separated in the R(t) data

^{109}Sn 11/2$^-$: New record for TDPAD g-factor measurement $T_{1/2} = 2$ ns

Calculations of g and Q: SM & DFT



Density Functional Theory (HFODD)

- tracks Q and g trends
- no effective charges
- bare M1 operator
- much larger basis space than shell model

Evaluating IMPAC

- How many IMPAC measurements are there not clearly superseded by other measurements?
- Distinguish implantation followed by decay from in-beam IMPAC.
- Distinguish cases where TF dominates or SF dominates.
- If SF dominates, distinguish cases where $\tau \gg 10\ \mathrm{ps}$
- Might be forced to largely discard IMPAC data for adopted g-factor values
  - Creates problems for TF calibration for $12 < Z < 46$

Evaluating IMPAC

Avoid if at all possible (with caveats below) because of difficulties:

- Implantation site(s) not well controlled (Gd seems to be worse than Fe)
- Pre-equilibrium quenching of the static hyperfine field
- Combined static- and transient-field effects: $\Delta\Theta_{obs} = \Delta\theta_{TF} + \omega\tau$

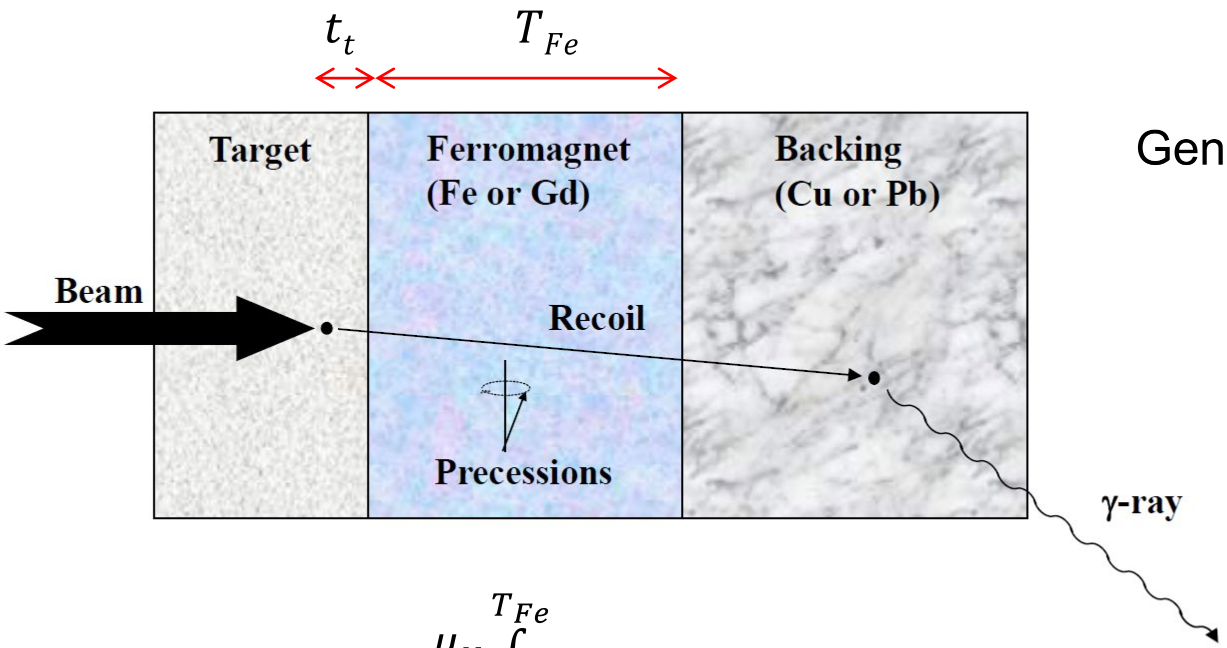
Caveats:

- If the lifetime is short and/or B_{static} is small then $\Delta\Theta_{obs} \approx \Delta\theta_{TF}$
  - Effectively a transient-field measurement – see comments on TF (mostly low-Z nuclei)

- If $\Delta\theta_{TF}$ is small and $\omega\tau$ is large then: $\Delta\Theta_{obs} \approx \omega\tau$
  - If $\tau \gg 10$ ps effectively an IPAC/IPAD measurement – evaluate on those criteria

Critical IMPAC cases for TF calibration: ^{56}Fe and ^{82}Se

Transient Fields



Generally insensitive to lifetime

$\tau \gg T_{Fe} < 1$ 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)
  - Issues with absolute calibration
  - Good if calibrate relative to independently known g factor
  - Parametrizations – what is the uncertainty?

TF parametrizations

Original linear (Eberhardt et al 1977, Hyp Int 3, 195): $B_{tr} = aZ(v/v_0)$ $\quad a = 12.5 \pm 1.7\ T$

Rutgers (Shu et al 1980, PRC 21, 1828): $B_{tr} = aZ^{p_Z}(v/v_0)^{p_v}\mu_B N_p$

$$B_{tr} = (96.7 \pm 1.6)Z^{(1.1 \pm 0.2)}\,(v/v_0)^{(0.45 \pm 0.18)}\mu_B N_p$$

Mainly Fe hosts. O – Nd;
Omits Pt - doesn't fit.

Chalk River: $B_{tr} = aZ(v/v_0)^p e^{-\beta v/v_0}$ (+ Lindhard-Winther term)

1. Fe hosts, 62 < Z < 70 (Andrews et al 1982, NPA 383, 509):

   $a = 15.5 \pm 0.8\ T$ $\quad \beta = 0.1$ (set) (Includes LW term)

2. Gd hosts, Z = 69 (Hausser et al 1983, NPA 406, 339):

   $a = 29.0 \pm 1.8\ T$ $\quad \beta = 0.135$ (set)

3. Gd hosts, Z = 82 (Hausser et al 1984, NPA 412, 141):

   $a = 28.0 \pm 2.6\ T$ $\quad \beta = 0.135$ (set)

TF parametrizations

Pd (Z=46) in Fe (AES et al 1980, PRC 21, 1828): $B_{tr} = aZ^{pz}(v/v_0)^{pv}\mu_B N_p$

$$B_{tr} = (5645 \pm 920)\,(v/v_0)^{0.41\pm0.15}\mu_B N_p$$

Higher velocity data ~ $7v_0$

Bonn Modified Linear (Speidel et al 1991, ZPhysD 22, 371):

$$B_{tr} = G_{beam}\,aZ\,(v/v_0)$$

$$a(Fe) = 12 \pm ?\ T$$

$$a(Gd) = 17 \pm 1\ T$$

- Not clear outside Bonn group how to evaluate G_{beam}
  - But at least an error is always assigned to it
  - The Bonn parametrization usually agrees quite well with Rutgers

TF calibration issues -1

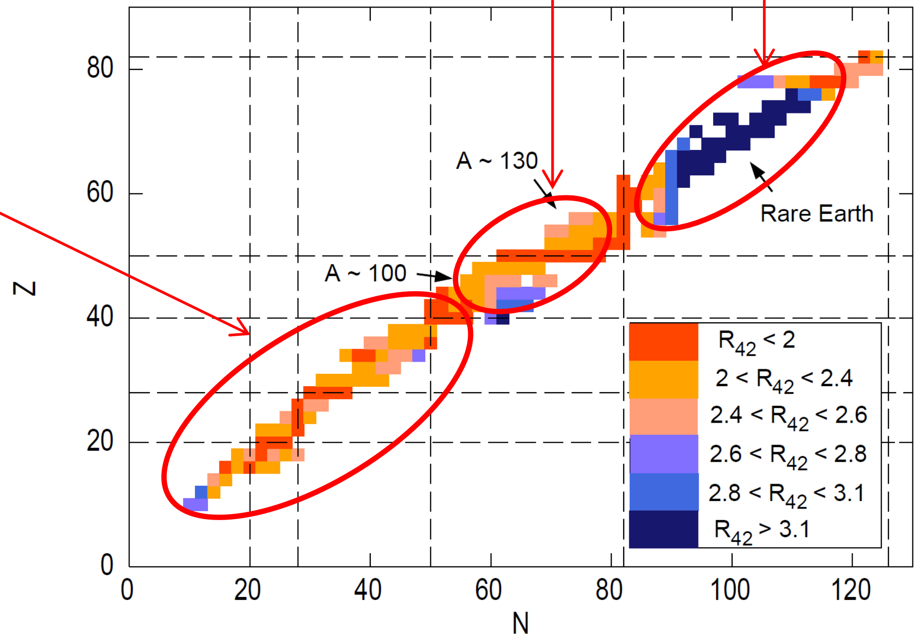
Lack of suitable calibration g factors for 12 < Z < 46

RE region 60 < Z < 82 – no problem!
Many independent measurements

40 < Z < 60 OK? but sparse independent data
^{106}Pd, ^{122,124}Te

12 < Z < 46 Big problem:
Essentially no good calibration data between ^{24}Mg and ^{106}Pd.

^{56}Fe data used are problematic!



TF calibration issues -1

Australian National University

Lack of suitable calibration g factors for 12 < Z < 46

PHYSICAL REVIEW C **79**, 024303 (2009)

g factor of the first excited state in ^{56}Fe and implications for transient-field calibration in the Fe region

M. C. East,[1] A. E. Stuchbery,[1] S. K. Chamoli,[1] A. N. Wilson,[1,2] H. L. Crawford,[3] J. S. Pinter,[3] T. Kibédi,[1] and P. F. Mantica[3]
[1]*Department of Nuclear Physics, Research School of Physics and Engineering, The Australian National University Canberra, ACT 0200, Australia*
[2]*Department of Physics, The Australian National University, Canberra, ACT 0200, Australia*
[3]*NSCL and Department of Chemistry, Michigan State University, Michigan 48824, USA*
(Received 22 September 2008; published 5 February 2009; publisher error corrected 14 July 2009)

The transient-field technique has been used to measure the g factor of the 2_1^+ state in ^{56}Fe relative to the independently determined g factor of the first $5/2^-$ state in ^{57}Fe. The new result for ^{56}Fe agrees with previous measurements but is more precise. Implications for calibrating the transient field and g-factor measurements in the fp region are discussed.

(Not satisfied with this and still trying to get an independent ^{56}Fe g factor measurement!)

We suggest, however, that caution is warranted when assigning uncertainties to absolute g factors in the $f_{7/2}$ and fp shells measured by the transient-field technique.

For the present evaluation uncertainties in TF strength must be quantified

TF calibration issues - 2

Discontinuities versus Z for TF in iron hosts

PRL 43, 1711 (1979)

Discontinuity in the Transient Magnetic Field around $Z_1 = 9$ and $Z_2 = 26$

K. Dybdal, J. S. Forster,[a] and N. Rud
Institute of Physics, University of Aarhus, DK-8000 Aarhus C, Denmark

(Received 13 August 1979)

K-vacancy fractions have been measured for O ions moving in Fe and for F ions moving in Fe, Co, and Ni at velocities $2.1 \leq v/v_0 \leq 10.5$. Discontinuities that explain those found for the transient magnetic field are observed. The present findings indicate that (i) the transient field cannot be approximated by a linear velocity dependence for $Z_1 \leq 8$ in Fe and for $Z_1 \leq 9$ in Co and Ni, and (ii) the discontinuity in the transient field is only present at velocities below $4v_0$.

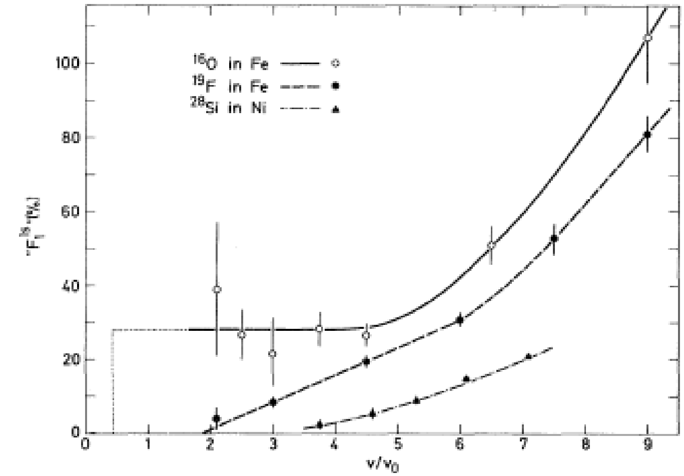
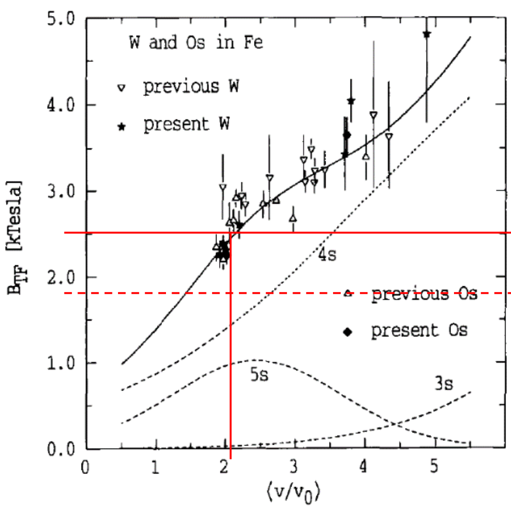
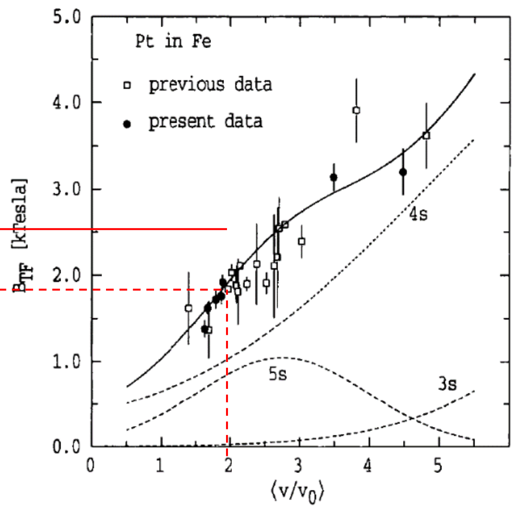


FIG. 2. Measured equilibrium *K*-vacancy fractions, "F_1^{1s}", for O and F in Fe, and previously published (Ref. 5) data for Si in Ni (in this case expected to be equivalent to Fe). The curves serve to guide the eye. The dotted curve represents a guess for O in Fe at low velocities (see text).

See Hyp. Int. 13,275 (1983) and 88, 97 (1994)





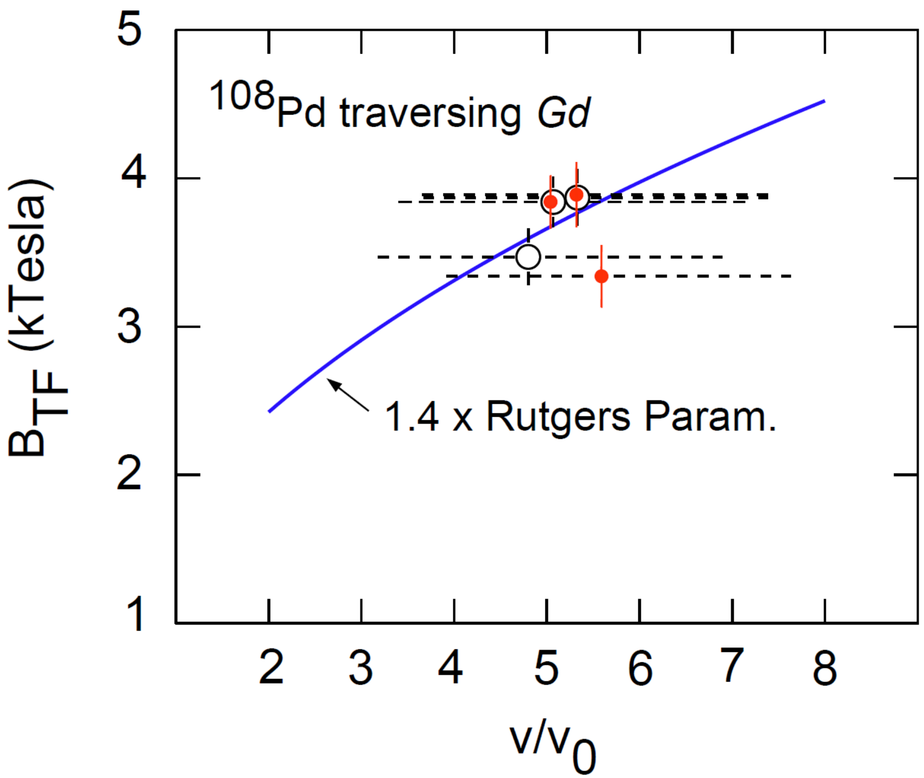
Explains why Pt in Fe data did not fit Rutgers parametrization

Danger zones are near Z=8, 26(!), 46, 78.

Not expected or observed for Gd hosts

TF calibration issues - 3

Parametrizations based on limited data for Fe can fail when used for Gd hosts



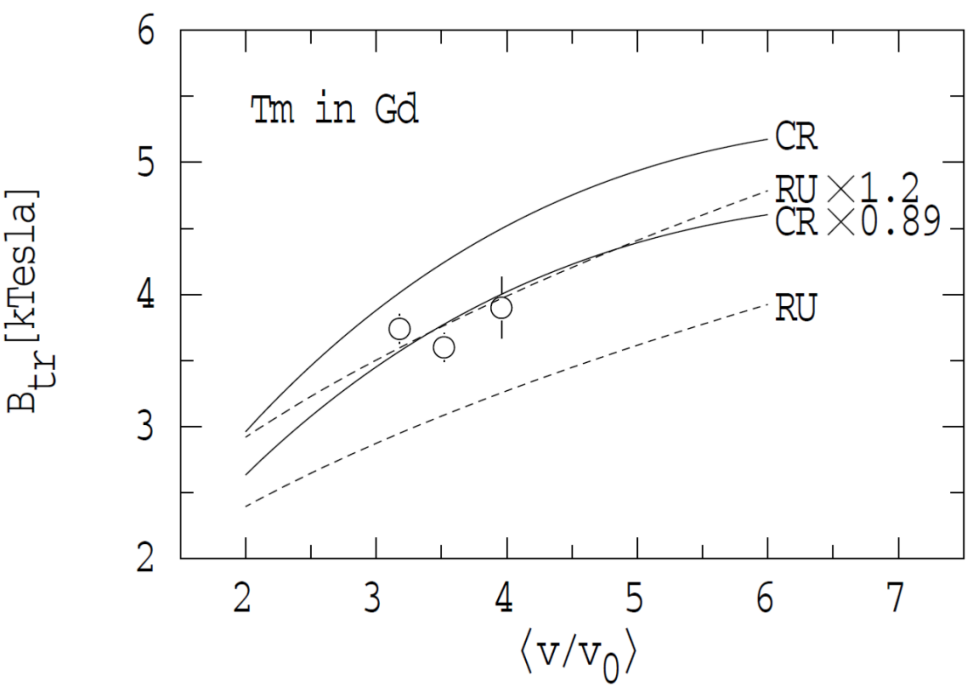
- Field for Pd in Gd is 1.4 times bigger than predicted
- Possibly related to level matching effects noted on previous slide
- **Need new TF parametrization for *Gd* hosts and Z < ~ 60**

Chamoli et al 2011, PRC 83, 054318

TF reproducibility

Generally ANU and Rutgers groups have agreed on measured precession angles.

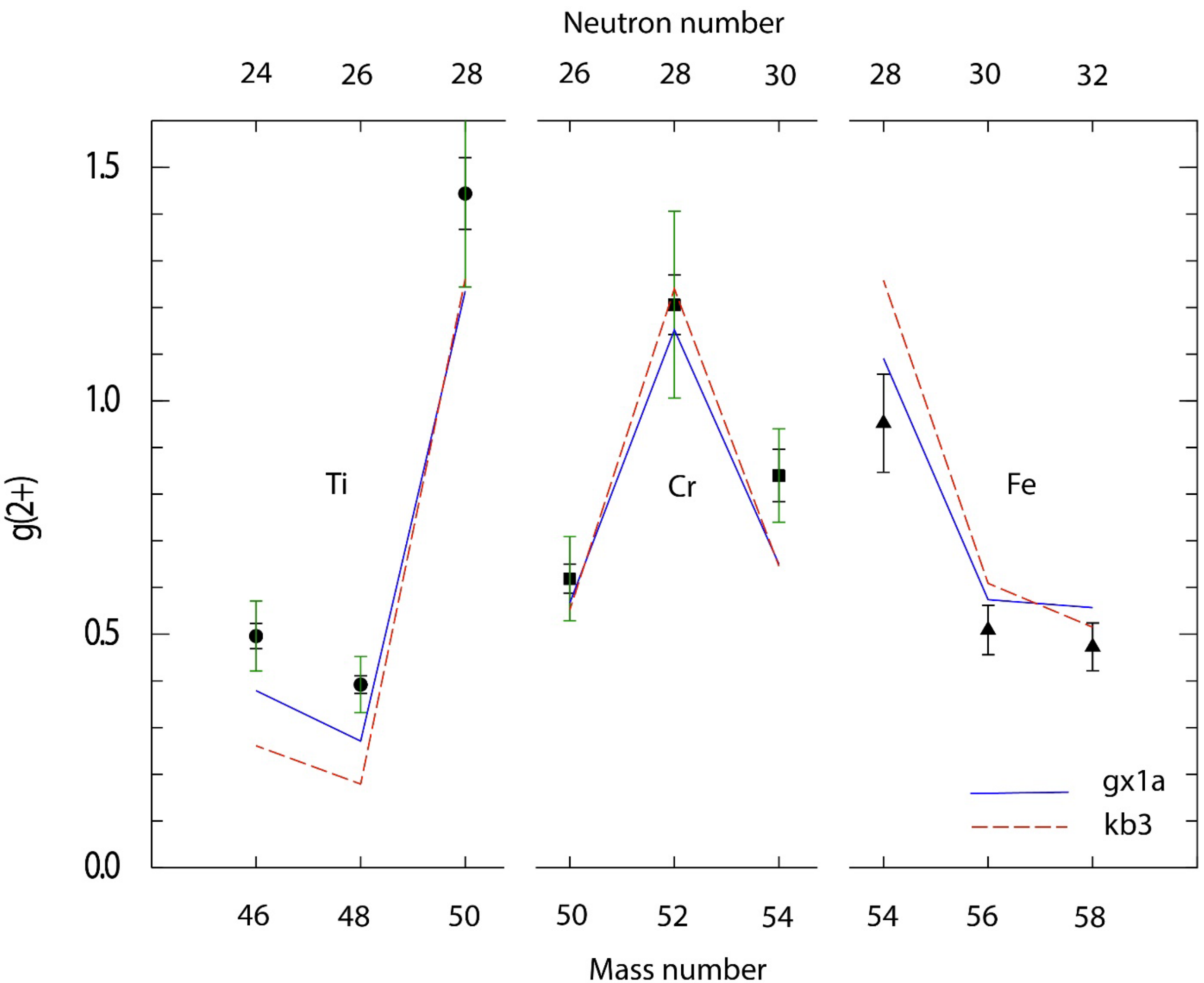
M.P. Robinson et al. / Nuclear Physics A 647 (1999) 175–196



ANU did not reproduce the CR parametrization for ^{169}Tm in Gd.

- Possibly because CR calculated rather than measured angular correlations
- Observed effect is very sensitive to detector angle
- Different stopping powers

Problem: Transient-field g-factors in Ti, Cr, Fe

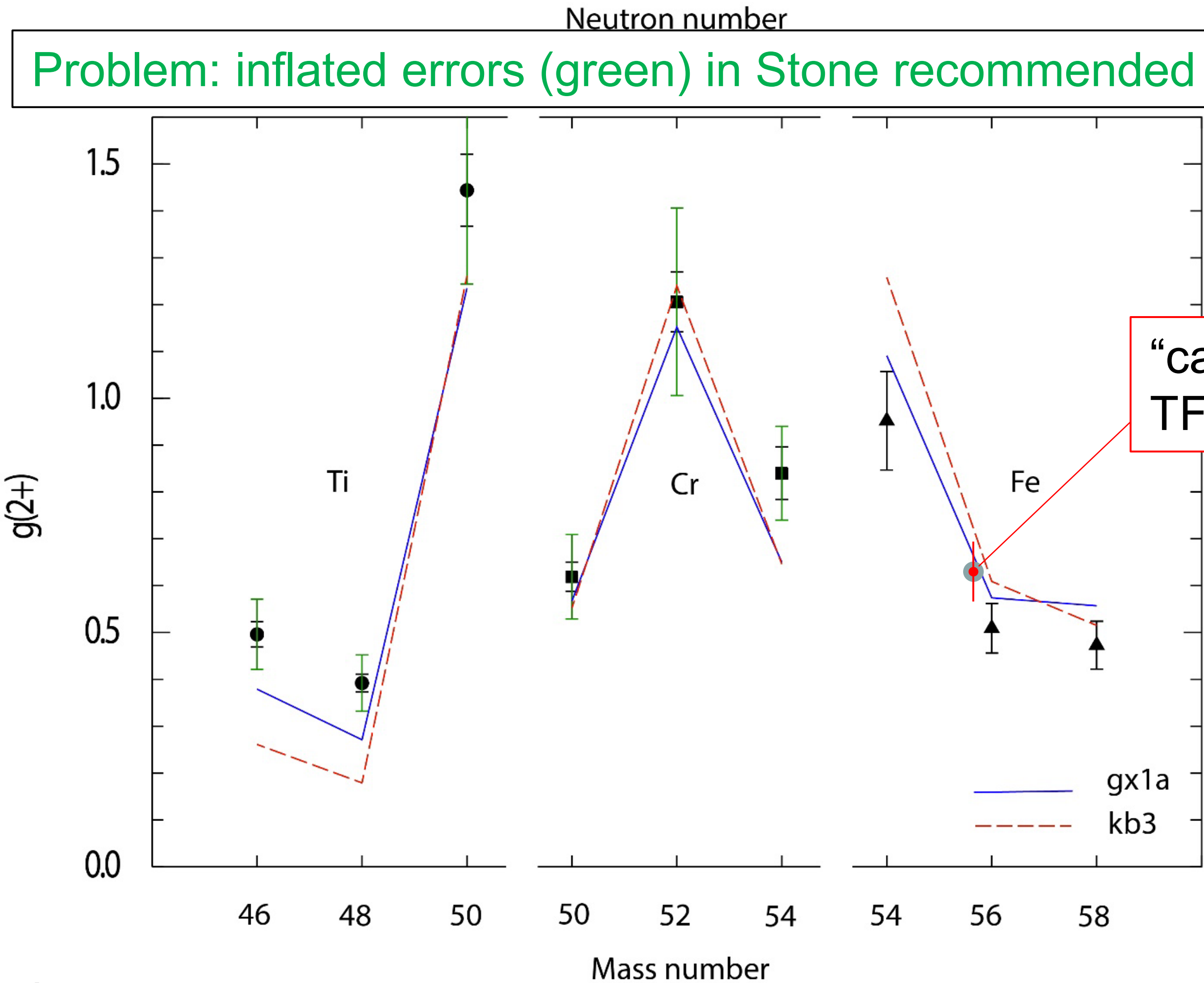


Problem: inflated errors (green) in Stone recommended values

https://www-nds.iaea.org/publications/indc/indc-nds-0816/

Transient-field g-factors in Ti, Cr, Fe

Problem: inflated errors (green) in Stone recommended values

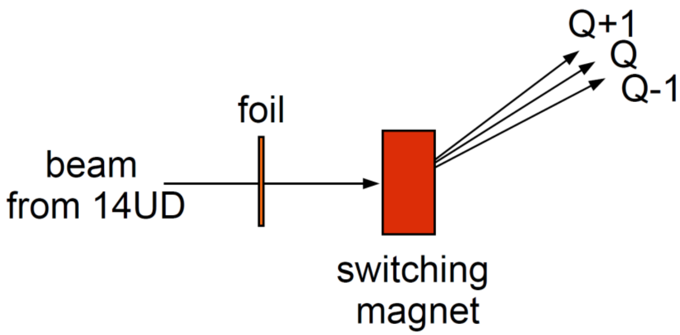


“calibration” value in TF parametrizations

Shell model calculations in full fp shell:

gx1a: Honma et al. EPJA **25** Supp 1, 499 (2005)
kb3: Poves et al. NPA **694**, 157 (2001)

TDRIV on Na-like ions

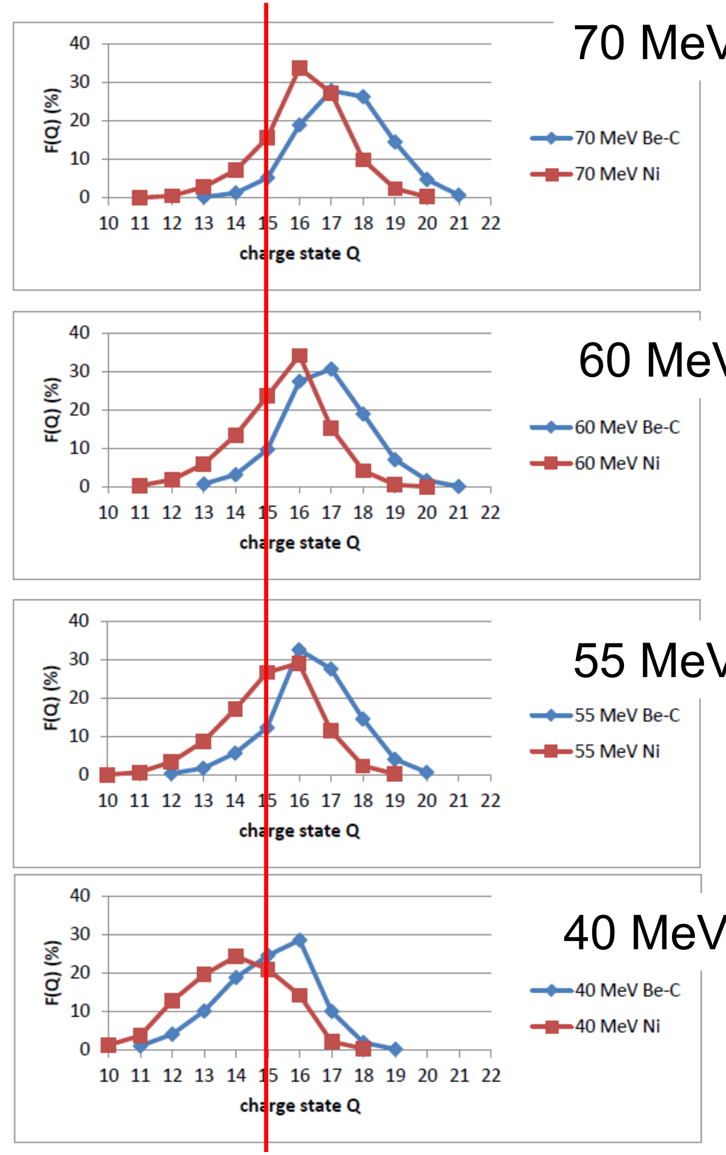


40 – 100 MeV ^{56}Fe beams

~100 $\mu g/cm^2$ Ni

~70 $\mu g/cm^2$ Be/C

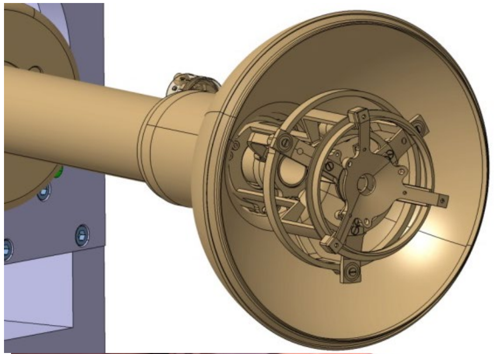
Q = 15+ (Na-like)

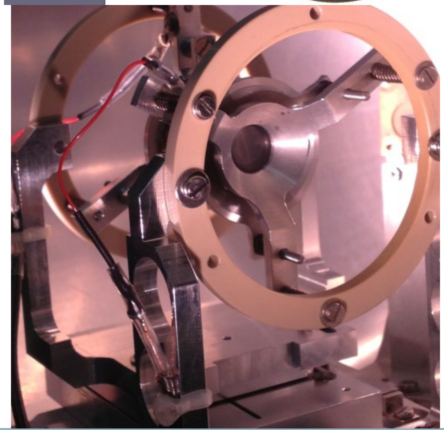


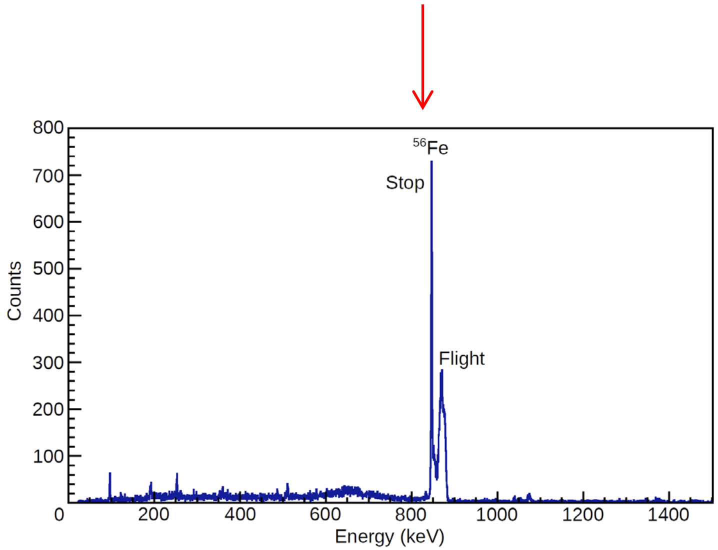
^{56}Fe TDRIV with Na-like ions

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

- 130 MeV ^{56}Fe beam on 0.2 mg/cm^2 C + 0.5μm Ni; 5.8 mg/cm^2 Ni stopper
- Orsay Plunger ‘OUPS’ and ORGAM+Miniball @ ALTO
- Reaction kinematics to optimize Na-like ions - based on detailed charge-state distributions from ANU; v/c=0.0446 (52 MeV ^{56}Fe)

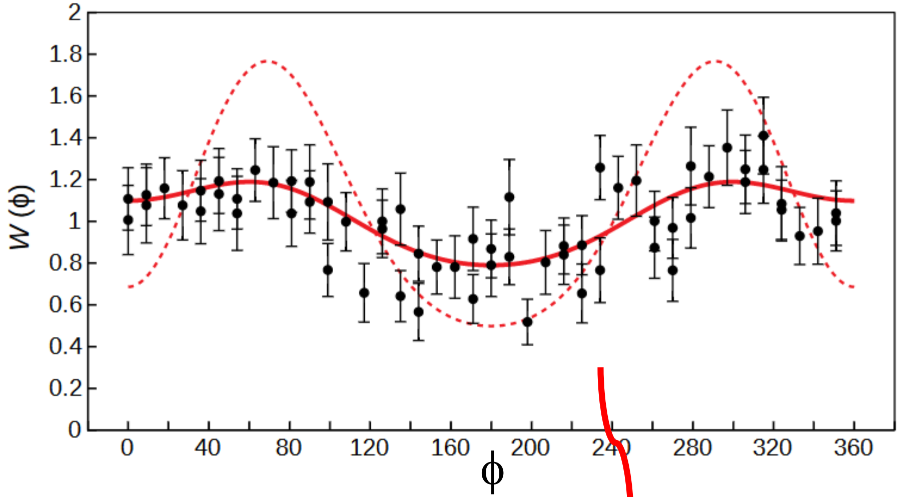






Analyze the stop peak to get $G_k(t)$ - t is the plunger flight time

From angular correlations to $G_k(t)$



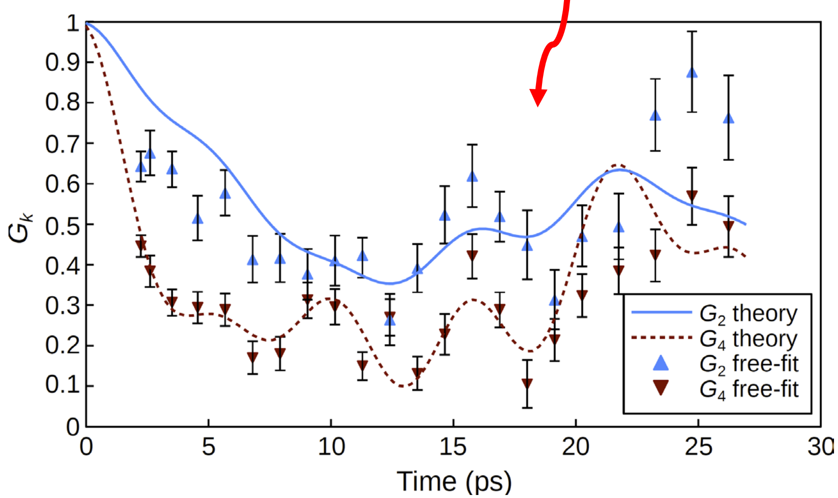
Measured angular correlations. (Stop peak.)

Unattenuated, $t = 0$

Attenuated, $t > 0$

$$W(\theta_p, \theta_\gamma, \Delta\phi, t) = \sum_{kq} B_{kq}(\theta_p) G_k(t) Q_k F_k D^k_{q0}(\Delta\phi, \theta_\gamma, 0)$$

Time–dependent attenuation coefficients: $G_k(t)$



Note $\tau(2^+) = 10$ ps

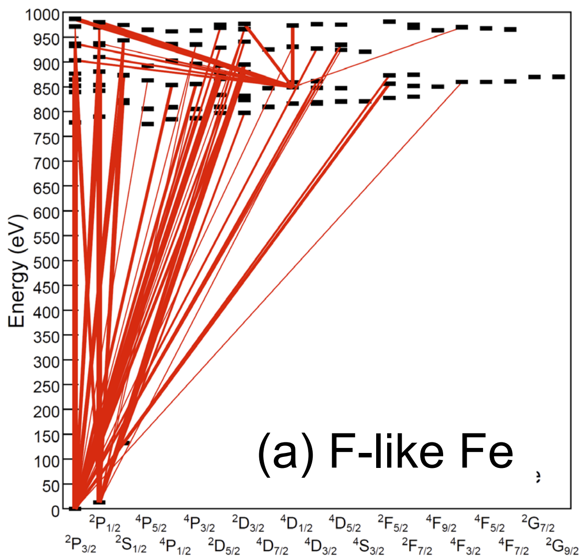
Atomic spectra and decays - GRASP2018

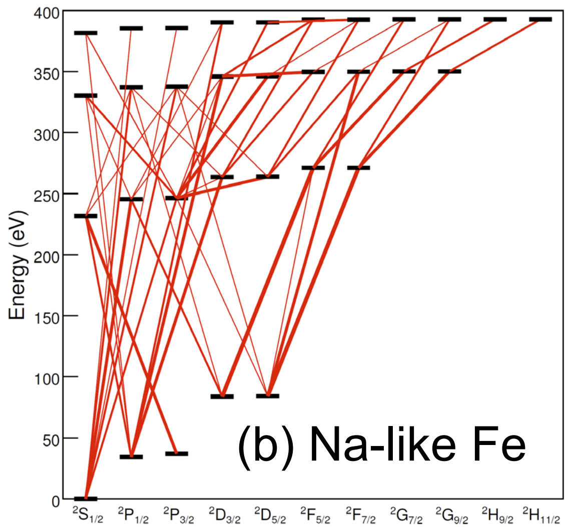
1. Calculate atomic levels and decay rates with GRASP2018
2. Monte Carlo calculation of atomic decay cascades
3. Evaluation of $G_k(T)$ in Monte Carlo

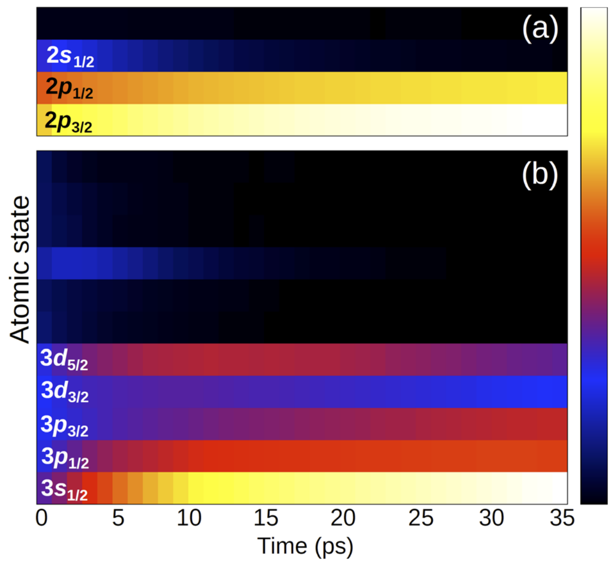
} RIV Simulate Code

Brendan McCormick PhD thesis

Excellent agreement between calculated and experimental atomic level energies (NIST data base)







Modeling $G_k(T)$ with GRASP2018

1. Calculate atomic levels and decay rates with GRASP2018
2. Monte Carlo calculation of atomic decay cascades
3. Evaluation of $G_k(T)$ in Monte Carlo

} RIV Simulate Code

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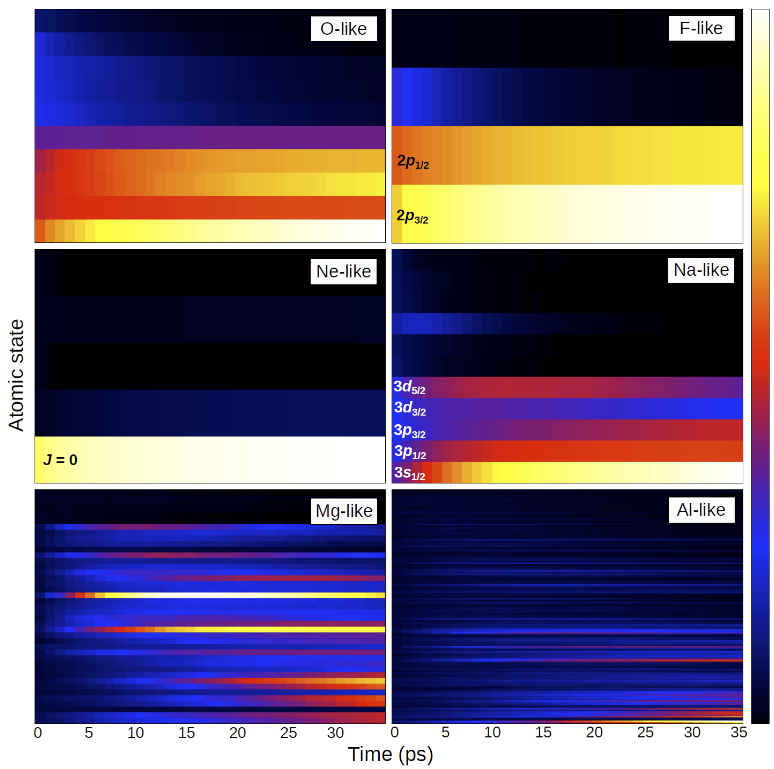
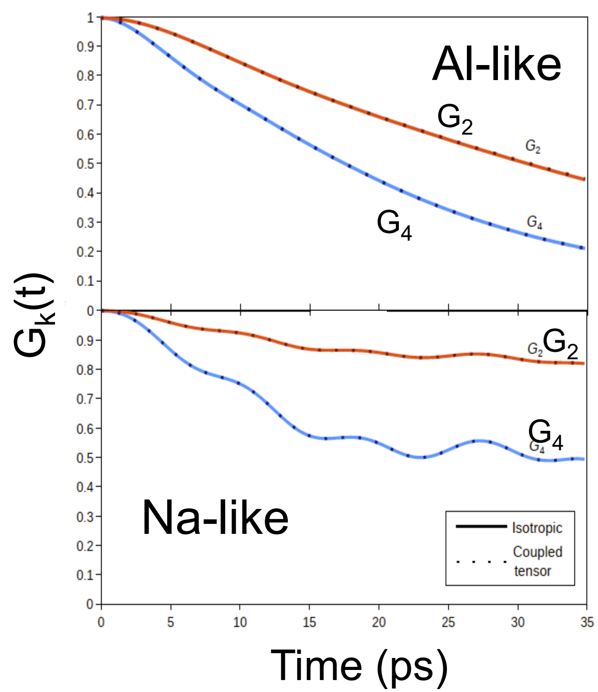


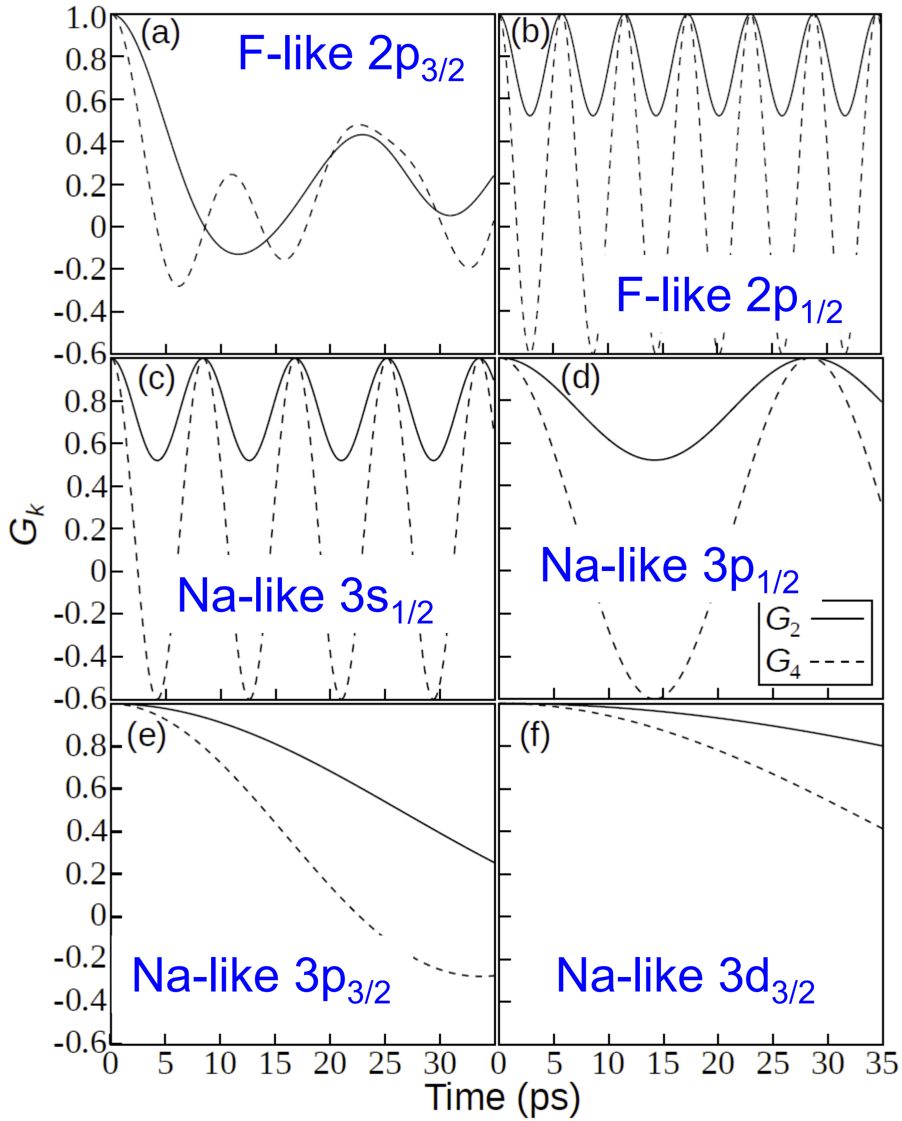


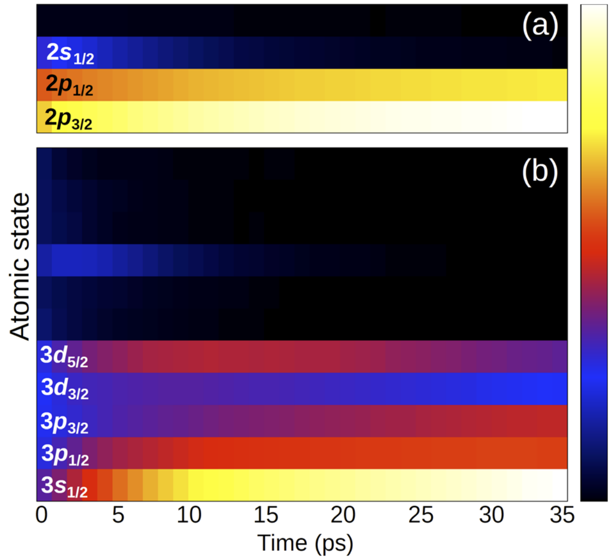
Note smooth "decay" pattern for Al-like ions

Oscillations for Na-like ions

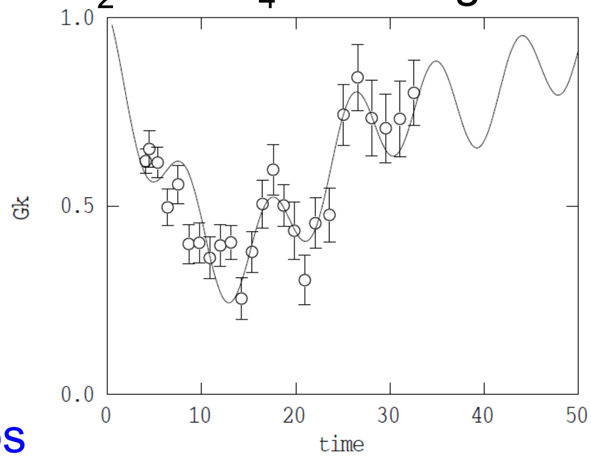
GRASP = General Relativistic Atomic Structure Package
Computer Physics Communications 237, 184 (2019)

Identifying oscillation frequencies





Rough analysis assuming G_2 and G_4 scale together:

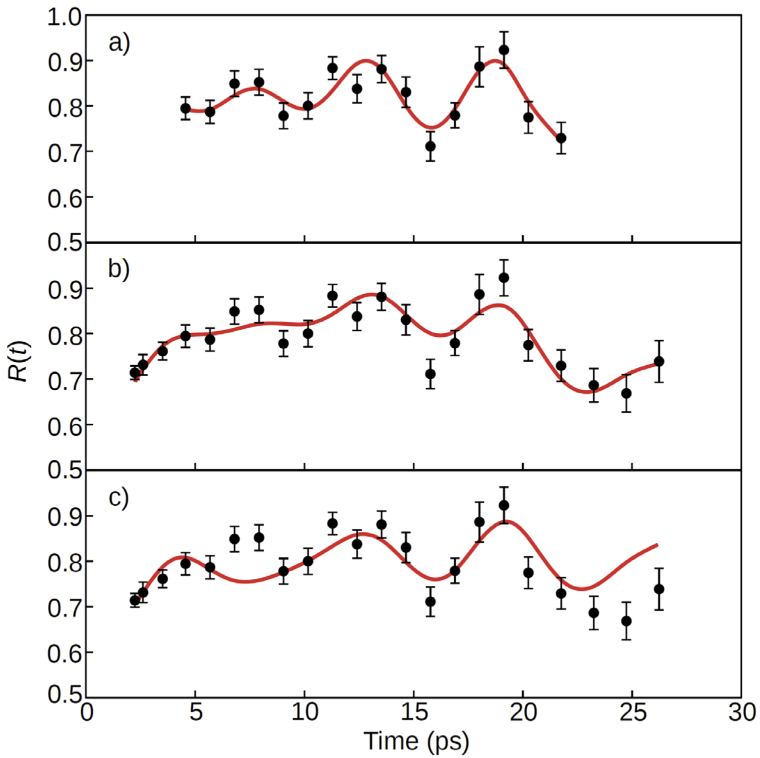


Note $\tau(2^+) = 10$ ps

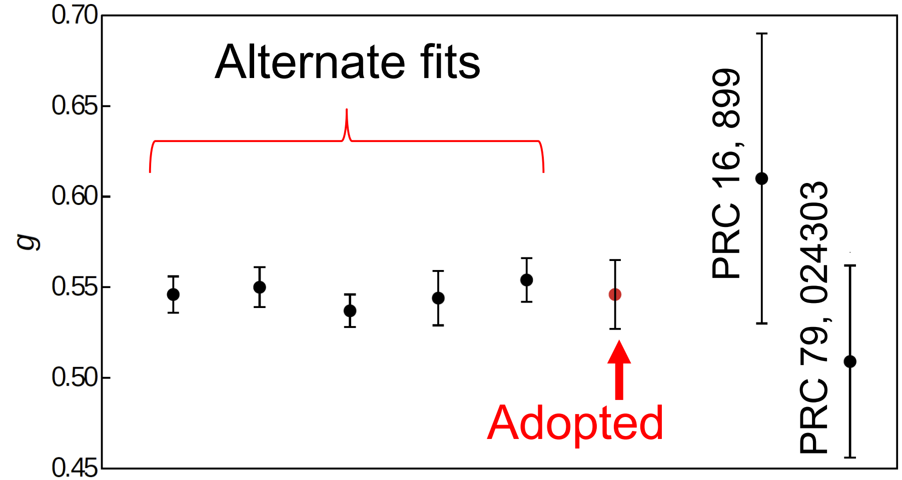
An R(t) function "covers a lot of sins"

Form R(t) function to remove smooth decay feature and enhance oscillations

Examples of fits to R(t)



Results

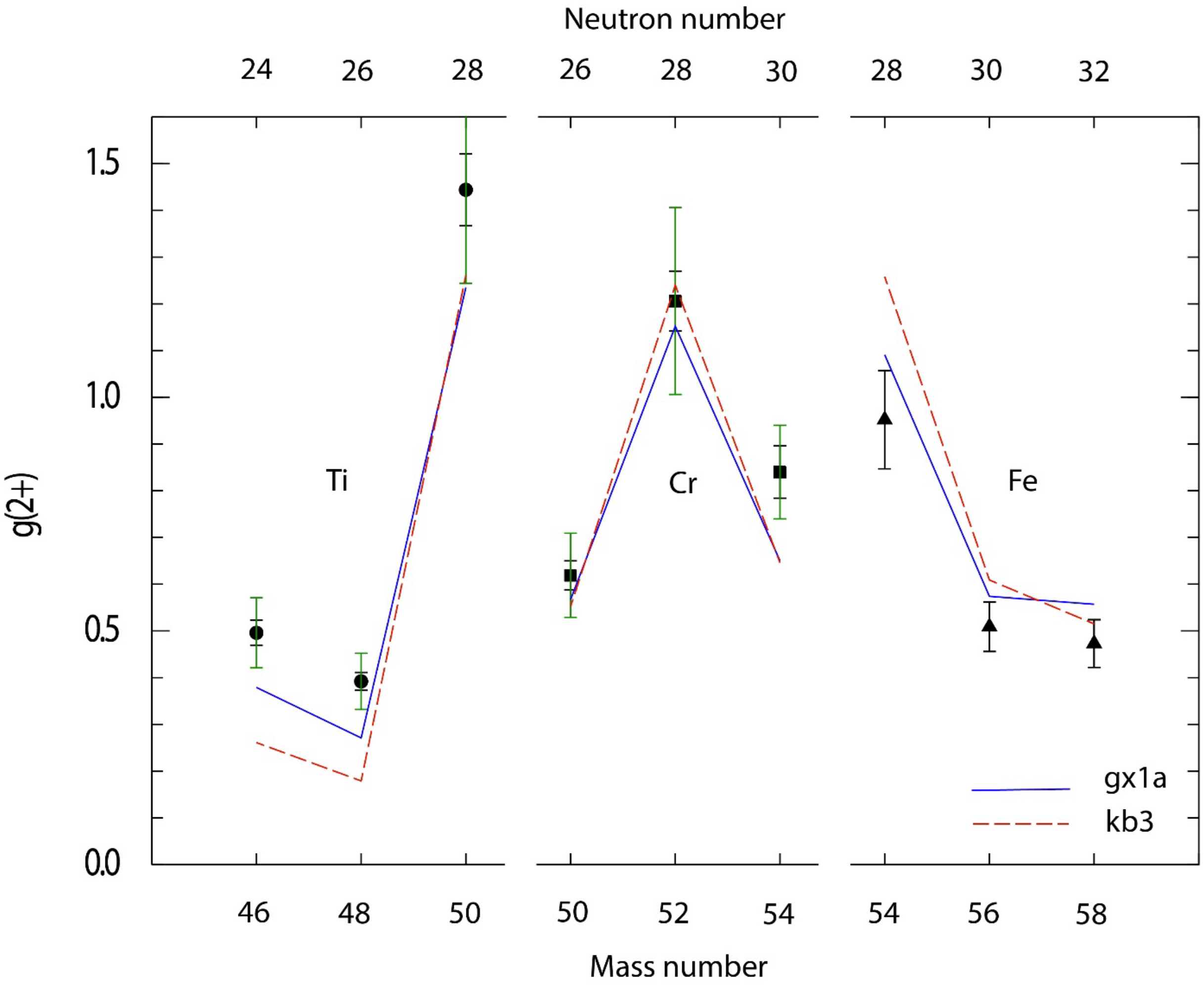


Adopted: g=0.546(19) (±3.5%)

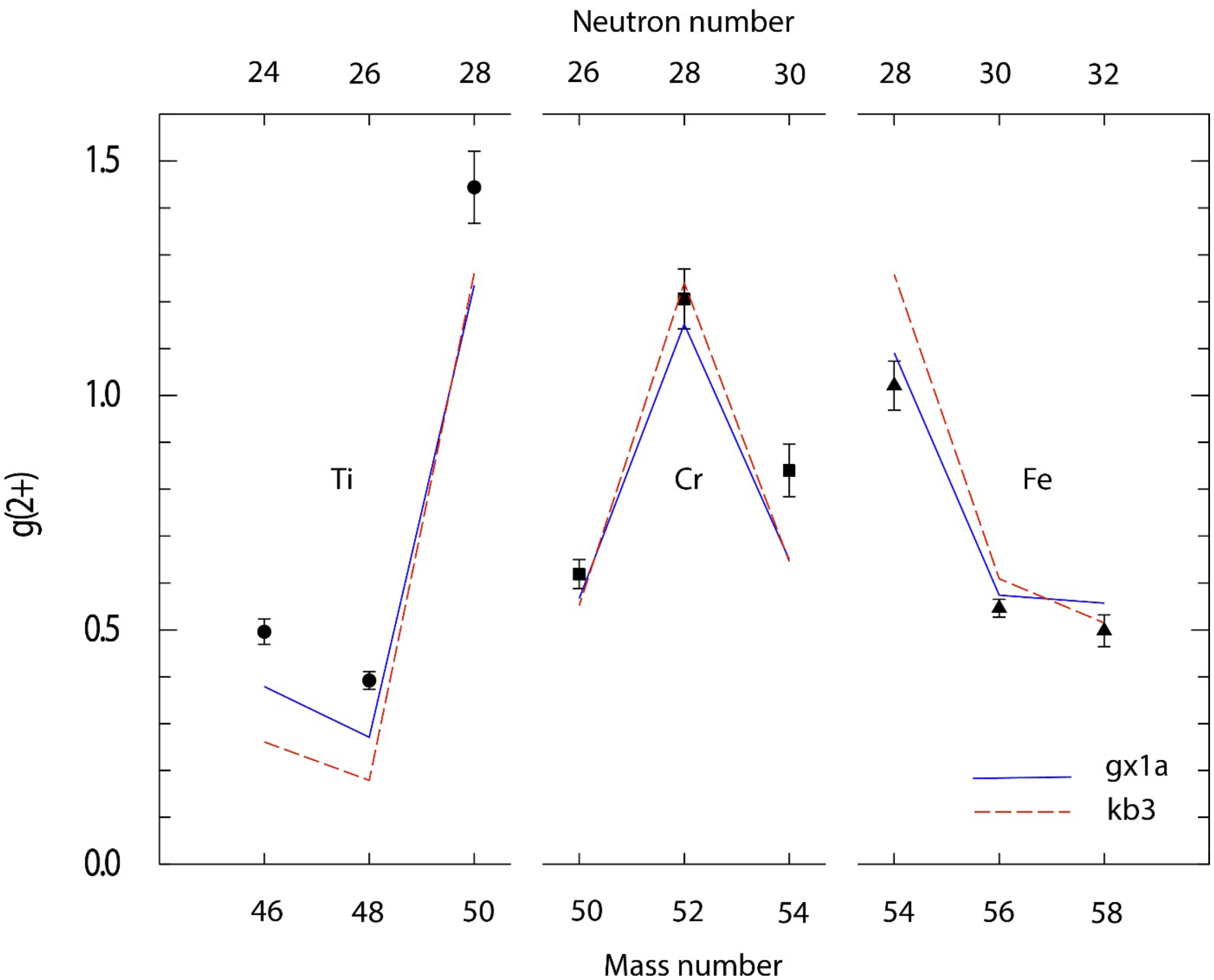
PRC 79, 024303: g=+0.509(53) (±10.4%)

Fits include $3s_{1/2}$, $3p_{1/2}$, $2p_{3/2}$, $2p_{1/2}$, & null components

Implications – where we were:



Implications – where we are now:



Happenstance: literature g(2^+) values are close to our new calibration values.

Experiment challenges theory … but should check Z- dependence of TF

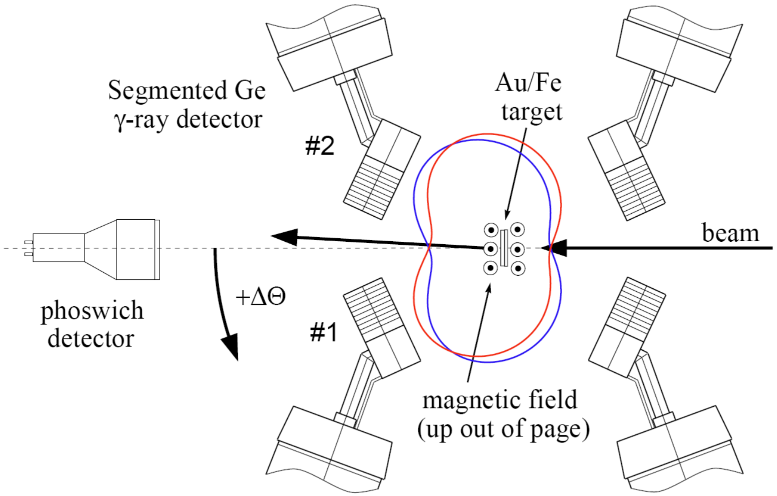
Evaluating TF IMPAC

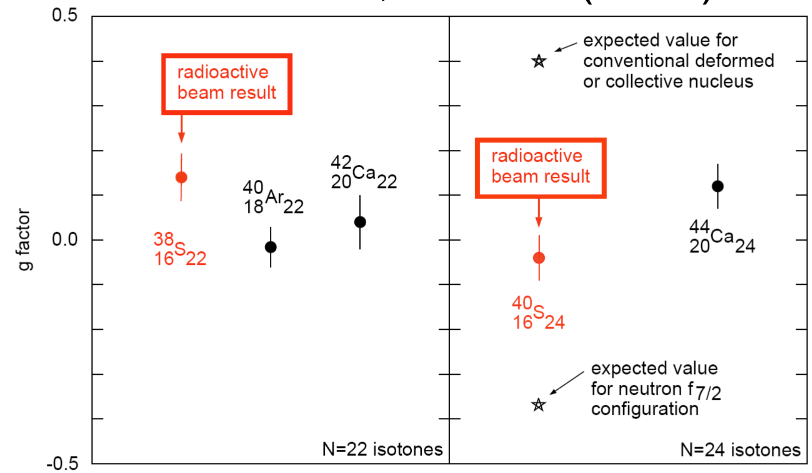
- Was it a thick-foil (IMPAC) or thin-foil measurement?
- If thin-foil, did the recoils all get out of the ferromagnetic layer ($v > \sim 2\ v_0$)?
- What is the TF calibration?
  - Relative to an independently known g factor – OK (? same/neighbouring *Z*)
  - Relative to a parametrization – needs scrutiny
  - **Did the authors include the TF strength uncertainty in quoted g factors?**
  - Is the level very short lived (τ < 1 ps) – hence lifetime dependent?
- Need to evaluate the uncertainty associated with TF parametrization
- Need policy to present data with appropriate uncertainties

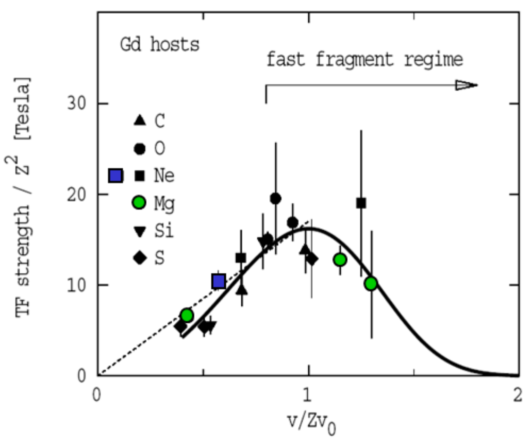
High Velocity TF

Radioactive beams from fragmentation facilities

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







Ion velocity/K-shell electron velocity
PLB 611 (2005) 81

A few cases – results are not critically dependent on the TF calibration.

^{72}Zn case? Polarization decreases with Z. Compare HVTF and LVTF measurements.

High Velocity TF

Radioactive beams from fragmentation facilities

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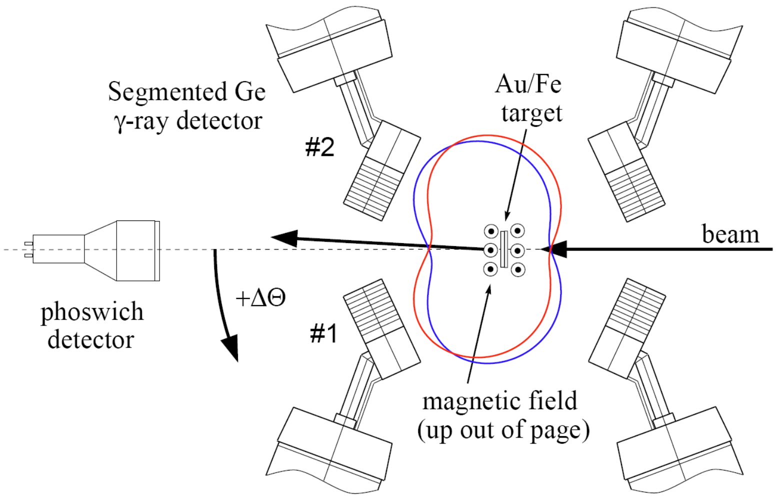
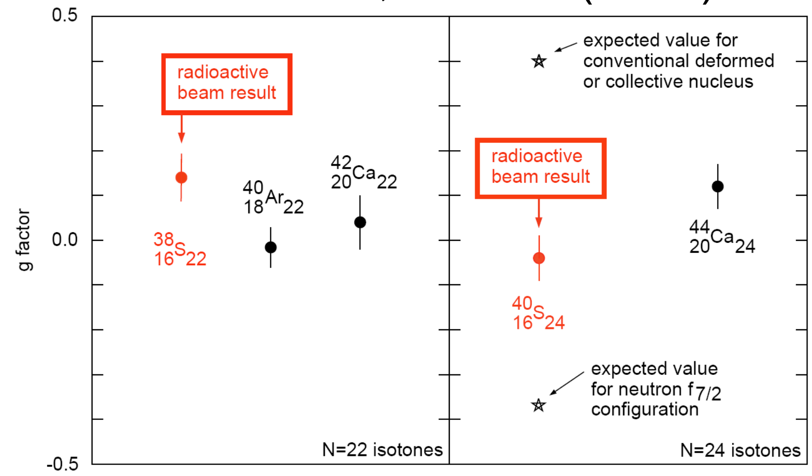
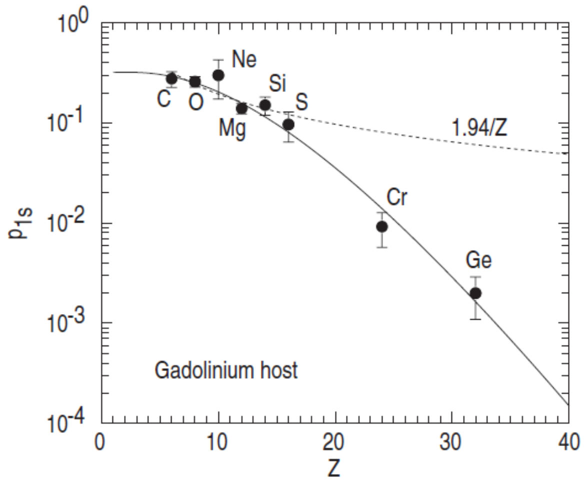




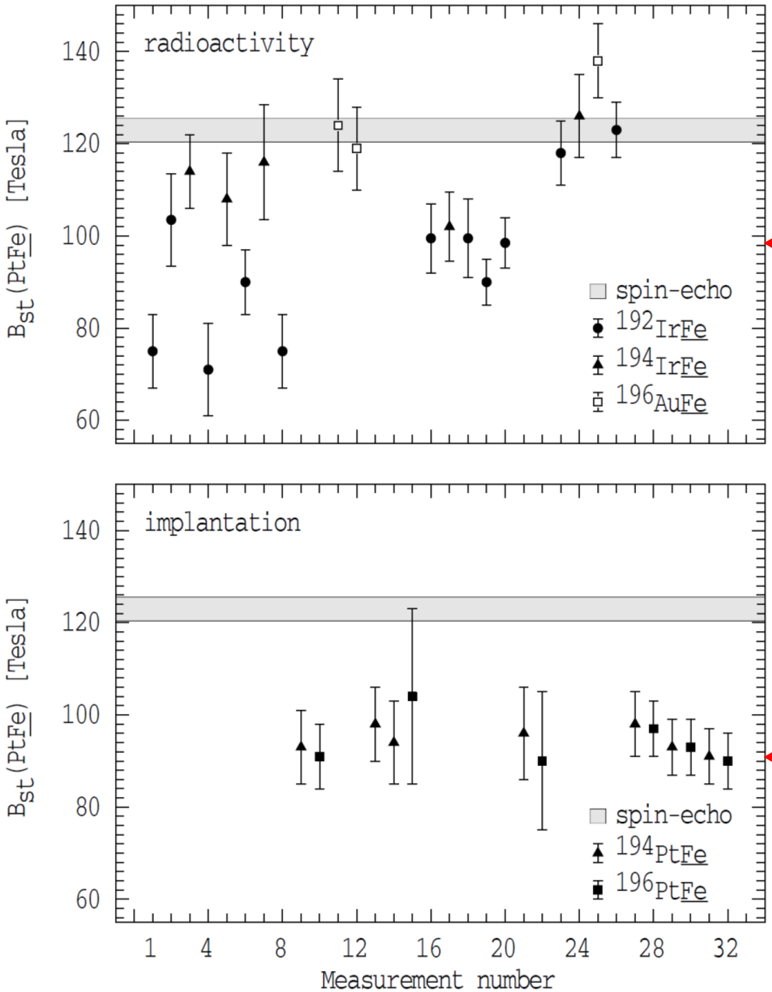


A few cases – results are not critically dependent on the TF calibration.

^{72}Zn case? Polarization decreases with Z. Compare HVTF and LVTF measurements.

Evaluating & Combining data

Taking averages/Selecting data. Need to discuss. Often no objective answer.



- "Avetools" for guidance

A blind average here would be wrong

A blind average here would be OK

- Consider $1/|\sigma|$ rather than $1/\sigma^2$ (Raman)

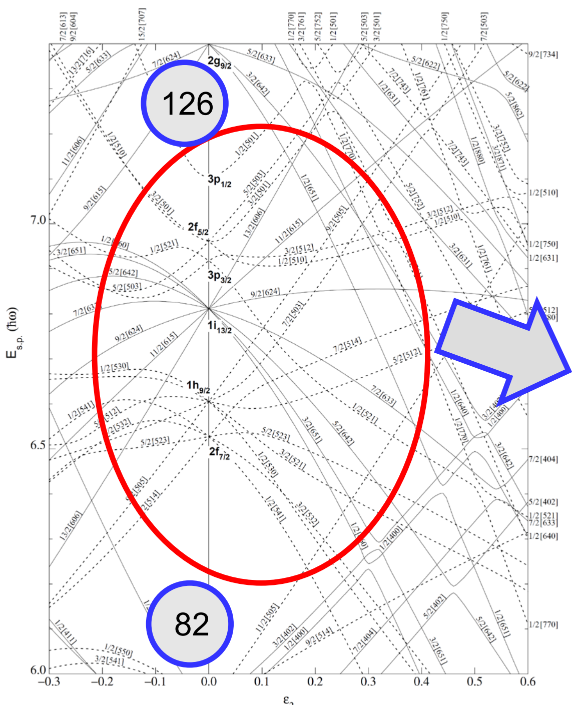
Evaluating & Combining data

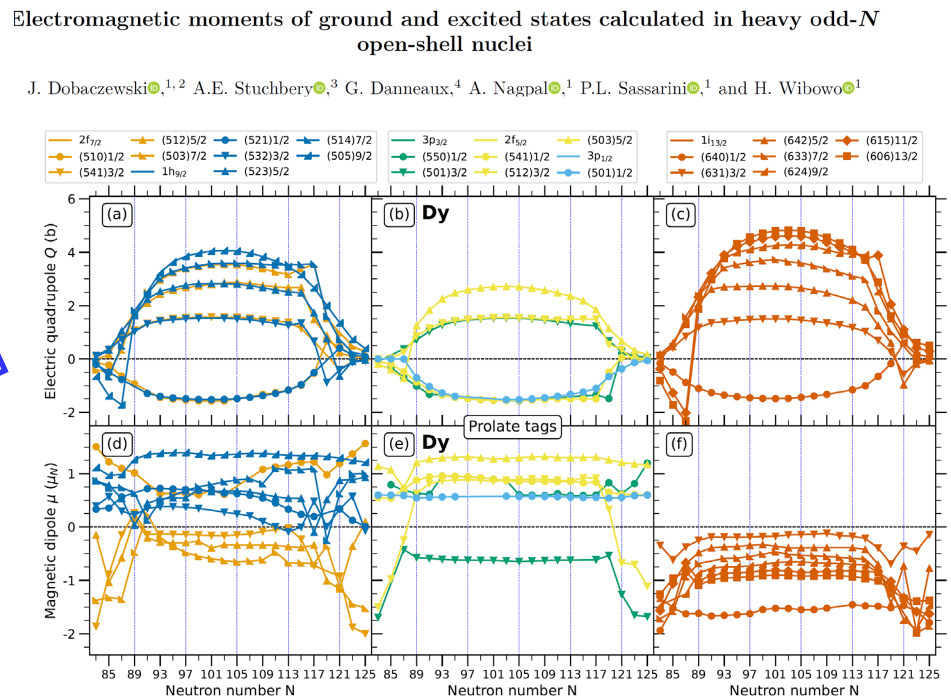
Taking averages/Selecting data. Need to discuss. Often no objective answer.

Perhaps each evaluated datum should have a short note attached describing the reasons for the choice. There is a precedent for such brief notes in ENSDF.

Systematic study of moments in DFT theory

Comprehensive DFT calculations of μ and *Q without effective g factors or charges:*





Jacek Dobaczewski et al. arXiv:2509.26549v1

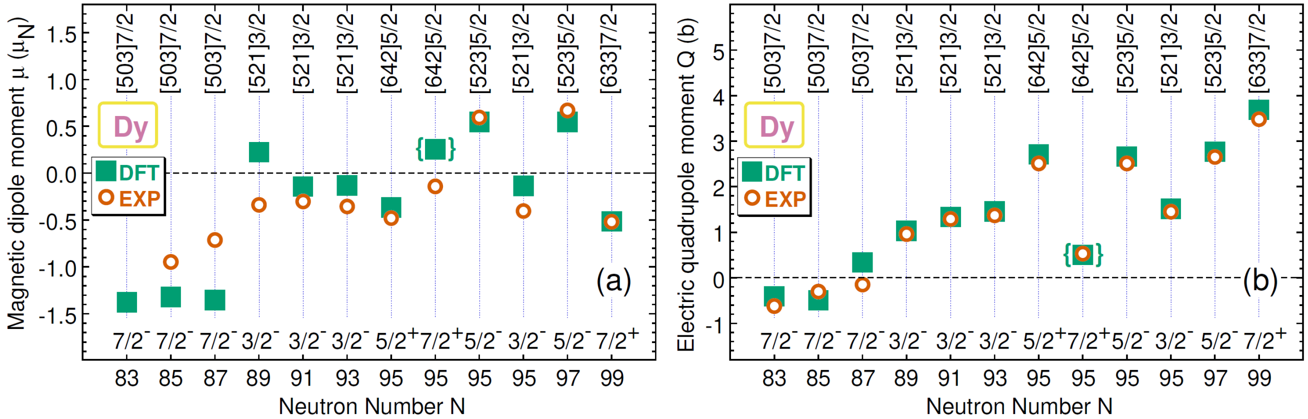
Accepted PRC

Example: Dy isotopes prolate "tags"

Moments of the band-heads for all Nilsson configurations in isotopes from Gd to Os

E2 & M1 moments in DFT

Some results: Dy isotopes



{} – sign not measured

Referee:

This paper concerns a wide-ranging yet deep comparison of experimental data on electric quadrupole and magnetic dipole moments of (deformed) odd-mass rare earth nuclei. This study is frankly a delight to read and will - I believe - be of great use in the years to come for both experimental and theory efforts in studying such observables in this (large) region of the nuclear chart for several reasons.

Let me list some:

(a) [theory] (b) [theory]

(c) the in-depth comparison with experiment on a nearly nucleus-by-nucleus basis, so deep that it (i) exposes what are likely errors in current compilations and (ii) suggests experimental efforts that would be useful to further understand differences between theory and experiment.

End