g-factors of sub-nanosecond states - opportunities and limitations of the Recoil-in-Vacuum [RIV] method.

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Workshop on Atomic Physics with Rare Atoms

U. of Michigan Ann Arbor June 2009

Nuclear magnetic (and electric) moments

high precision methods - NMR and laser spectroscopy
long lived states > ms

measure energy levels associated with [dipole] moment in [field]

physically the levels involve precession of the moment about the field axis

Precession frequencies for nuclear moments are ~ 10^9 Hz/magneton in 100 T field

Shorter lived states - observe precession directly

decay is usually anisotropic with respect to nuclear spin axis

decay pattern rotates ~ 1 rev/ns in 100T
1 rev/ps in 100,000T

Stronger magnetic interactions access moments of shorter lifetime states

Talk concerns development of an old technique - Recoil In Vacuum- not often used but of potentially great value with the advent of RIBs.

The emphasis is on the need for basic atomic physics calculations to support the method and progress towards this end is reported.

Examples - but no details - of test experiments.

The beautiful Law Reading Room
of the University of Michigan

Outline of the talk:

- **The development of existing methods of g-factor study in sub-nanosecond states**
- **Working with stable beams: the Transient Field Method**
- **Prospects for g-factor studies with RIBs: the RIV method**
- **Can a general theory of RIV be developed?**
- **Progress to date**

A little history:

First measurements of sub-nanosecond excited state g-factors were made in the 1960's.

The first techniques were:

Integral Perturbed Angular Correlation [IPAC] and

Integral Perturbed Angular Distribution [IPAD]

in which rotation of the anisotropic angular distribution of a gamma transition, from a non-randomly oriented spin state, caused by a known magnetic field, is measured without time resolution.

Mean rotation angle

$$\Delta\theta = -\frac{g\mu_N B_{eff}\tau}{\eta}$$

$$B_{eff} = B_{applied}$$

magnetic fields of < 10 Tesla applied

The next step saw the discovery of large magnetic hyperfine fields $B_{hyperfine}$ [~10 - 100 Tesla] at impurity nuclei at lattice sites in ferromagnetic metals.

$$B_{eff} = B_{applied} + B_{hyperfine}$$

This, combined with the use of ion implantation, opened up a wider range of excited states to g-factor measurement by PAC methods

However….

Shorter lived states could decay in flight before stopping in the lattice. It became clear that, in flight through the ferromagnetic metal lattice, the nuclei experienced even larger fields B_{TR} [~ 1000 Tesla].

At first attempts were made to separate the rotation of the angular distribution during flight from that after stopping. This proved problematic.

A better idea was to allow the ions to pass through a thin [few mg/cm^2] ferromagnetic layer in which rotation took place and then enter a non-magnetic metal in which the ion stopped, without further perturbation of the angular distribution.

Thus was born the Transient Field method of excited state g-factor measurement.

$$\Delta\theta = \int \omega(t) e^{-t/\tau} dt = -\frac{g\mu_N}{\eta} \int_{t_{in}}^{t_{out}} B_{TR}\left[\frac{v}{v_0}, Z\right] \exp(-t/\tau) dt$$

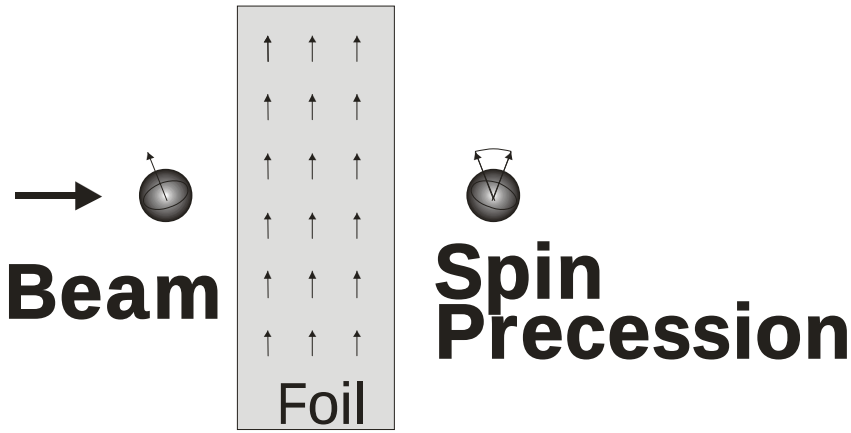
This IPAD method has been actively developed and has produced the great majority of sub-nanosecond g-factor results.

Features: The angles of rotation are small [usually less than 2 degrees] so that extremely good statistics [~0.1%] are needed for a useful g-factor result.

The sign of the g-factor is measured directly.

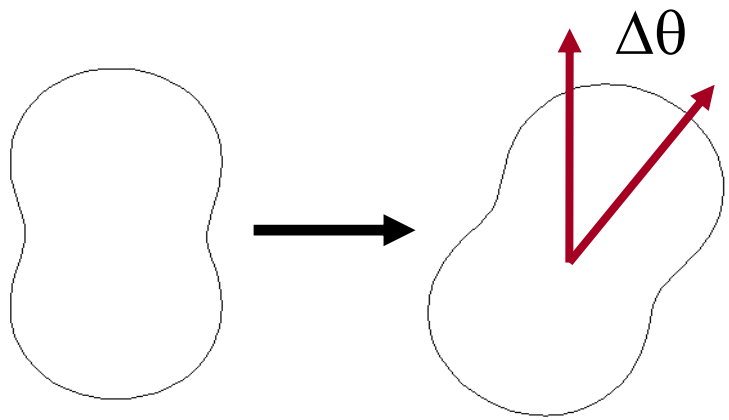
Transient field method: Principle

Side view



Magnetized

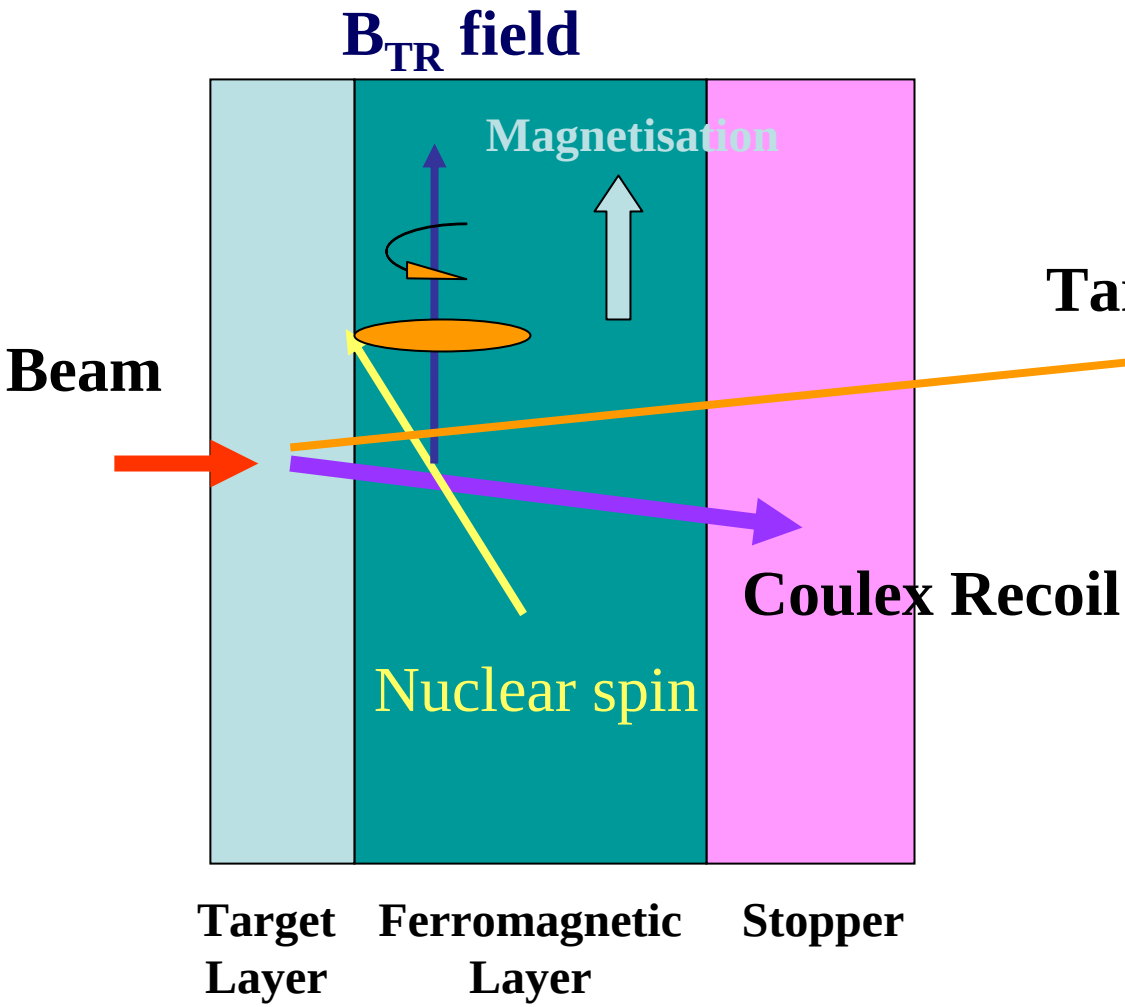
Plan view



γ-ray angular correlation

The ion picks up polarized electrons in the ferromagnet

Transient Field Method



In the ferromagnet layer the B_{TR} field direction is set by a small applied magnetising field. Recoiling nuclear spins, initially aligned in plane of target, precess about B_{TR} , so rotating the angular distribution of decay gamma emission.

Recoil in Vacuum

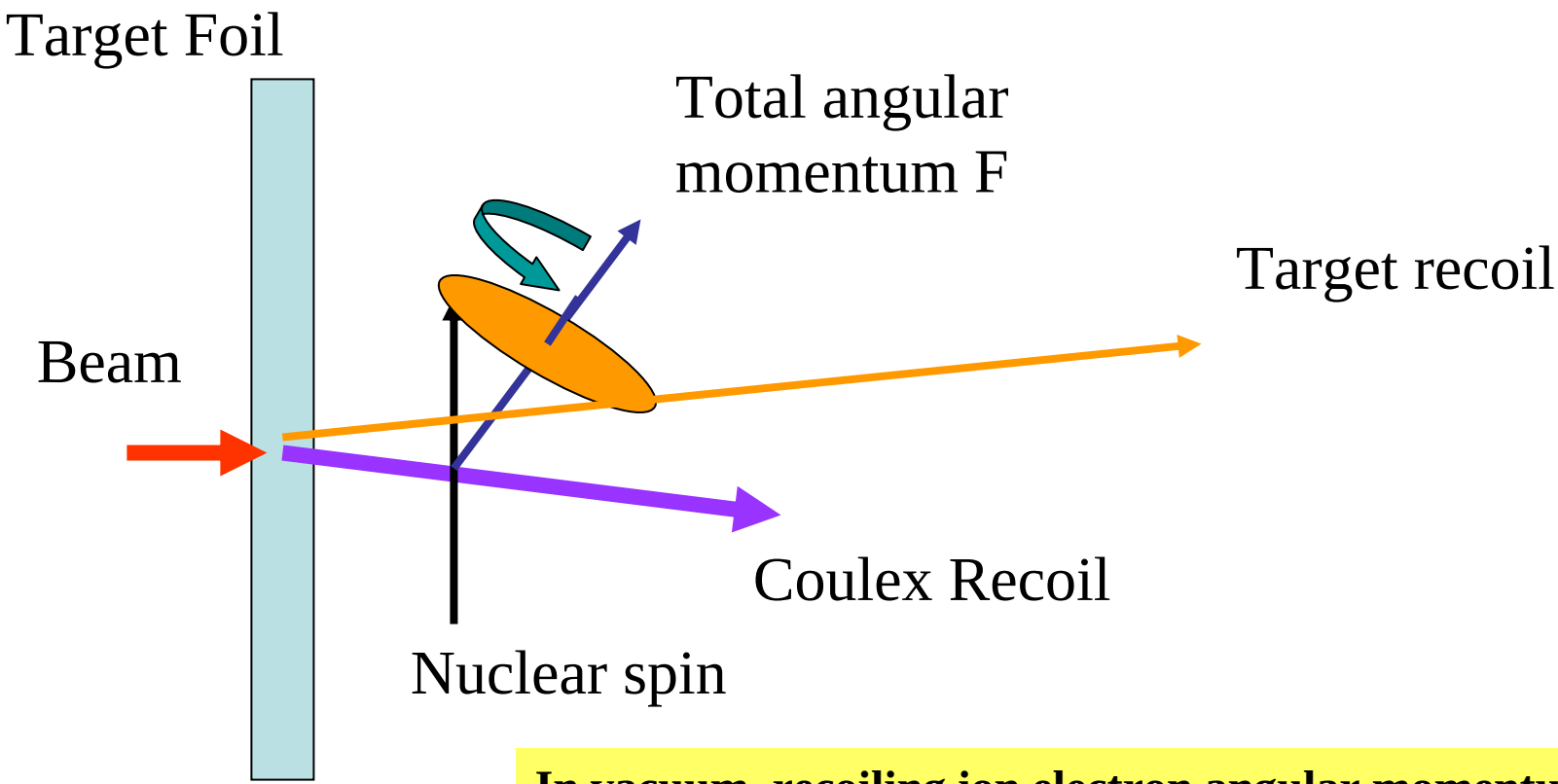
Also in the late 1960's it was found that when ions emerge from a target after excitation by Coulomb excitation and enter vacuum, the angular properties of their decay gamma radiations are perturbed.

- The anisotropy of the angular distribution is attenuated.
- The attenuations are determined by the precession of the excited state nuclear spin in the hyperfine interaction of the ion

It is established that magnetic effects are dominant, thus the attenuation was also a measure of the g-factor of the decaying state.

This is the basis of the Recoil In Vacuum [RIV] method of g-factor determination.

Recoil in Vacuum



In vacuum, recoiling ion electron angular momentum J has random direction. Recoiling Coulex nuclear spin I, initially aligned in plane of target, precesses about resultant F=I+J.

Anisotropy of angular distribution of decay gamma emission becomes attenuated.

Features:

•Particularly for 2^+ - 0^+ gamma decays in even-even nuclei, the angular distribution is highly anisotropic. Generally applicable to states of any spin - better for low values. Needs pure multipole or known mixing ratio.

•Useful g-factors can be extracted from attenuations measured with moderate statistics [few %].

•The method does not give the sign of the g-factor.

The Recoil-in-Vacuum method proved in general difficult to calibrate and adequate atomic theory calculations of the hyperfine interaction were not practical at that time.

RIV has been little used for g-factors since the early 1970's

Since ~ 1970 the TF method has been used for sub-nanosecond state g-factors.

The method has its problems, including:

(i) small angular changes need very good [fraction of %] statistics

(ii) calibration of interaction to obtain absolute g-factors

(iii) target complexity, crystal structure and magnetisation.

Consider question (ii) - the problem is B_{TR} which determines $\Delta\theta/g$

A) work from ratios.

For some elements there exist prior g-factor results from IPAC methods. However over wide ranges of the nuclear chart these have very limited accuracy, seldom better than 10%.

[There are exceptions, mainly in the higher Z region where Mossbauer effect g-factors give better [few %] calibrations.]

The inescapable use of these pre-existing results for calibration introduces limitations of 10% or more to the precision of many TF results based on ratios to previously measured g-factors.

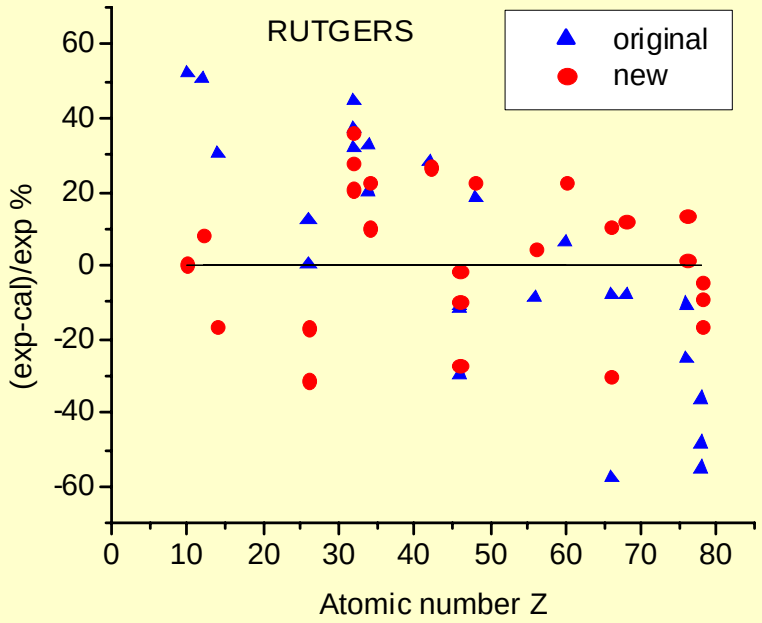
Where no prior g-factor result exists for an element by different techniques the problem is more serious.

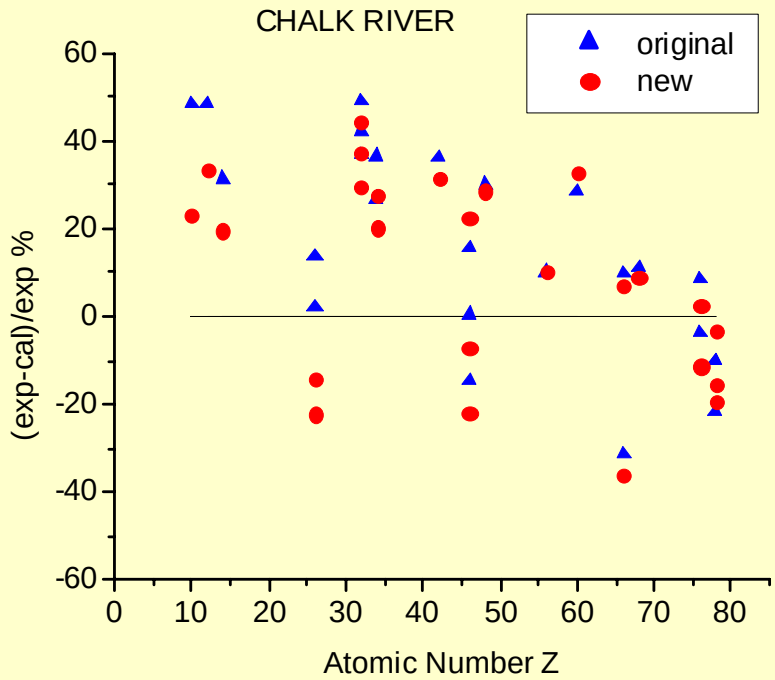
B) Rely on estimated B_{TR}

No satisfactory theory for the transient field has been found.

Simple ideas of the moving ions picking up and losing polarised electrons in the ferromagnetic lattice have not led to a microscopic theory.

Although the fields experienced by the nuclei have been shown to vary with the nuclear charge Z and the velocity v of the ion [scaled by its Bohr velocity v_0], only very general, essentially empirical, parameterizations have been investigated.





In a 2005 project study by two Oxford students, Jonathan Edge and Amy Bonsor, the quality of the Rutgers and Chalk River parameterizations has been investigated, taking into account all data now available. They compared experimental $\Delta\theta/g$ with that predicted.

[25 data sets including the original 12/15 used by the Rutgers group.]

The red points show the result of using the original published parameters. The blue points are results using new refitted parameters.

The general % deviation is see for both old and new to be in the range of 20% .

The new fits give χ^2 not far above 1 but this just reflects the relatively poor input data, based on IPAC g-factors.

The predictive quality of these parameterizations is seriously limited.

There is a third model for B_{TF} from the Speidel [Bonn] group who find evidence for perturbations of the magnetisation of the ferromagnetic metal caused by the beam flux - not apparently identified by other groups.

Other required parameters [to which g-factors are less sensitive] are stopping powers and lifetimes, each with limited accuracy.

Targets are complex, may be liable to effects of non-uniformity, channeling and magnetisation problems.

Conclusion:

For many elements the TF method has built-in accuracy limitations around +/- 15 - 20 % although other elements have local calibrations good to 3-5%.

A doubtful practice

Quite a number of published TF g-factor results, from several groups, are based on adoption of the parameterization-based fields without error,

- thus claiming apparently improved precision.

New opportunities and challenges for the study of ps state g-factors with RIB's:

RIB's having beam intensity < 10^8 ions/s - orders of magnitude weaker than conventional beams.

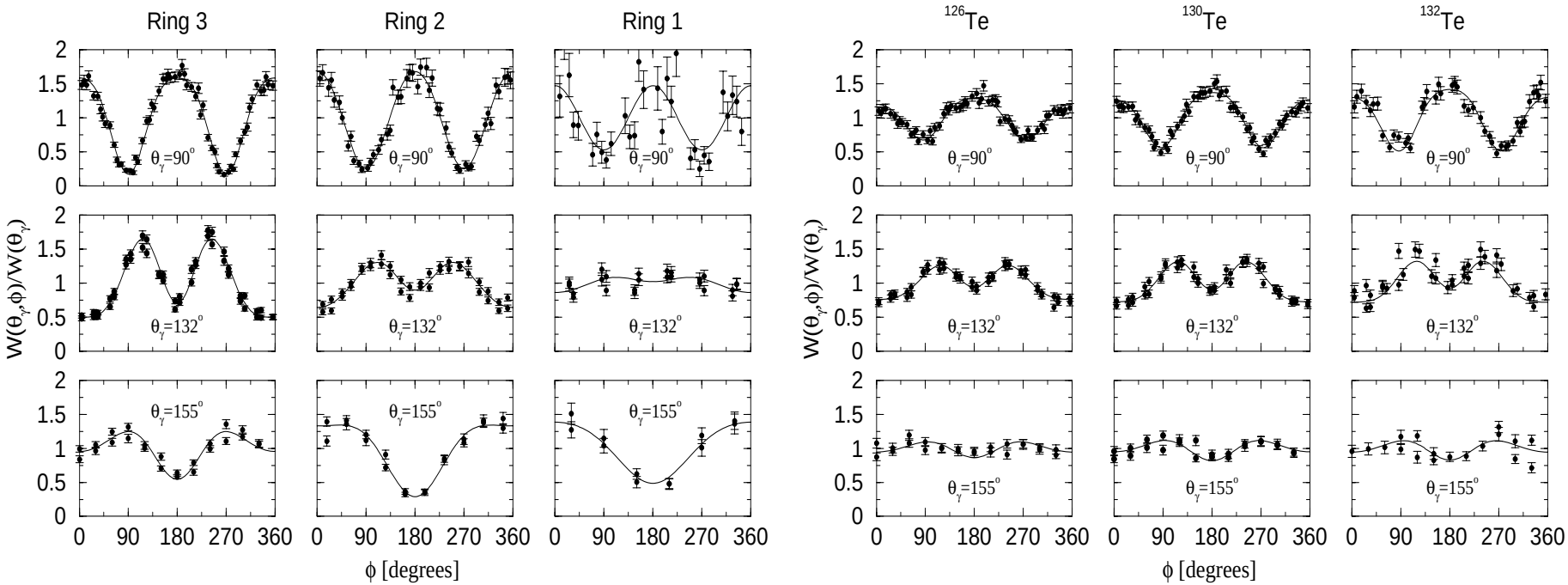
It is clear that with the advent of RIB's and inevitable poorer statistics the RIV method offers prospects of useful g-factor study.

1. **Example of RIV with RIB's**
2. **Can we hope to provide a sound theoretical grounding for the RIV method?**

In principle the recoiling ion is a more attractive system for theoretical approach than an ion moving in a lattice. The number of electrons is fixed [after allowing for Auger effects] and the system is fully understood.

Brief description of the recent RIB ^{132}Te RIV measurement at HRIBF

[N.J.Stone et al PRL 94 192501 (2005)]



UNATTENUATED Distribution for ^{126}Te stopped in Cu. **RIV ATTENUATED distributions from 2^+_1 states in ^{122,126,130}Te [known g-factors and lifetimes].**

$$W(\theta_\gamma,\phi) \approx \sum_{k.q} G_k \rho_{kq} A_k Q_k D_q^{k*}(\phi,\theta_\gamma,0)$$

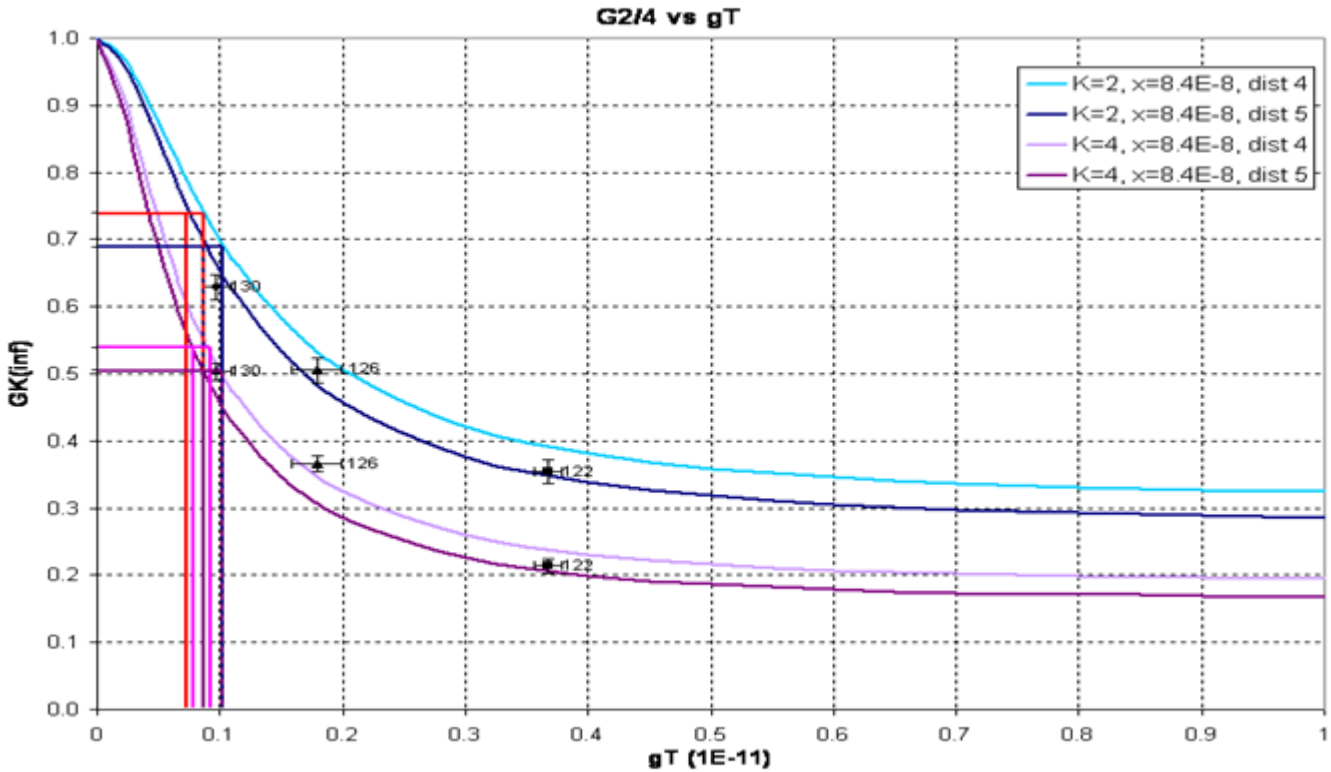
G_k are the g-factor dependent attenuation coefficients.

For the RIV method we need to extract g from the G_k.

Compared unattenuated with attenuated to obtain G_2, G_4 from isotopes with known g-factors and lifetimes τ to form calibration for their $g\tau$ dependence.

RIV result: |g-factor| 2^+_1 ^{132}Te (1.8 ps) = 0.35(5).

Compare 5-day TF result: g = + 0.28(15)



Plotted curves are result of empirical 'theory' with fitting parameter to stable isotope results - not an a priori theory.

Toward an a-priori theory for RIV experiments

Difficulties:

We have to accept and deal with complexity associated with:

a range of ionic charges present [can be determined readily in stable beam auxiliary experiments]
a considerable number [can be several thousand!]
electron terms [ion quantum J,L,S states] for each charge.

There are simplifications:

for high ionisation states, Z_{eff} is high (20-30) so lower *n* level vacancies fill fast:
n=3 to *n*=2 with Z_{eff}=20, lifetime ~ 2.6 x 10^{-14}s ~ 0.03 ps
we are concerned only with ionic states living for > 0.1 ps
we are not concerned with small probability states - the attenuation affects the ensemble of nuclei

Nothing is entirely new!

Pioneers in this field attempted a precursor calculation long ago.

[Broude, Goldring et. al. Nuclear Physics A215 617 (1973)]

Experiment was on the 3^- state in ^{16}O.

Hartree - Fock calculations in LS coupling gave estimates of the hyperfine interaction of recoiling 2^+, 3^+, 4^+ oxygen ions based on unpaired s-electron contact interactions only.

A considerable degree of success was achieved - both RIV and decoupling experiments were interpreted.

Their model gave the g-factor 0.57(5), accurate to 9% and in excellent agreement with the best value we have today +0.556(4).

The work was not continued at that time [clear computation limitations].

Concept of an RIV experiment following Coulomb Excitation

1. **Beam enters target: electrons stripped, nuclei aligned in Coulex process.**

   Calculated accurately through e.g. Winther-de Boer theory.

2. **Ions leave target with charge state distribution.**

   Known from stripping foil studies.

3. **Nuclei precess about resultant interaction axis F in flight.**

   Object of present calculation. - ONLY MISSING LINK!

4. **Gamma emission in flight shows angular distrubution characteristic of initial alignment followed by random axis precession.**

   Fully understood - requires detection of both recoiling [target] particle [e.g.C ion - highly efficient] and gamma decay [array].

At HRIBF detection involved Hyball particle and Clarion gamma arrays

Atomic multi-electron theory has advanced strongly.

Problems inaccessible in the 1970's are now approachable.

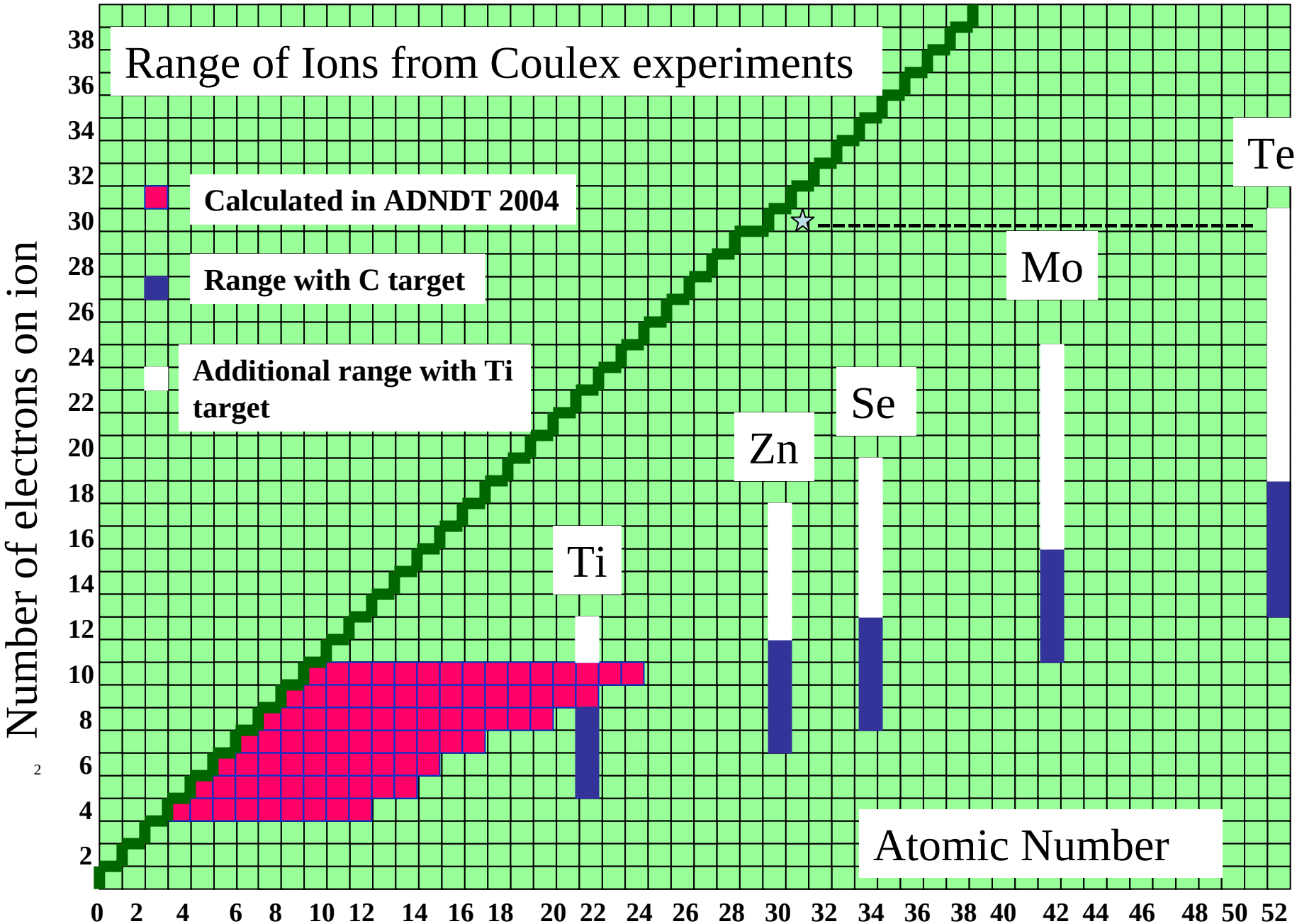
Energy levels, life-times, transition probabilities and hyperfine interactions are calculated using multi-configuration Hartree-Fock method including relativistic effects through the Breit-Pauli Hamiltonian.

Colleagues in this work are some of the most experienced atomic theorists: [C.Froese-Fischer and G.Tachiev ADNDT 87 1 (2004), Computational Atomic Structure: C. Froese-Fischer, T. Brage, P. Jonsson IoP Publishing 1997]

Calculation of hyperfine interaction strength in several terms of Ga II compared with experiment.

Jonsson et al - to be published

	theory		exp
Level	A^{69}Ga	B^{69}Ga	A^{69}Ga
$4s4p\ ^3P^o_1$	3903	−52.64	3987 ± 270
$4s4p\ ^3P^o_2$	3215	101.1	
$4s4p\ ^1P^o_1$	297.3	69.96	
$4s5s\ ^3S_1$	7580	0.01036	7795 ± 180
$4p^2\ ^1D_2$	342.4	91.85	
$4s4d\ ^3D_1$	−3131	3.044	
$4s4d\ ^3D_2$	1116	4.305	
$4s4d\ ^3D_3$	2151	9.202	
$4p^2\ ^3P_1$	−9.804	49.56	
$4p^2\ ^3P_2$	462.2	−102.9	
$4s5p\ ^3P^o_1$	4034	−10.57	4227 ± 150
$4s5p\ ^3P^o_2$	3311	20.70	3417 ± 210
$4s5p\ ^1P^o_1$	−437.8	24.20	
$4s4d\ ^1D_2$	310.9	91.78	
$4s6s\ ^3S_1$	7027	0.00	
$4s5d\ ^3D_1$	−3279	1.165	3417 ± 150
$4s5d\ ^3D_2$	1141	1.654	1109 ± 330


Range of Ions from Coulex experiments
Calculated in ADNDT 2004
Range with C target
Additional range with Ti target
Te
Mo
Se
Zn
Ti
Number of electrons on ion
Atomic Number
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38

The aim of the calculation is to give the nuclear lifetime integrated attenuation factors for a spin I state of a given element taking into account the spread of charge states in the isotope ions emerging from a foil.

[For theory of static model of gamma angular distribution attenuation see e.g Steffen and Fraunfelder, Perturbed Angular Correlations, North Holland, 1964]

$$G_k(\infty) = \sum_{F,F'} q(J) \frac{(2F+1)(2F'+1)}{2J+1} \begin{Bmatrix} F & F' & K \\ I & I & J \end{Bmatrix}^2 \frac{1}{(\omega_{F,F'}\tau)^2+1}$$

This requires knowledge of the J [and F] states, their magnetic hyperfine interactions A and their probabilities for each charge state in the emerging ions.

The energies are $E_F = A\underline{I}.\underline{J} = A[F(F+1) - J(J+1) - I(I+1)]/2$

and the precession frequencies are given by $\omega_{FF'} = A[F(F+1) - F'(F'+1)]/2$

[N.B. NOT a single frequency as for a simple applied magnetic field B_{hf}

- the frequencies here depend upon the nuclear spin I as well as J and A]

Calculation uses code GRASP2K

[Jonsson, He, Froese-Fischer and Grant
Computer Physics Comm. 177, 597, 2007]

For each charge state the possible low-lying electronic configurations are calculated to find the spectrum of ionic angular momentum J states they produce.

Starting from Thomas-Fermi wavefunctions the magnetic hyperfine interaction parameter A for each state is calculated in the multi-configurational Dirac-Hartree-Foch method.

Examples of results [for relatively low ionisation states and light elements]

are available in ADNDT 87, 1, 2004.

The states are weighted by q(J) = (2J+1) and an average G_2 and G_4 for the experiment is evaluated by summing over all configurations and all charge states.

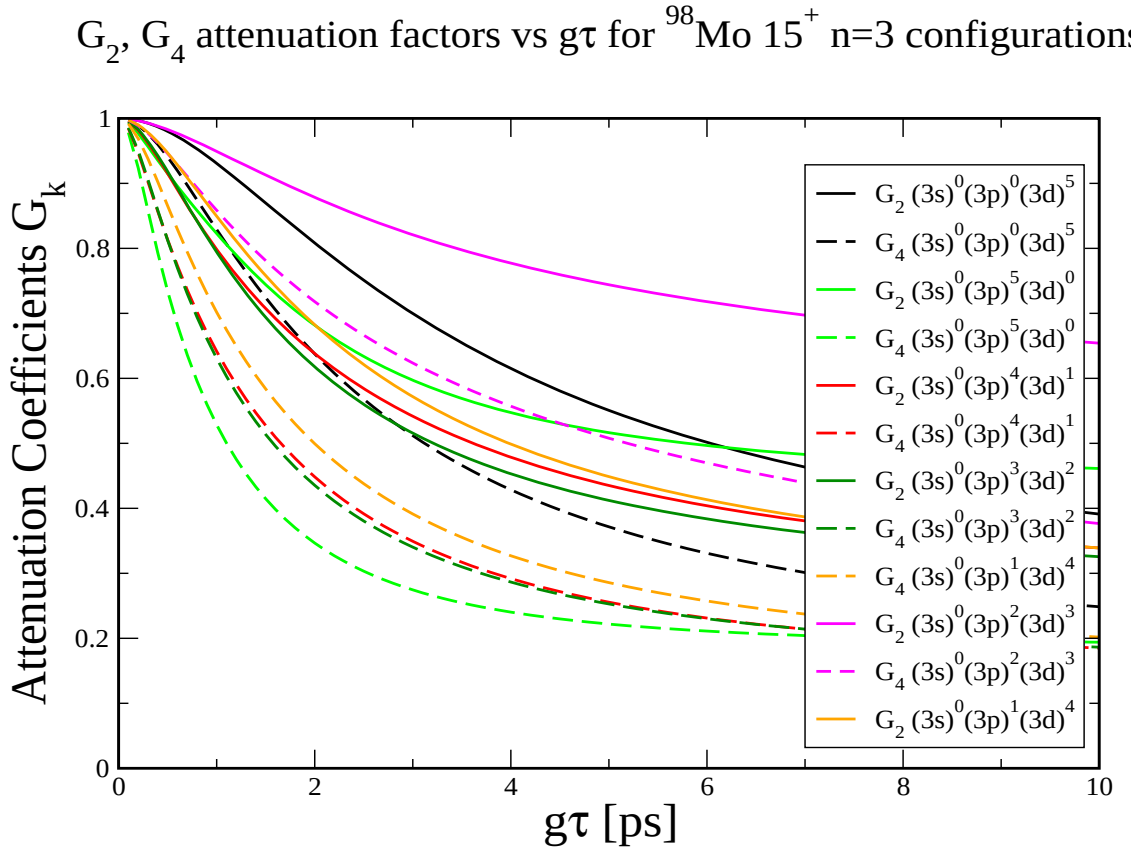
An example to show the numbers of J states for typical configurations:

15 electrons: states within a few hundred eV of the ground state energy

Neon core [fast filled] $(1s)^2(2s)^2(2p)^6$ + 5 in longer lived excited states $(3s)^x(3p)^y(3d)^z$

Configuration			Numbers of J states								Total
x	y	z	1/2	3/2	5/2	7/2	9/2	11/2	13/2	15/2	
2	3	0	1	3	1						5
2	2	1	5	8	8	5	2				28
2	0	3	7	11	11	9	5	2			45
1	4	0	3	3	2						8
1	3	1	13	19	19	14	6	1			72
1	2	2	29	47	51	41	27	12	4		211
-	-	-	-	-	-	-	-	-	-	-	-
0	3	2	19	32	34	28	17	9	2		141
0	2	3	31	52	59	51	37	20	9	2	261
0	1	4	21	35	39	36	26	15	6	2	180
0	0	5	4	7	10	7	5	3	1		37

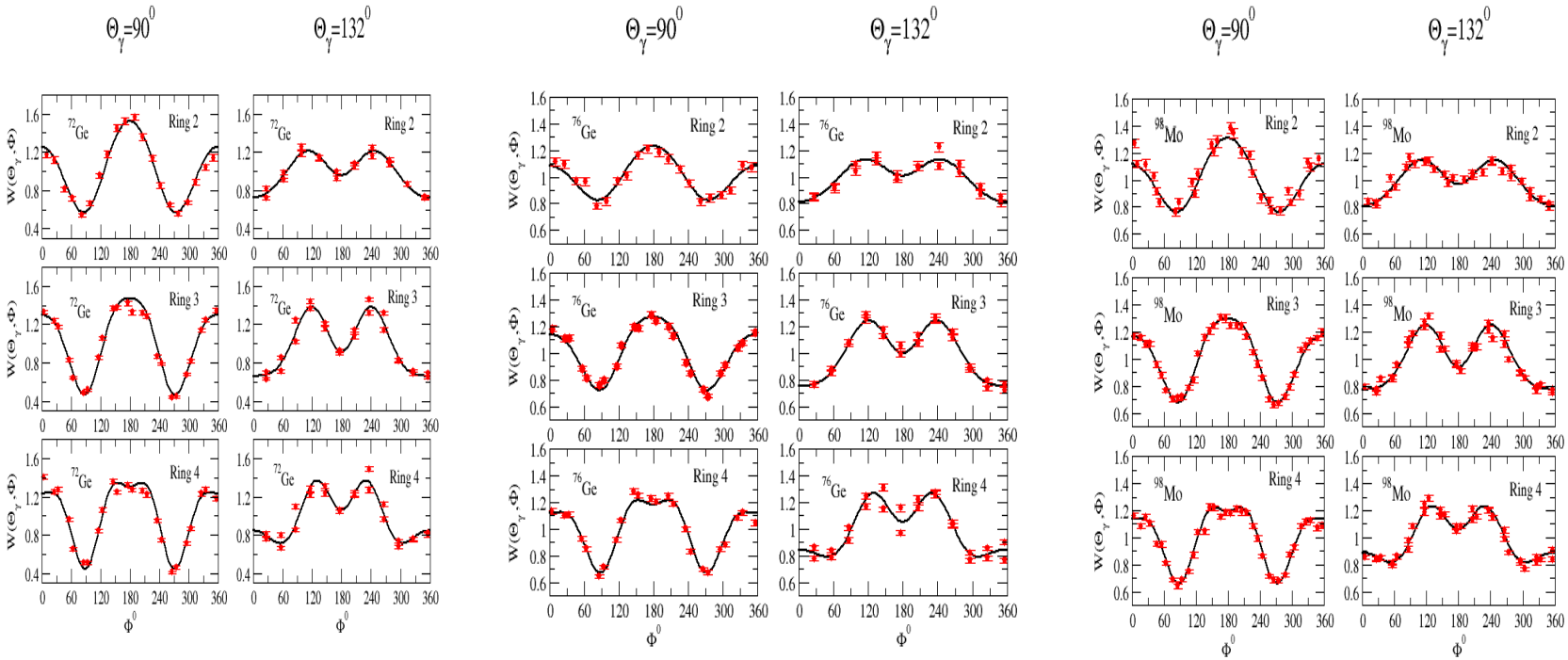
Example: Attenuation factors for different configurations of 15 electron ion for a Mo isotope. G_2 and G_4 for the same configuration have the same colour



Notice the wide variation in results for different configurations.

To obtain the charge state average values, the calculated G_k's for each configuration are summed with weights proportional to the total number of J states in that configuration.

Comparison with experiment: new stable beam data taken at HRIBF in late 2006 - ^{72,76}Ge and ^{98}Mo

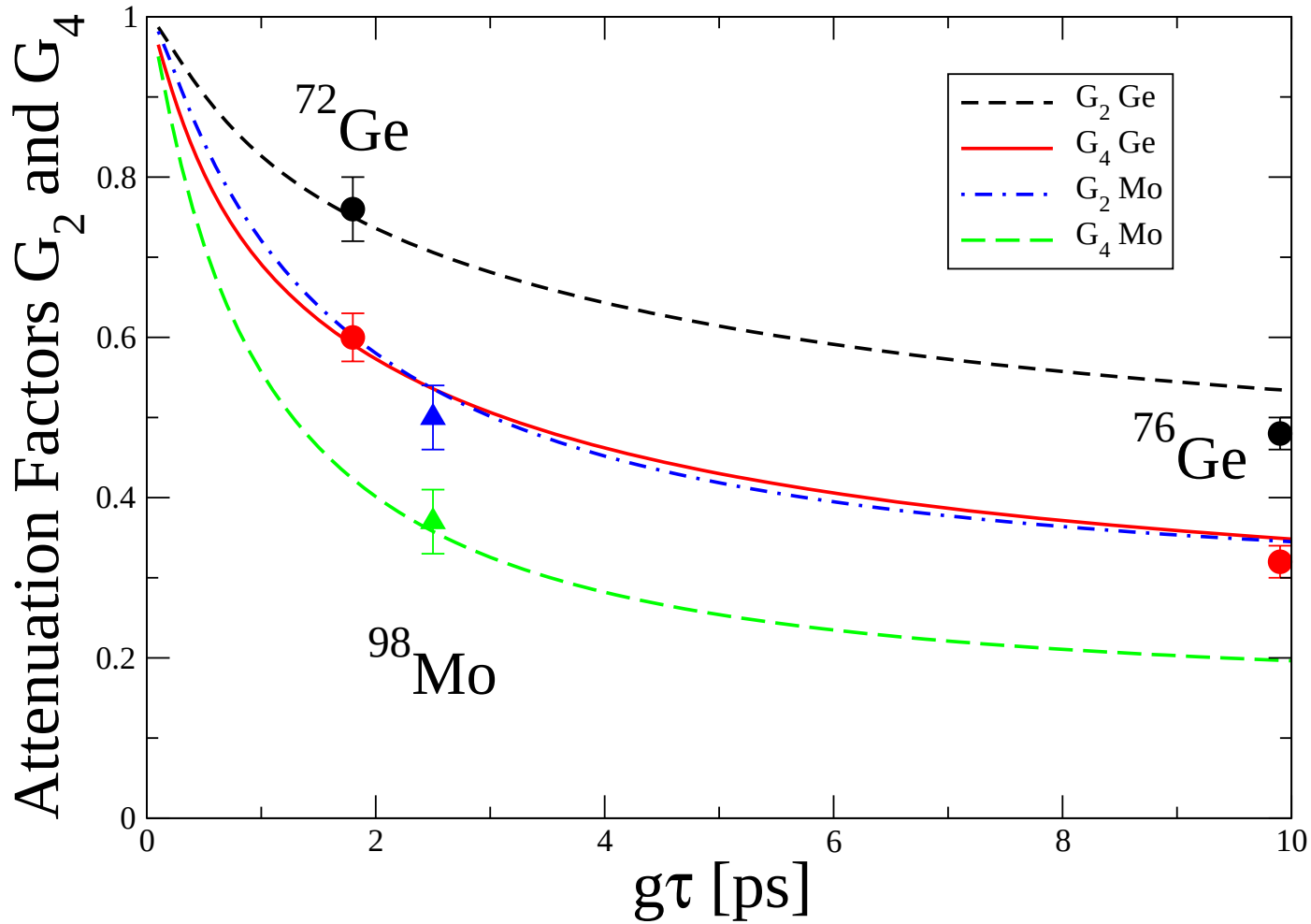


[Acknowledgement to E Padilla for access to part of her Ge and Se data, and for its initial analysis.]

Charge distributions vs numbers n of electrons remaining on the ions (%)

n	7	8	9	10	11	12	13	14	15	16
Ge	6	16	25	25	16	7				
Mo				3	10	18	23	21	13	7

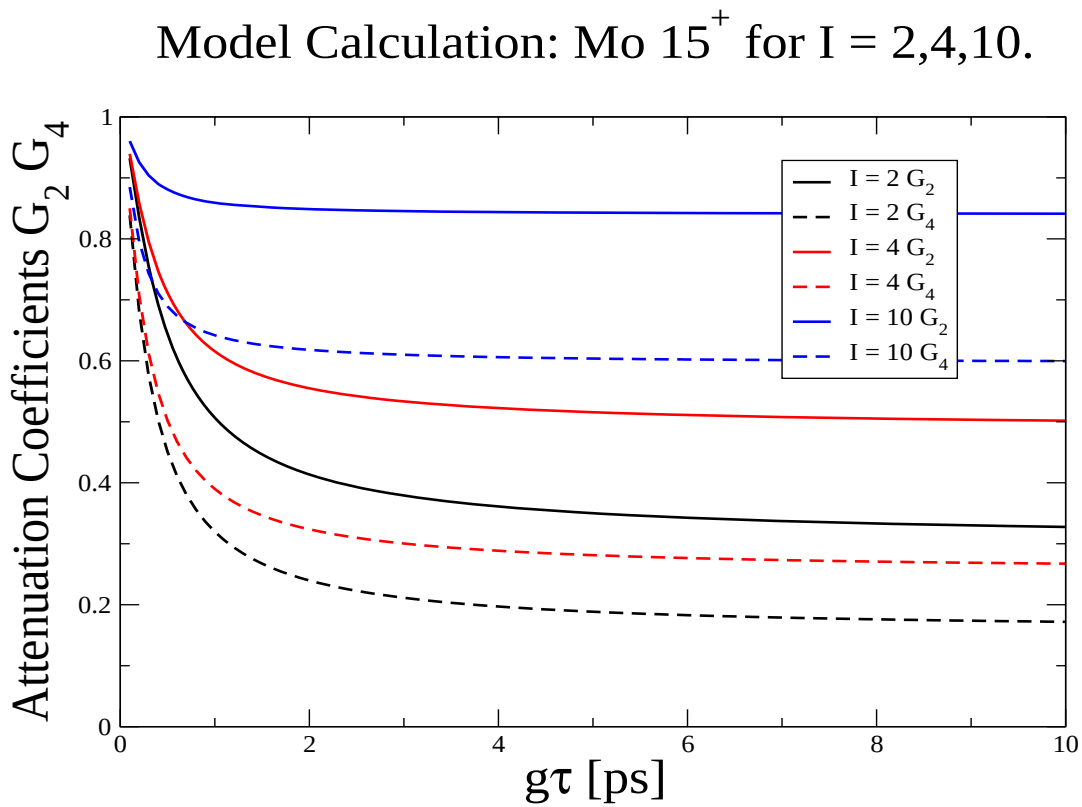
Model compared with Experiment: ^{72,76}Ge, ^{98}Mo.



Calculation demonstrates sensitivity to nuclear level spin I

RIV method may struggle when I > J since then the angle of the precession cone and alignment reduction effects are small.

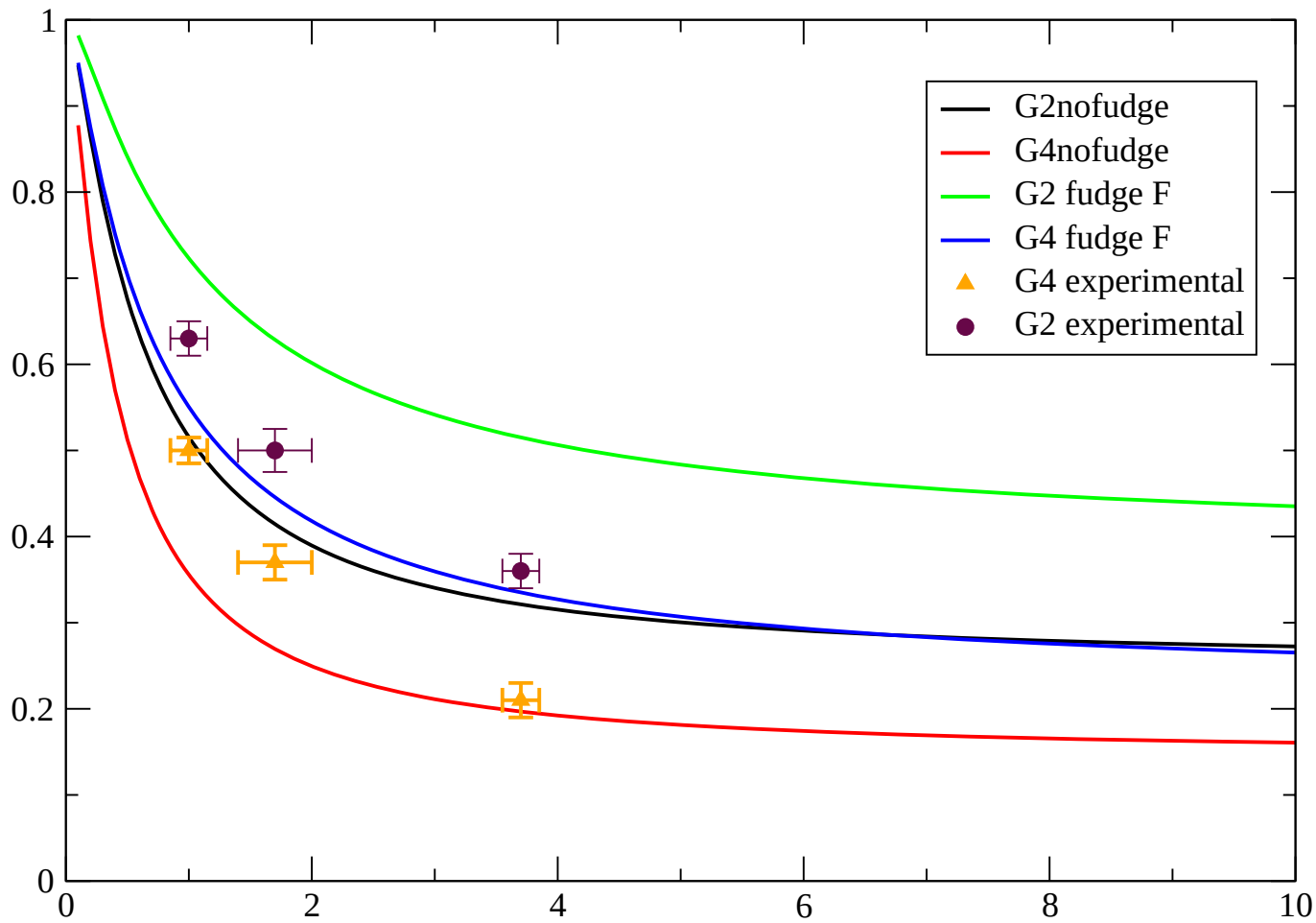
Loss of sensitivity slight for I < 4-6.



Theory gives direct access to detailed adjustment for different nuclear level spins

Not all is so easy: Te calculation involves many more states, many with high J values. Trial fudge factor alters weighting and shows ability to obtain better result.

Problem - lifetimes?



What about transitions between states during the precession?

In principle:

Transitions to different electronic states will alter both the frequency and axis of the nuclear precession. If many transitions occur during the nuclear lifetime they fundamentally alter the picture of precession - the Abragam-Pound limit of relaxation - see Steffen and Frauenfelder reference.

However all data give evidence for few if any transitions during the 1-20 ps lifetimes of recently studied nuclear levels.

The code calculation:

The code provides half-lives of all electronic states calculated. These allow a more quantitative answer to the probability of transitions and a realistic description of their effects on the attenuations observed.

With time the ion ensemble loses angular momentum and higher J states, which precess fastest, are depopulated, slowing the observed attenuation.

Active current investigation.

Present status

We have been running the code for this purpose for only a short time.

First results suggest considerable success in a-priori calculation to provide calibration for RIV methods.

A variety of different RIV-based methods for g-factor measurement are possible, including Coulomb excitation and fission fragment-gamma correlations/distributions.

$g\tau$ ranges ~ 1 - 20 gps are accessible.

Recall that RIV yields useful results with limited statistics - RIB's.

The calculation, which has no free parameters, allows:

Adjustment for different nuclear spins.

Access to odd-A isotopes for which calibration g-factors don't exist.

Possibility of predictable 'tuning' of good sensitivity to states of different lifetime by adjusting target thickness and hence emerging ion energy and charge state distribution.

Conclusions:

Availability of a-priori calibration for RIV attenuations

Will allow g-factor study on weak RIBs avoiding 'calibration' time even if this is possible. Can be adjusted for all nuclear level spins.

Gives new access to odd-A nuclear states of all spins for which suitable experimental based calibration is not available.

This is a step forward for both stable and radioactive beams.

[N.B. Mixed gamma transitions require multipole mixing ratios for angular distributions]

Allows tailoring of the target thickness to provide ionic charge states of suitable HFI strength for lifetimes of levels under study.

Theory - new nuclear model parameter $g\tau$ to be calculated [straightforward].

Thank you