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

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Fission and Properties of Neutron-Rich Nuclei, Sanibel November 2007

Outline of the talk:

- Reminder of existing methods of g-factor study in sub-nanosecond states
- Desirability of general theory of hyperfine interactions in ions recoiling in vacuum
- Development of such a theory
- Applications to specific methods

    RIB experiments

    Fission measurements [252Ca]

Recoil in Vacuum

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

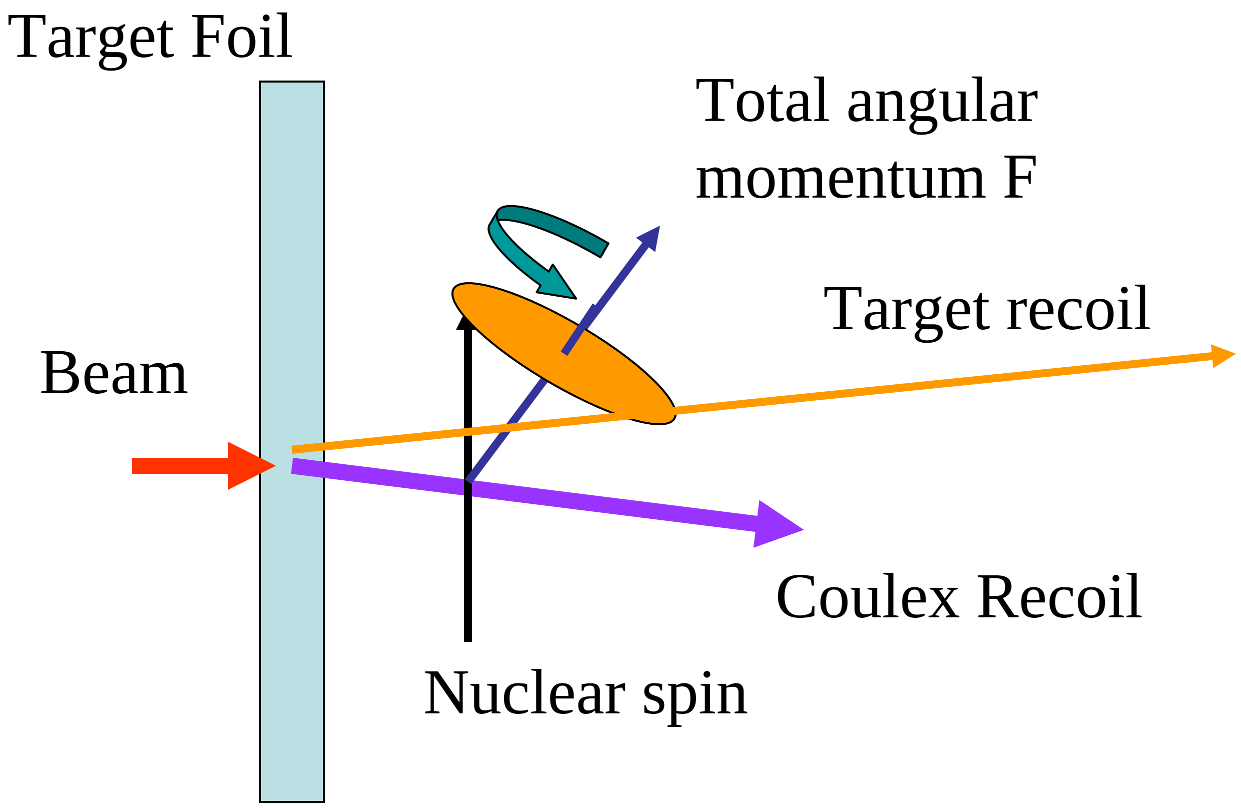
It is established that magnetic effects are dominant, thus the attenuation was a measure of the

g-factor [g = magnetic moment μ / spin I]

of the decaying nuclear state.

This is the basis of the Recoil In Vacuum [RIV] method of g-factor determination [**see e.g. Broude, Goldring et. al. NPA215 617 (1973)**].

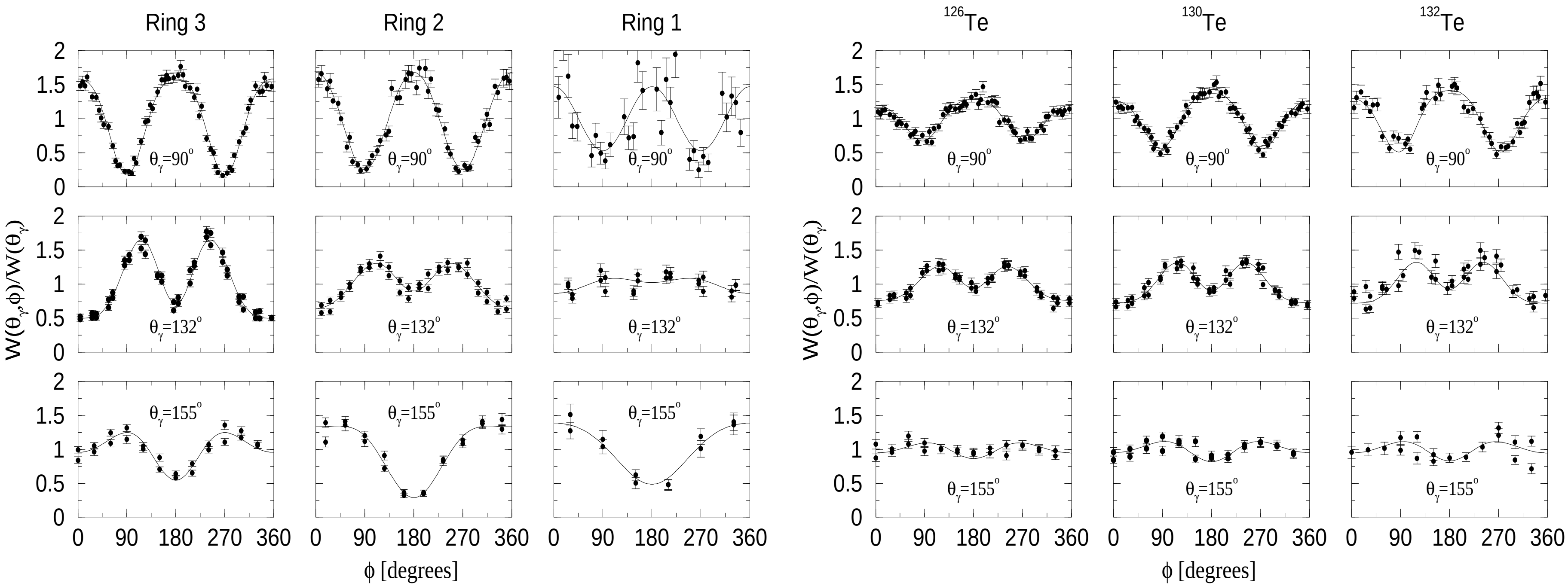
Recoil in Vacuum



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

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].

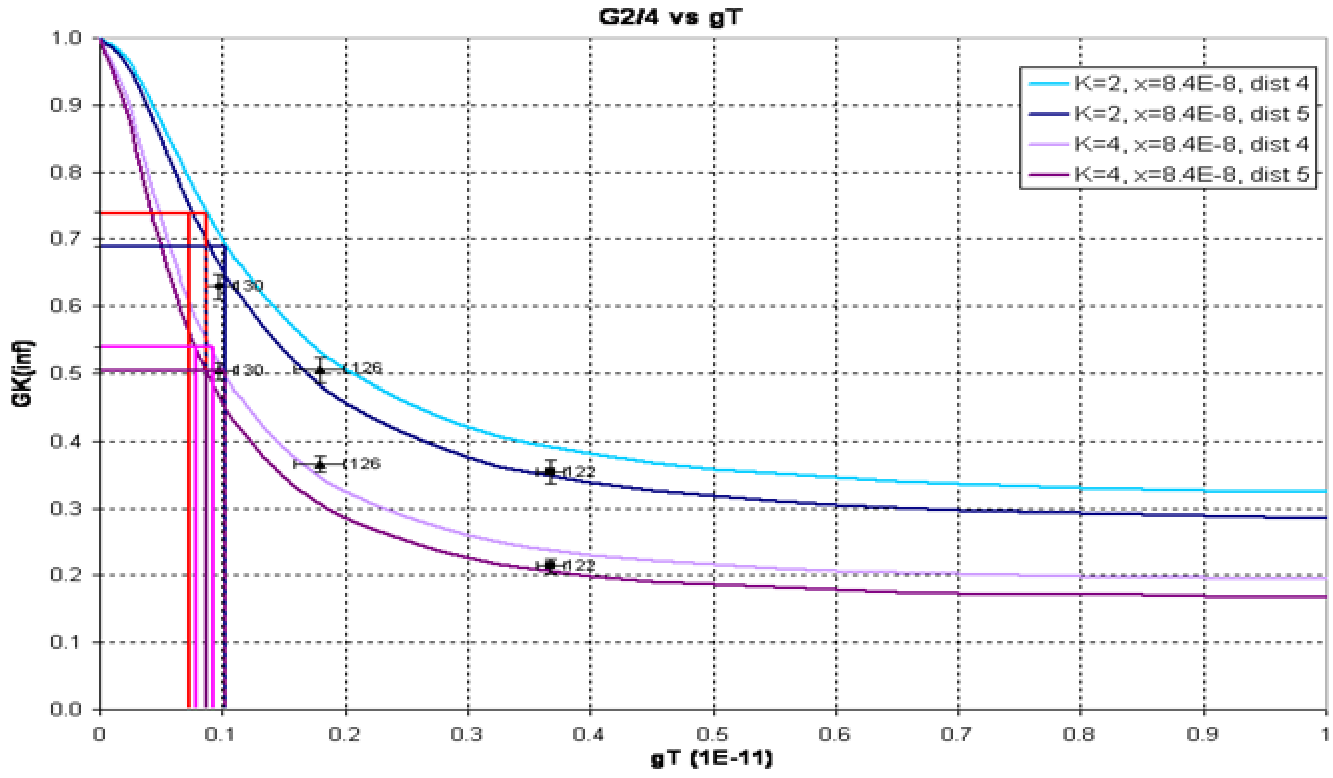
$$W(\theta_\gamma,\phi) \approx \sum_{k.q} G_k \rho_{kq} A_k Q_k D_q^{k*}(\phi,\theta_\gamma,0)$$

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.

Result: |g-factor| 2^+_1 ^{132}Te = 0.035(5).



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

Features of the RIV method

- Particularly for 2^+ - 0^+ gamma decays in even-even nuclei, the angular distribution is highly anisotropic.

- Useful g-factors can be extracted from attenuations measured with moderate statistics [RIB's].

- 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

New Opportunities and challenges for the study of ps state g-factors:

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

With the advent of RIB's and inevitable poorer statistics the RIV method offers prospects of useful g-factor study.

Calibration as for the Te 2+ states not possible for other spins and odd-A isotopes - too few measured g-factors exist. An a priori approach is required.

Can we hope to provide a sound theoretical grounding for the CALIBRATION OF RIV ATTENUATIONS?

The problem

In principle the recoiling ion is an attractive system for theoretical approach. The number of electrons is fixed [neglecting Auger effects] and the physics is fully understood [Coulomb] although complex.

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 and good estimates exist for thin foil targets - beam stripper experience]
a considerable number of electron terms [ion quantum 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 ~ 2.6×10^{-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 majority of nuclei

A new approach to theoretical RIV calibration

Atomic multi-electron theory has advanced strongly.
Problems inaccessible in the 1970's are now approachable.

The hyperfine interaction in RIV ions is open to calculation.

Energy levels, life-times, transition probabilities and hyperfine interactions can be calculated from first principles with accuracy in the few % range.

Colleagues in this work are some of the most experienced atomic theorists:

Computational Atomic Structure: C. Froese-Fischer, T. Brage, P. Jonsson
IoP Publishing 1997

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, Frose-Fischer and Grant Computer Physics Comm. 177, 597, 2007]

For each charge state the possible low-lying electronic configurations are analysed for 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 ADNDT 87, 1, 2004.

The hyperfine interaction is described in terms of the splitting A**I.J** with total angular momentum F. A is directly proportional to the nuclear g-factor

The energies are EF = AI.J = A[F(F + 1) - J(J + 1) - I(I + 1)]/2
and the precession frequencies are given by hnFF' = A[F(F + 1) - F'(F' + 1)]

[N.B. NOT a single frequency as for a simple applied magnetic field Bhf
- the frequencies here depend upon the nuclear spin I as well as J and A]

For each state, the integrated attenuation coefficients are given by

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

where τ is the nuclear state lifetime.

The states are weighted by q(J) = (2J+1) and an average G2 and G4 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

For each charge state

for each J state

for a given nuclear spin I

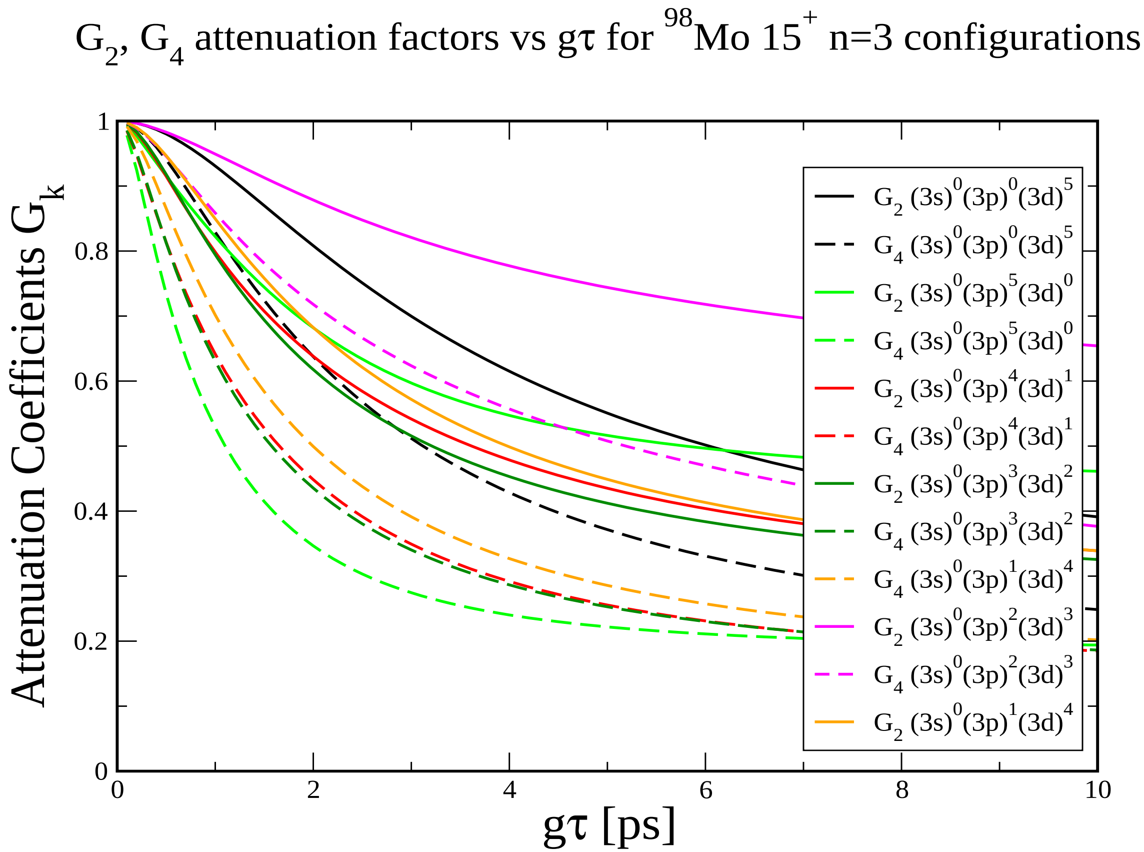
with code value of A

calculate the $G_k(\infty)$ values, including (2J + 1) weighting factors

as a function of the product g-factor x nuclear state lifetime (τ) (ps)

Take sum over all J states for a given configuration

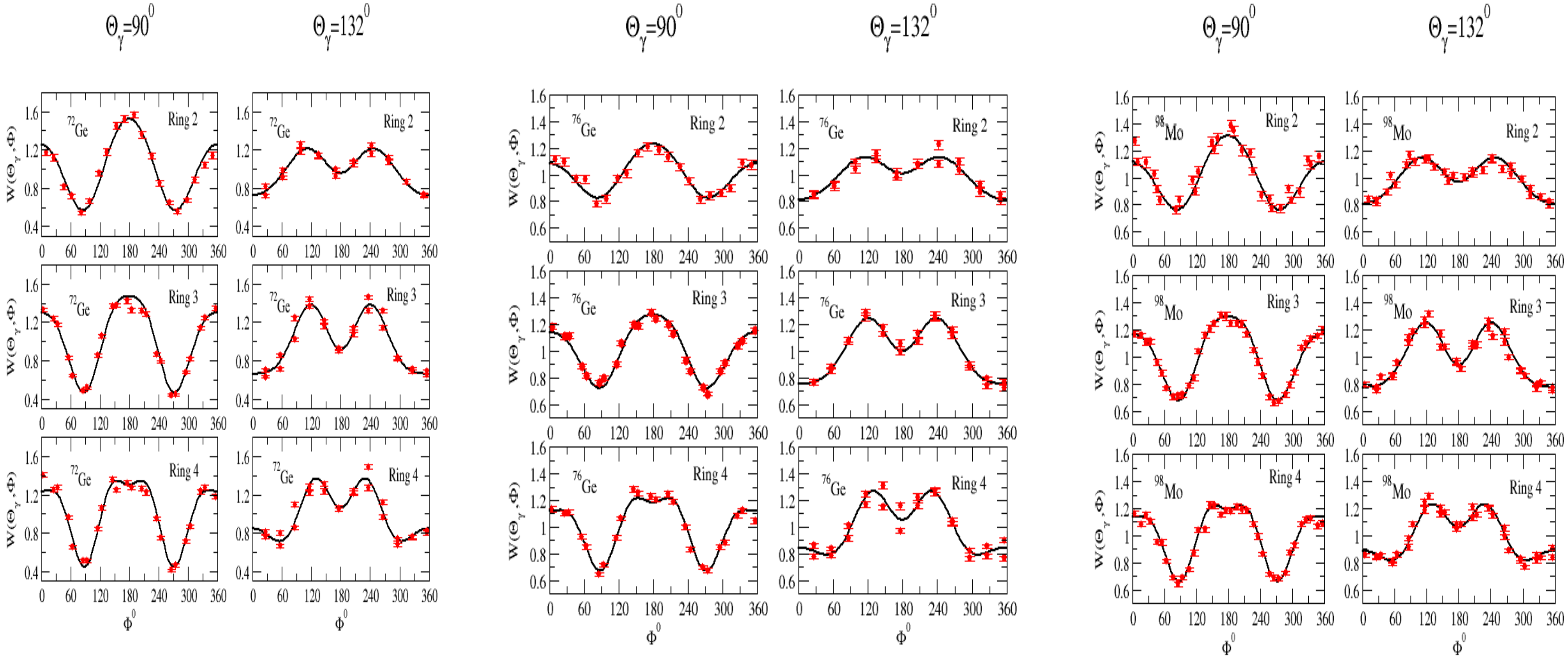
Example: Attenuation factors for different configurations of 15 electron ion for a Mo isotope. G_2 and G_4 for the same configuration have the same colour



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

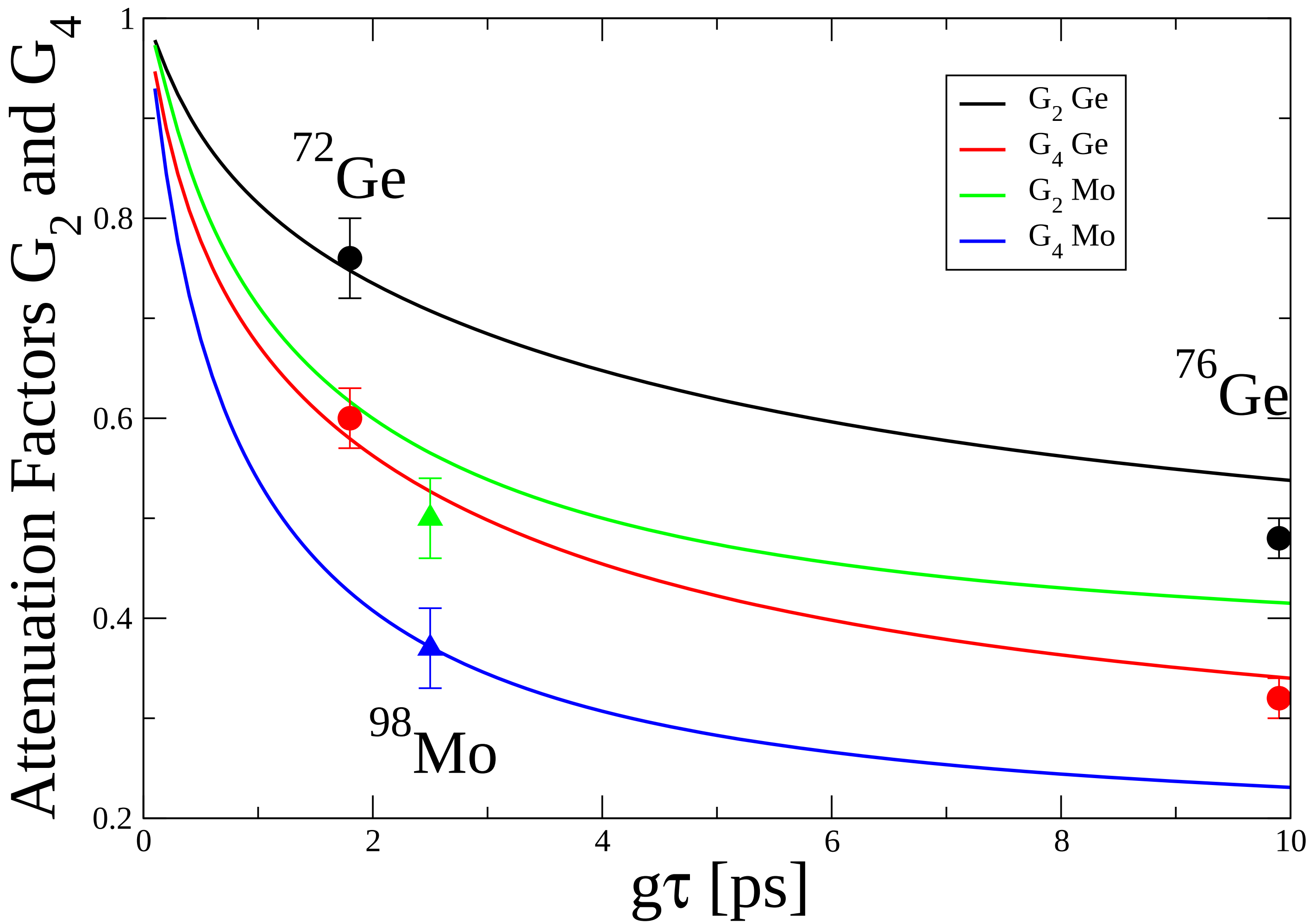


[Acknowledgement to E Padilla for access to part of her Ge and Se data, and for its initial analysis.]

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

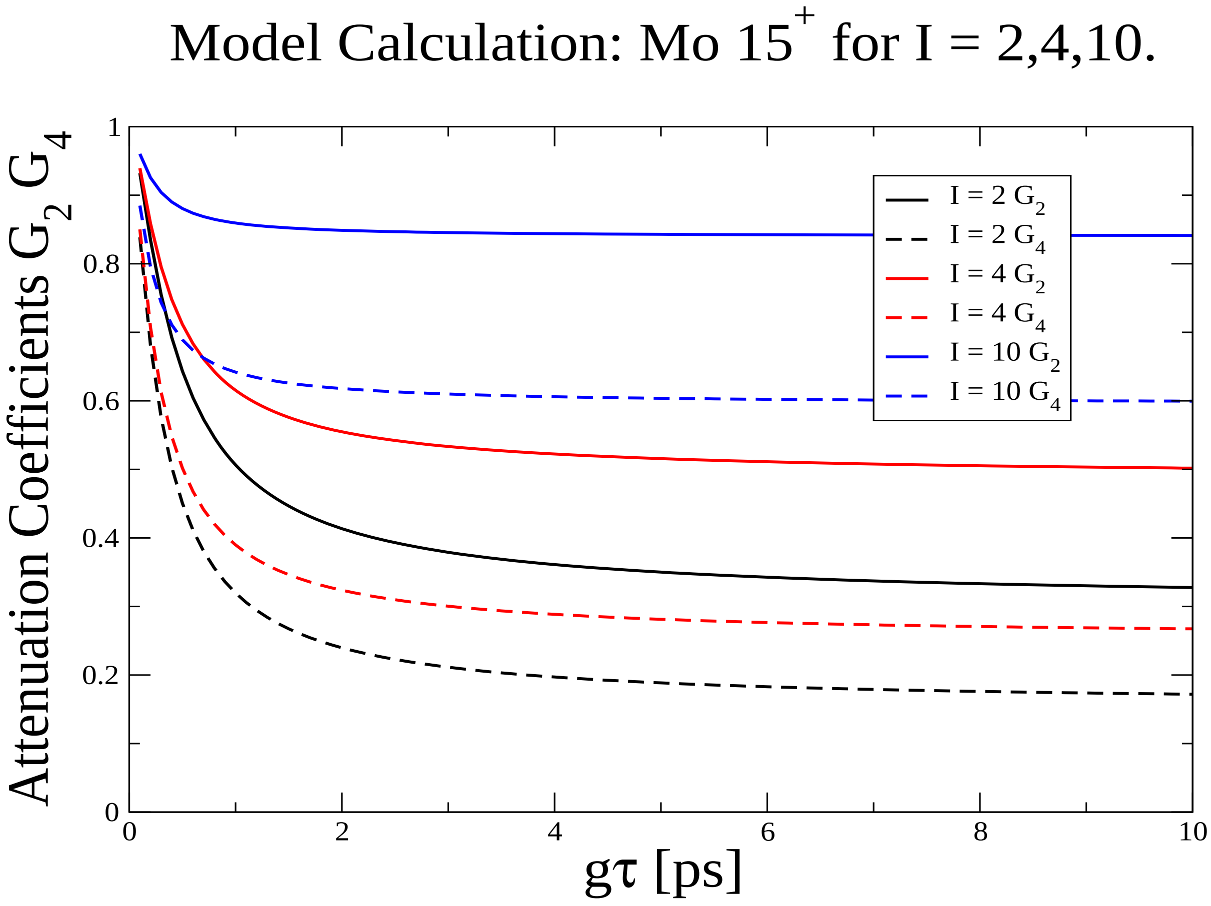
Results, after summing over charge states with weights given by calculated cor … ons of 2



No free parameters - choice of configurations made by excitation energy.

Calculation demonstrates sensitivity to nuclear level spin I

Struggling when I > J since then the angle of the precession cone and alignment reduction effects are small.



Theory gives direct access to detailed adjustment for different spins

Connection to Fission!

Recoil-in-Vacuum requires:

- **Nuclear alignment mechanism**
- **Vector to define co-ordinate axes**
- **Detector system to allow access**

to EITHER (or BOTH) of θ and ϕ distribution gamma emission wrt the axis.

Fission produces alignment and e.g. measurements on 252Cf with detection of the fragment direction provides the axis.

Attenuations require measurements with sources with and without a metallic layer in which the products are stopped [and ions rapidly neutralised] to provide unattenuated distribution information to compare with data taken under Recoil-in-Vacuum conditions.

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 will allow a more quantitative answer to the probability of transitions and a realistic description of their effects on the attenuations observed.

Conclusions

We have been running the code 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 seem accessible.

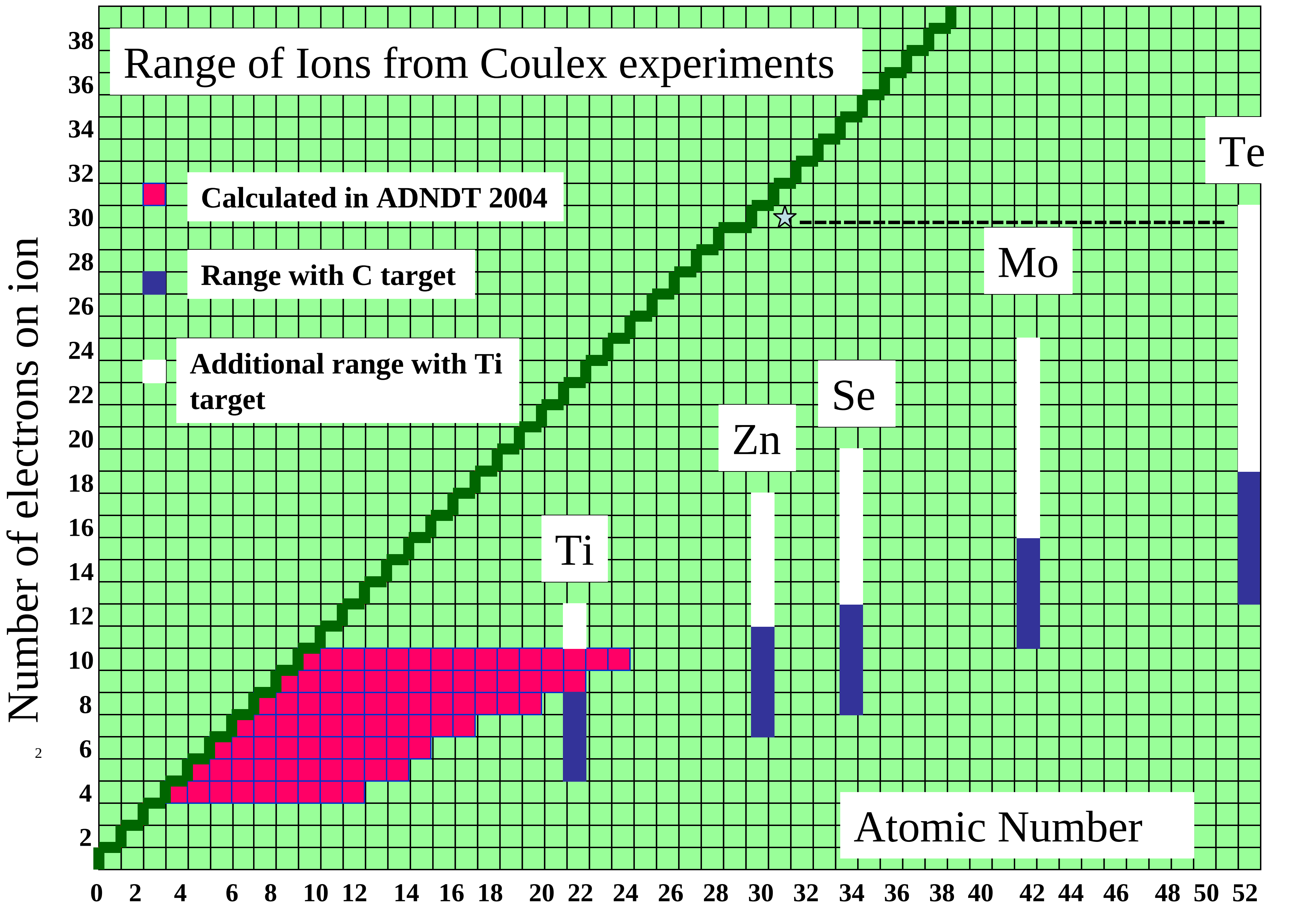
Recall that RIV yields useful results with limited statistics - RIB's.

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.



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

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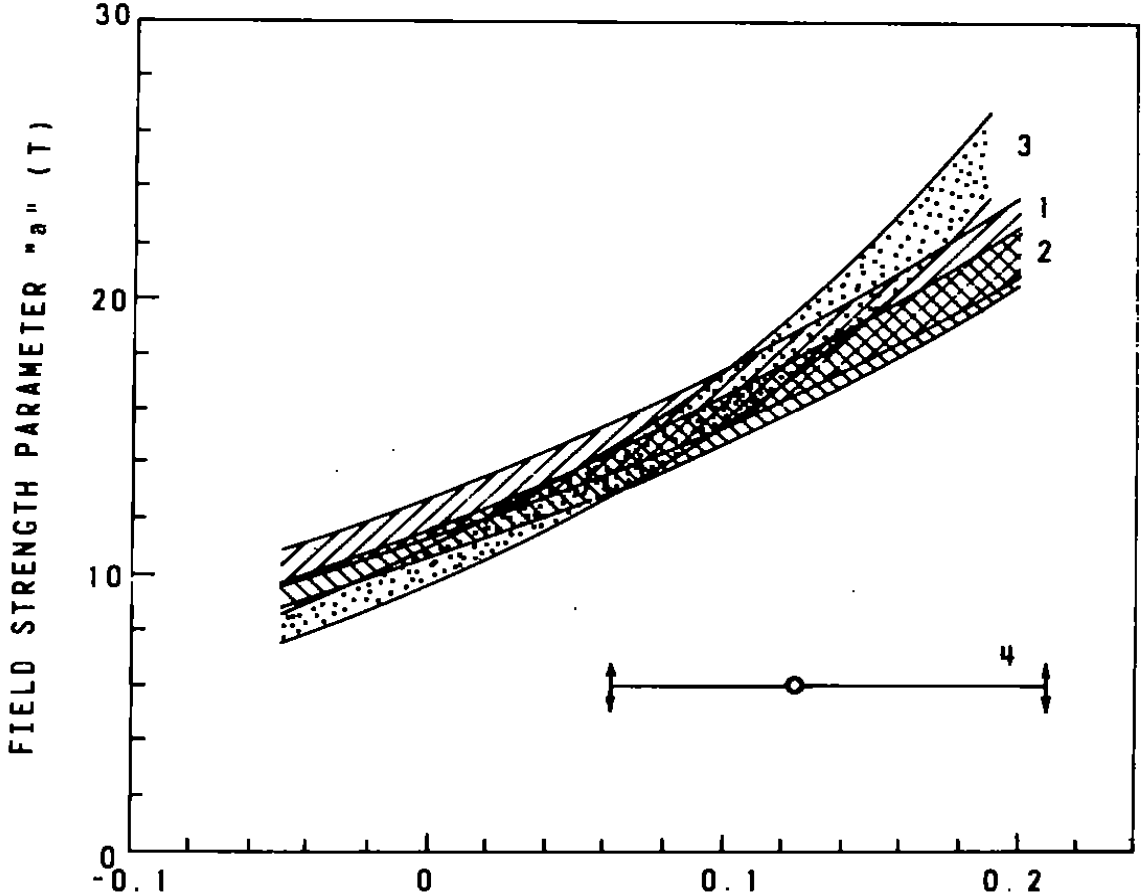
$$W(\theta_\gamma, \phi) \approx \sum_{k.q} G_k \rho_{kq} A_k Q_k D_q^{k*}(\phi, \theta_\gamma, 0)$$


30
20
10
0
-0.1
0
0.1
0.2
FIELD STRENGTH PARAMETER "a" (T)
3
1
2
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