# A-priori calculations of hyperfine interactions in highly ionised atoms: g-factor measurements of pico-second states aligned in nuclear reactions.

N.J.Stone, J.R.Stone

Oxford and Tennessee

and P. Jonsson

Malmo

HFI - NQI

CERN September 12-17 2010

# Outline of the talk

- **The Recoil-in Vacuum method for g-factor measurement in pico-second states**
- **New theoretical approach for calibration of RIV attenuations**
- **Examples of current status**
- **Extension to excited states in nuclei produced in fission and other reactions**

**Magnetic moment and g-factor [ = magnetic moment/nuclear spin] measurements have the potential to give access to detailed information important for the accurate description of both collective and single particle make-up of nuclear state wavefunctions.**

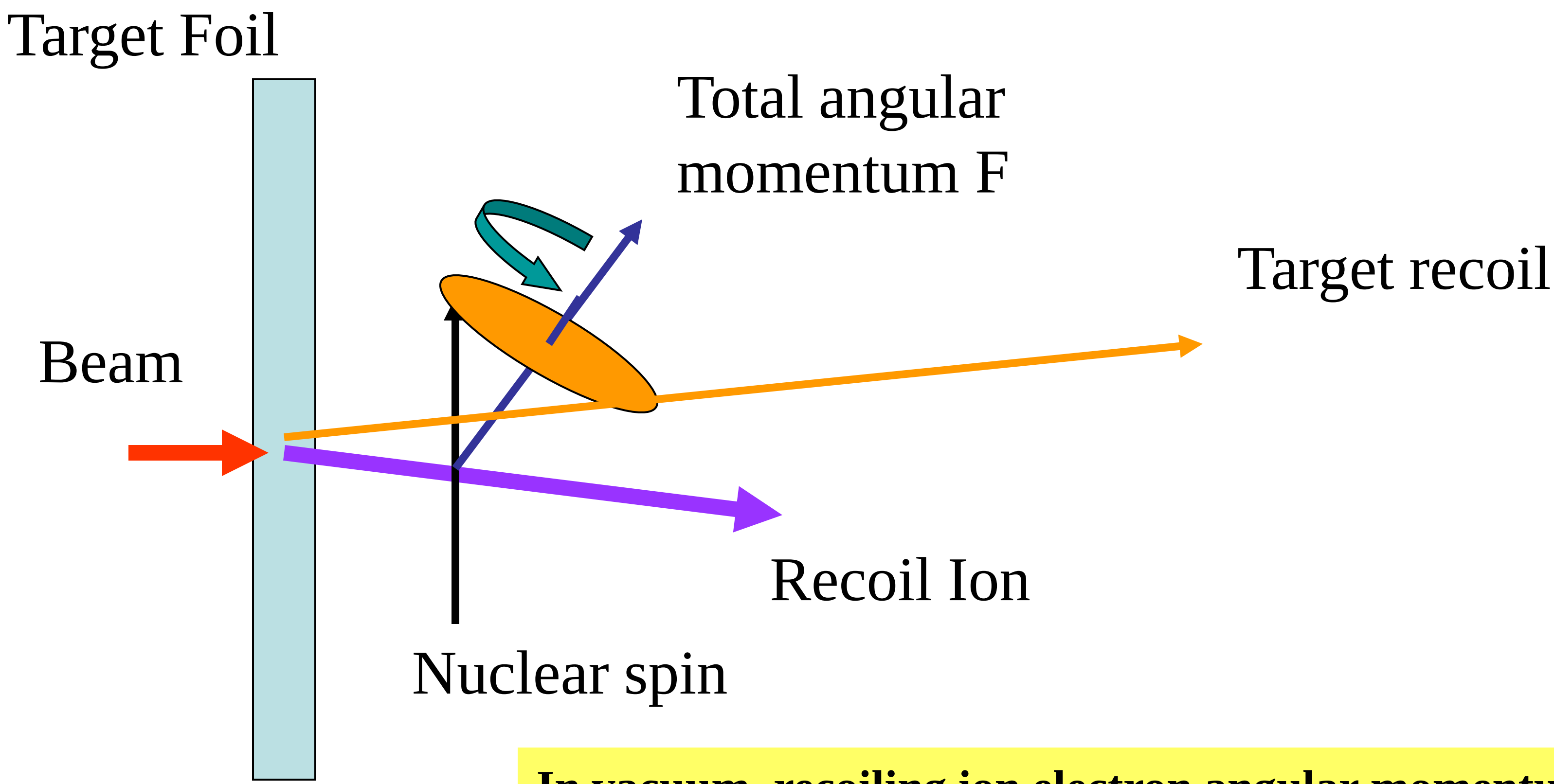
**Many techniques exist for precise measurement of magnetic dipole moments of long lived and stable nuclear states.**

**This potential has been under-exploited because of the lack of suitable methods of general applicability to shorter lived nuclear excited states.**

**Systematic studies of e.g. first 2+ states in stable even-even nuclei are quite extensive but there are few examples of systematic g-factor measurements of excited states of odd-A and odd-odd nuclei.**

**Increased availability of experimental g-factors would provide valuable Input and strong challenges to nuclear theory.**

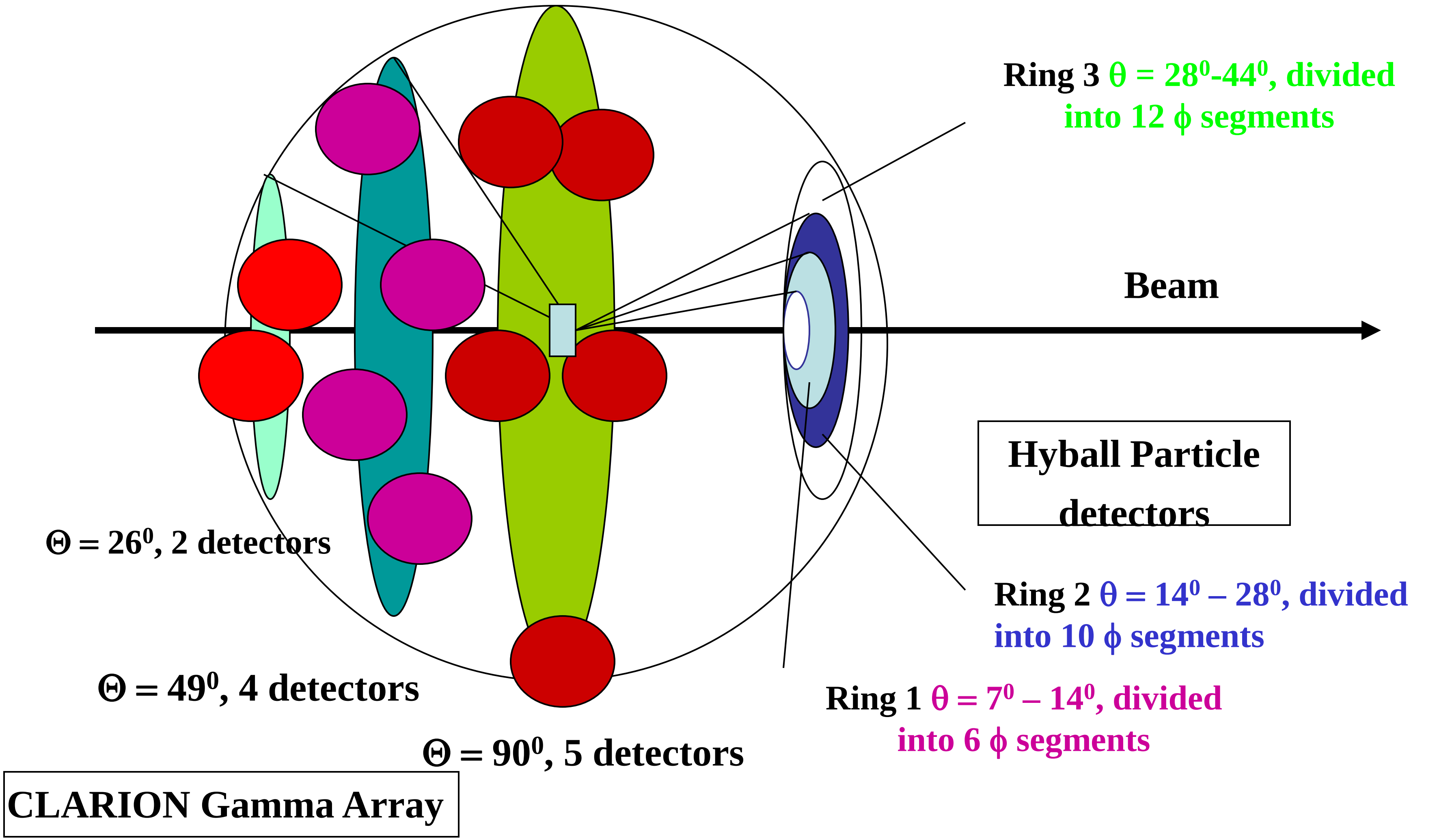
# Recoil in Vacuum




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

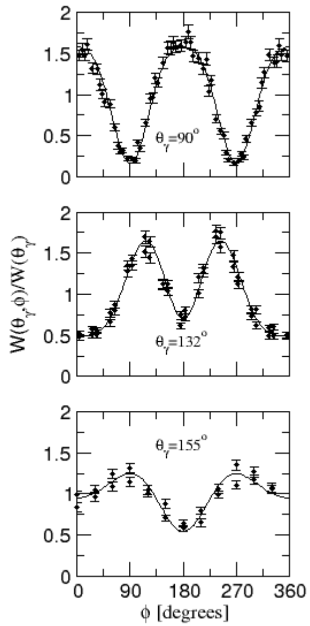
**Anisotropy of angular distribution of decay gamma emission becomes attenuated.**

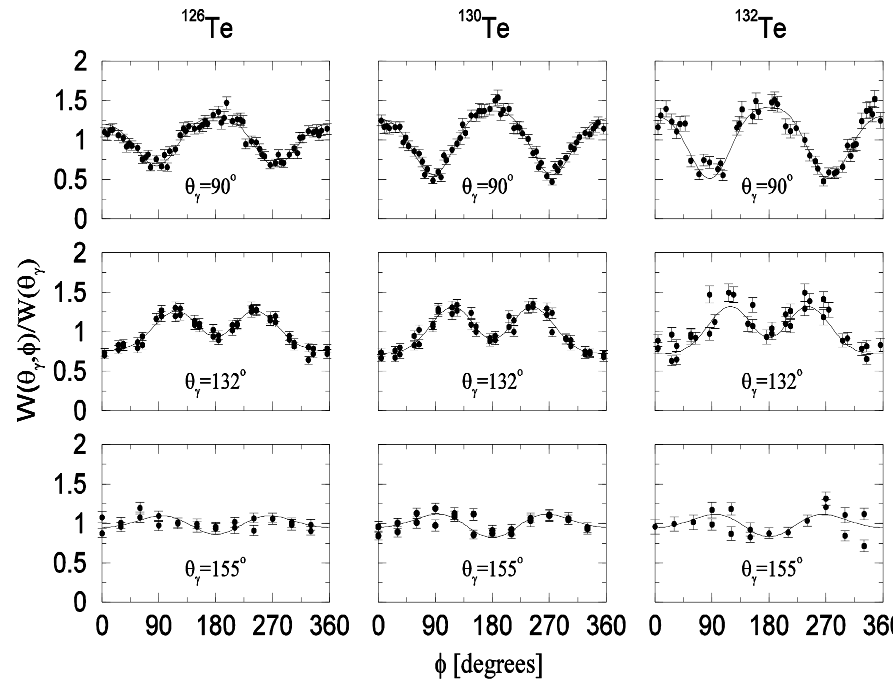
# Schematic CLARION-Hyball set-up



# 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].

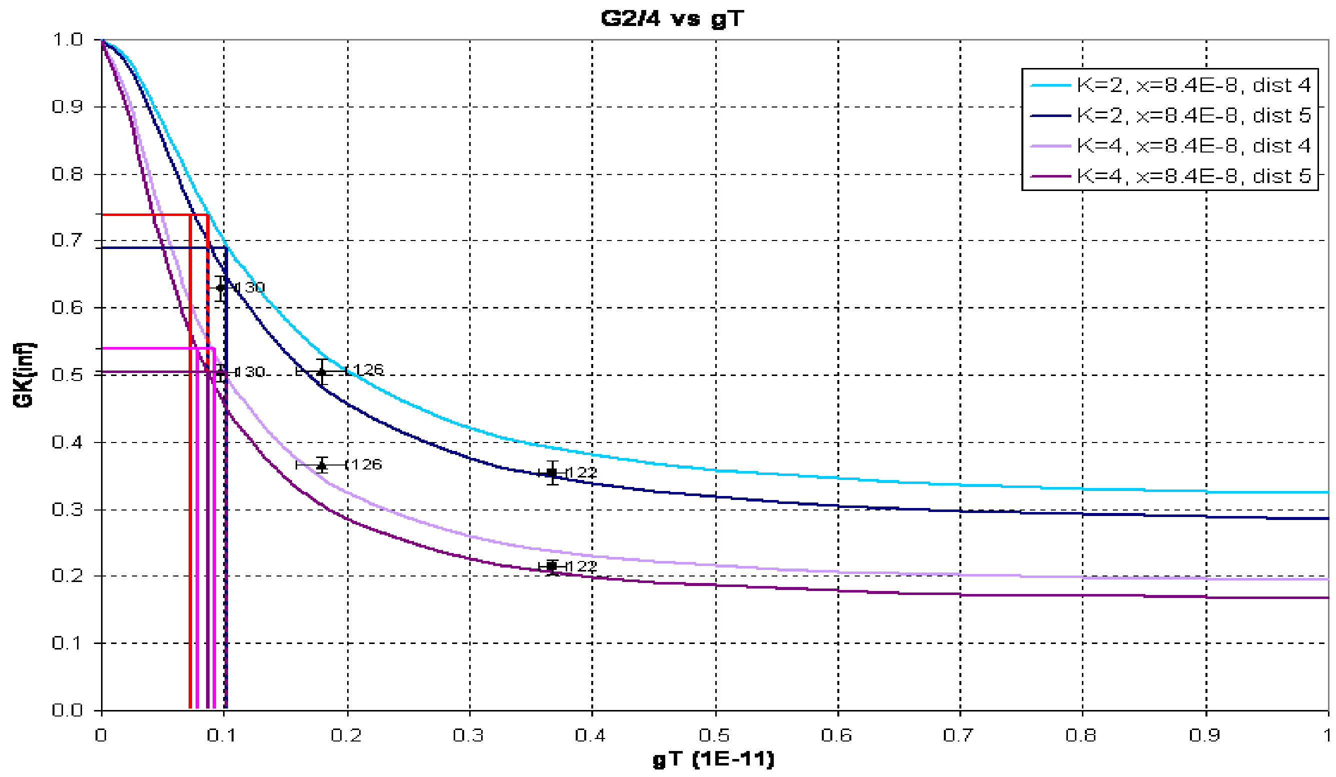
$$W(\theta_\gamma, \phi) \approx \sum_{k.q} G_k \rho_{kq} A_k Q_k D_q^{k*}(\phi, \theta_\gamma, 0)$$

**$G_k$ are the g-factor dependent attenuation coefficients.**

**For the RIV method we need to extract g (or gτ) from the $G_k$.**

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

**Result: |g-factor| $2^+_1$ $^{132}$Te = 0.35(5).** **[N.B. sign not given.]**




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

## The $^{132}$Te experiment has demonstrated that:

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

## However:

**Calibration as for the Te 2+ states not possible for other spins and odd-A isotopes - too few measured g-factors exist.**

***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]

a considerable number [can be 1000's] 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 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 majority of nuclei

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.

For each state the $G_k$ attenuations can now be calculated.

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.

The charge state fractions are estimated using the code EQFOIL developed for accelerator stripper foils, knowing the recoil energies (Felix Liang - HRIBF Oak Ridge)

Thus the atomic physics of the problem is under control!

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

$$\omega_{F,F'} = \frac{\pi}{h} A(J)[F(F+1) - F'(F'+1)] = \frac{2\pi}{h} A(J) F$$

The nuclear parameters are the nuclear state g-factor, spin and life-time.

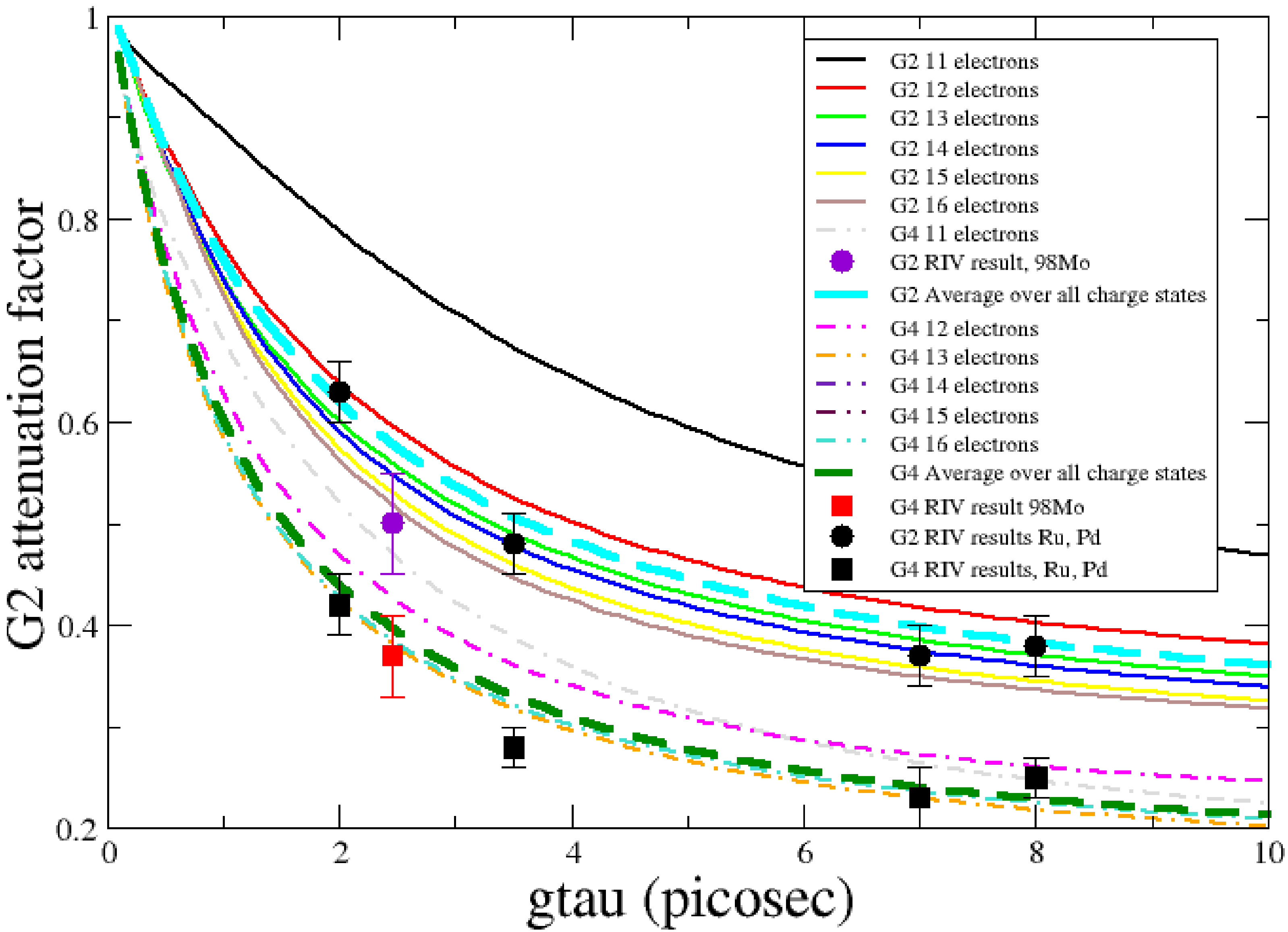
- The hyperfine interaction parameters A and the frequencies $\omega_{FF'}$ are linear in the g-factor.
- The $G_k$ coefficients involve the nuclear state spin I through the F quantization where F = J + I
- The $G_k$ coefficients involve the life-time through the products frequency x life-time ($\tau$)

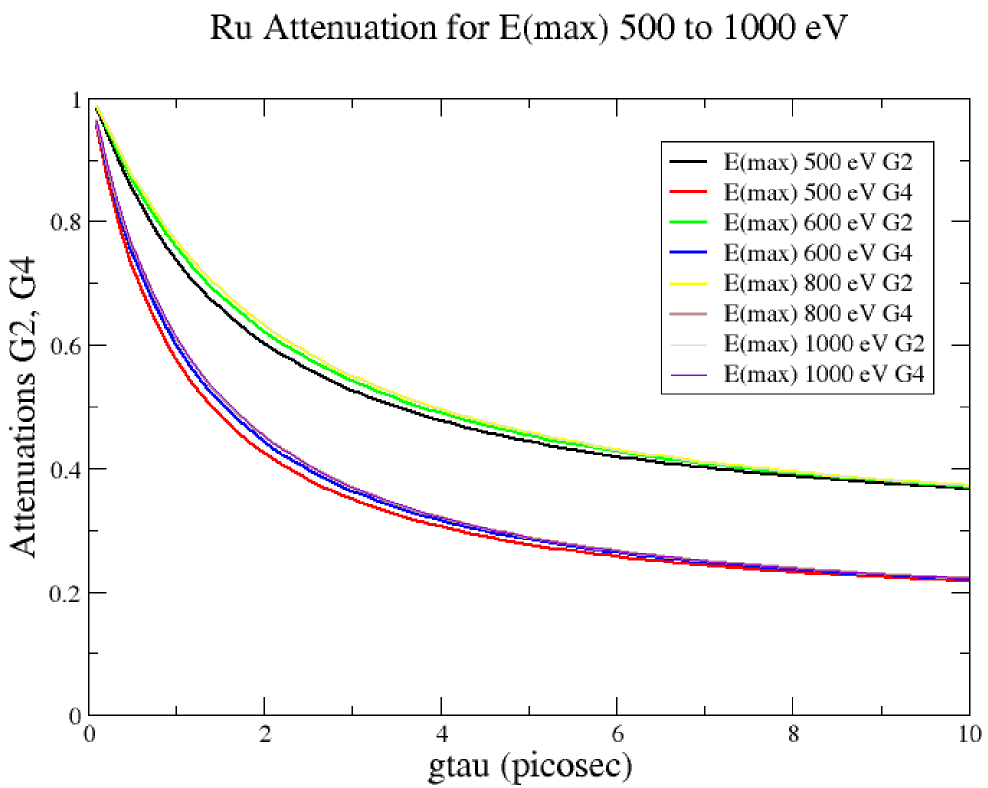
The output of the calculation:

The $G_k$ coefficients for a given spin tabulated as a function of the product g-factor x nuclear state life-time ($\tau$)

# Examples of results of calculations

# Calculated and experimental G2 factors for Mo, Ru, Pd.






**Ru ions**
**200 MeV**

**Figure shows results with upper energy limit**
**500 eV**
**600 eV**
**800 eV**
**1000 eV**

**Plot shows the calculation is not sensitive to the upper energy limit.**

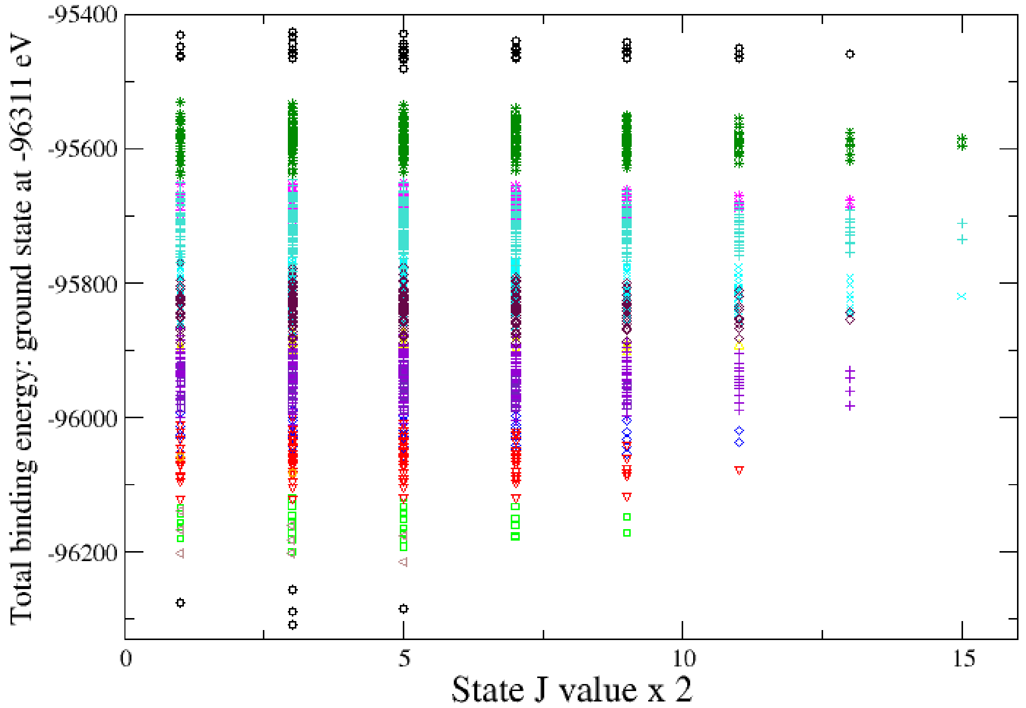
**This is expected when electron state energy distribution is quasi-continuous**

**e.g Ru ions recoiling with ~ 200 MeV which have several electrons in n=3 shell.**

**Excitation to n=4 costs > 1000 eV and there are many hundreds of states**

**deriving from configurations $(3s)^x$ $(3p)^y$ $(3d)^z$.**

# Combined density of J states for Ru 15 electron ions



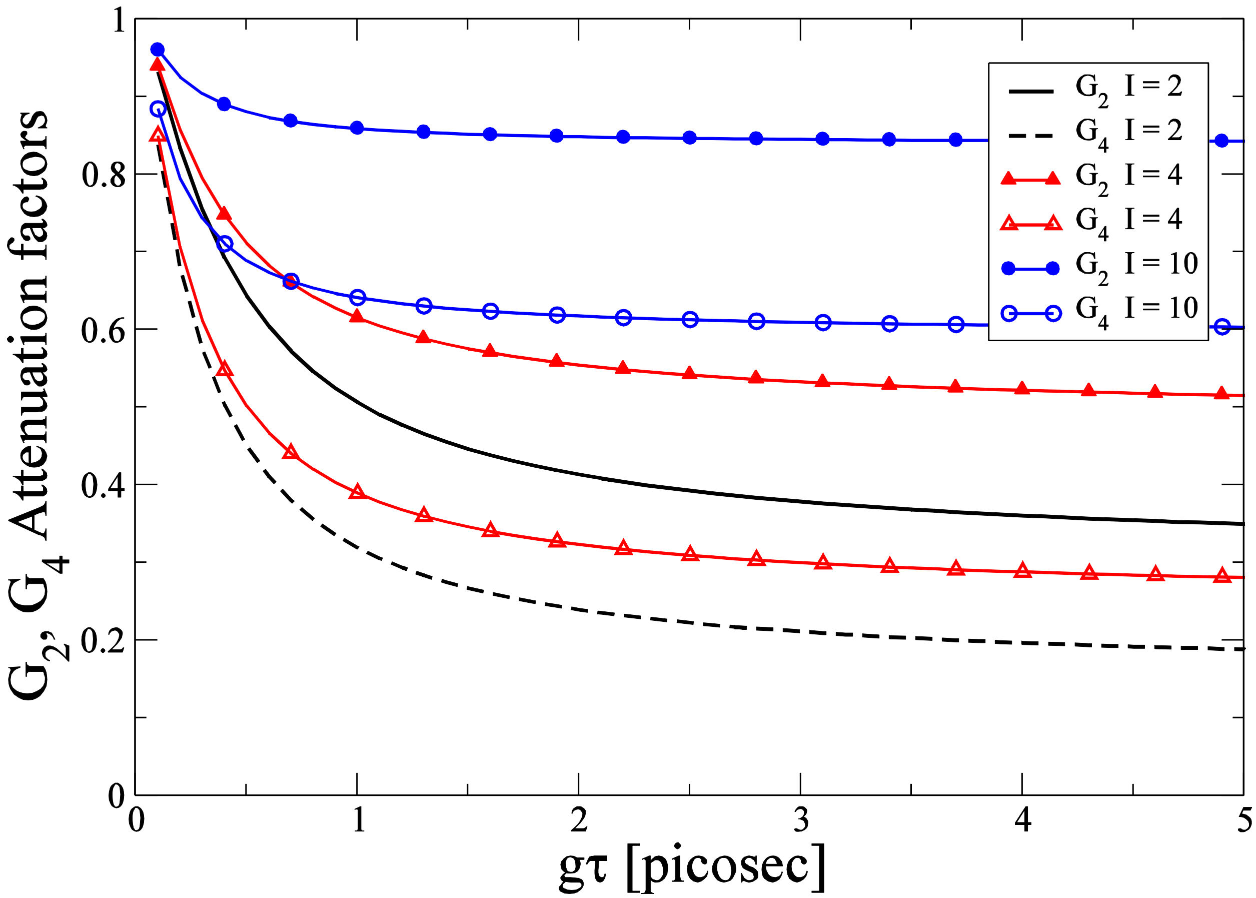

**15 electrons : 5 in n = 3 shell : configurations $(3s)^x(3p)^y(3d)^z$ , x+y+z = 5**

**Total number of states: 1323 having J values between 1/2 and 15/2**

**Density of states approximately uniform between ~ 200 and 900 eV**

# Adaptation for different nuclear spin values

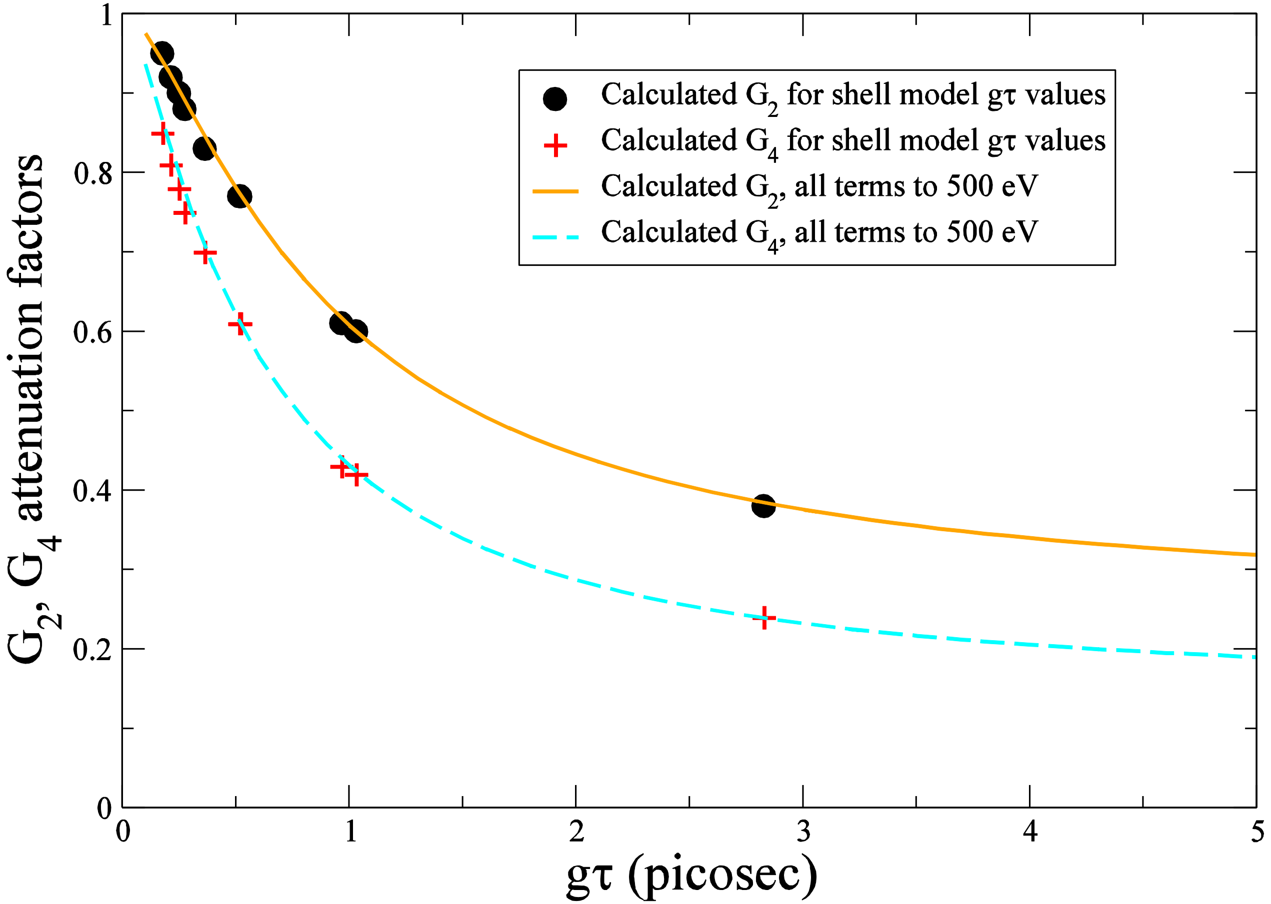
**Calculation gives direct access to detailed adjustment for different nuclear state spins.**




**Struggles for larger I, but $G_4$ term maintains useful sensitivity even for I = 10.**

# Range of accessible nuclear ps excited states

Calculated $G_k$-factors for shell model $g\tau$ estimates in $^{129}Sb$



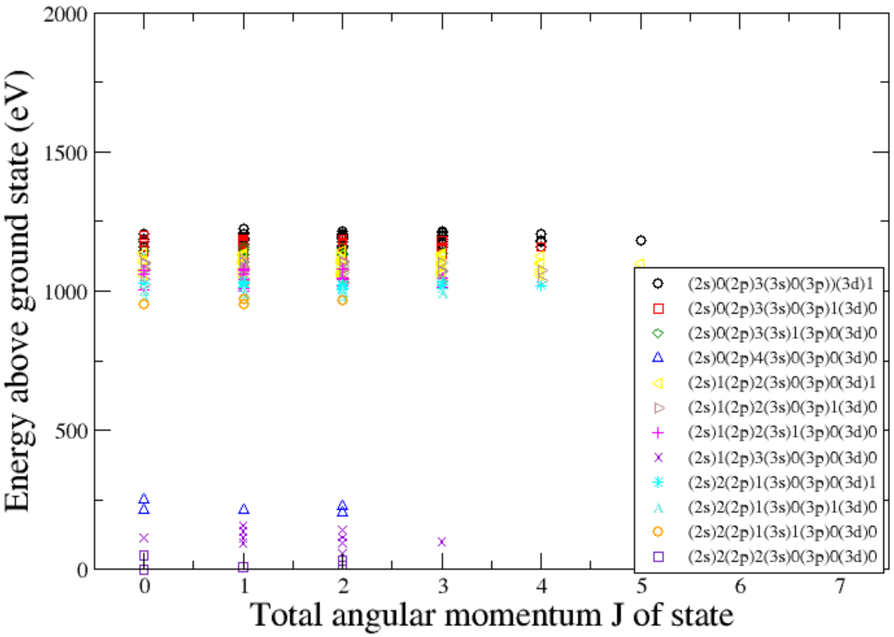

**The sensitive range of $G_2$ and $G_4$ is sufficient to cover predicted $g\tau$ values for many nuclear excited states.**

**[$G_2$, $G_4$ plots not adjusted for different nuclear spin values.]**

# Beyond the $(2J + 1)$ weighting model

# Beyond the (2J + 1) weighting model.

Plot of state energies vs J for Fe 6 electron configurations




**180 MeV Fe ions have few electrons in the n = 2 shell.**

**Excitation to n = 3 costs ~ 1100 eV.**

**Few states for configurations without excitation to n=3.**

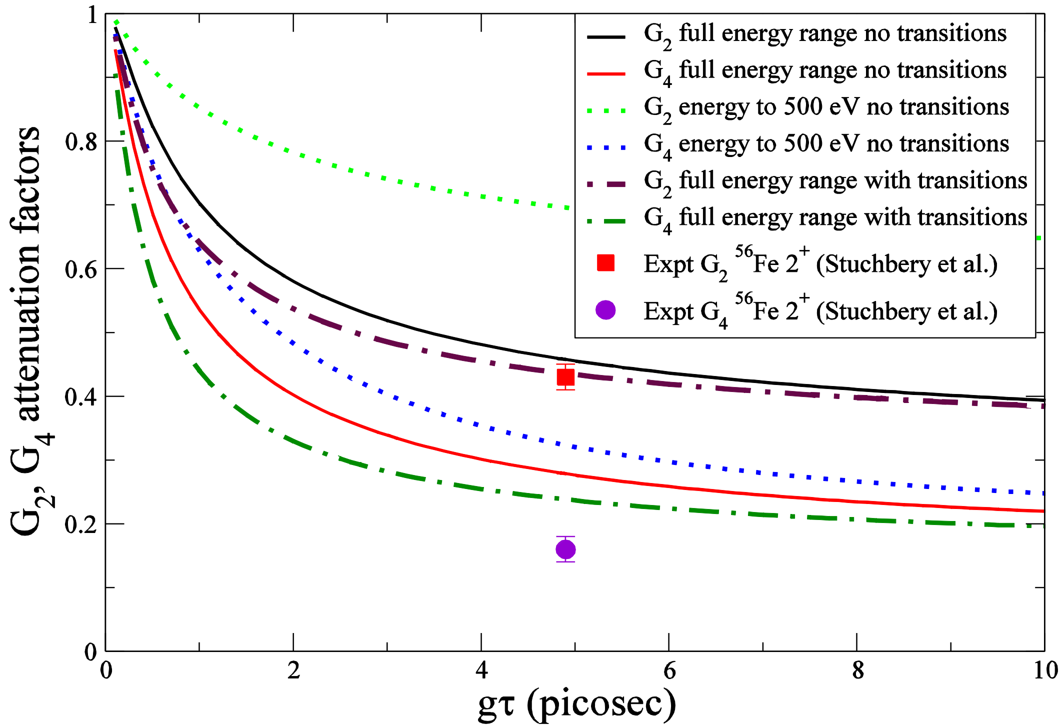
**Large energy gap.**

**Grasp2K calculation gives state lifetime as well as energy and interaction strength. Thus an electronic state ‘decay scheme’ can be constructed, with population fed down to lower states through decay.**

**This has been recently implemented by Per Jonsson – a physically more realistic model.**

**Such detail not previously available although early experiments reported fits improved if weights were free of (2J = 1) restriction.**

# Modelling Fe 5 electron ions with and without decay




Full energy range to > 1000 eV   full lines   unrealistic: many lifetimes < 1 ps

Energy to 500 eV: no transitions   dotted lines   poor agreement

Full energy range with transitions   dot-dash lines   better agreement

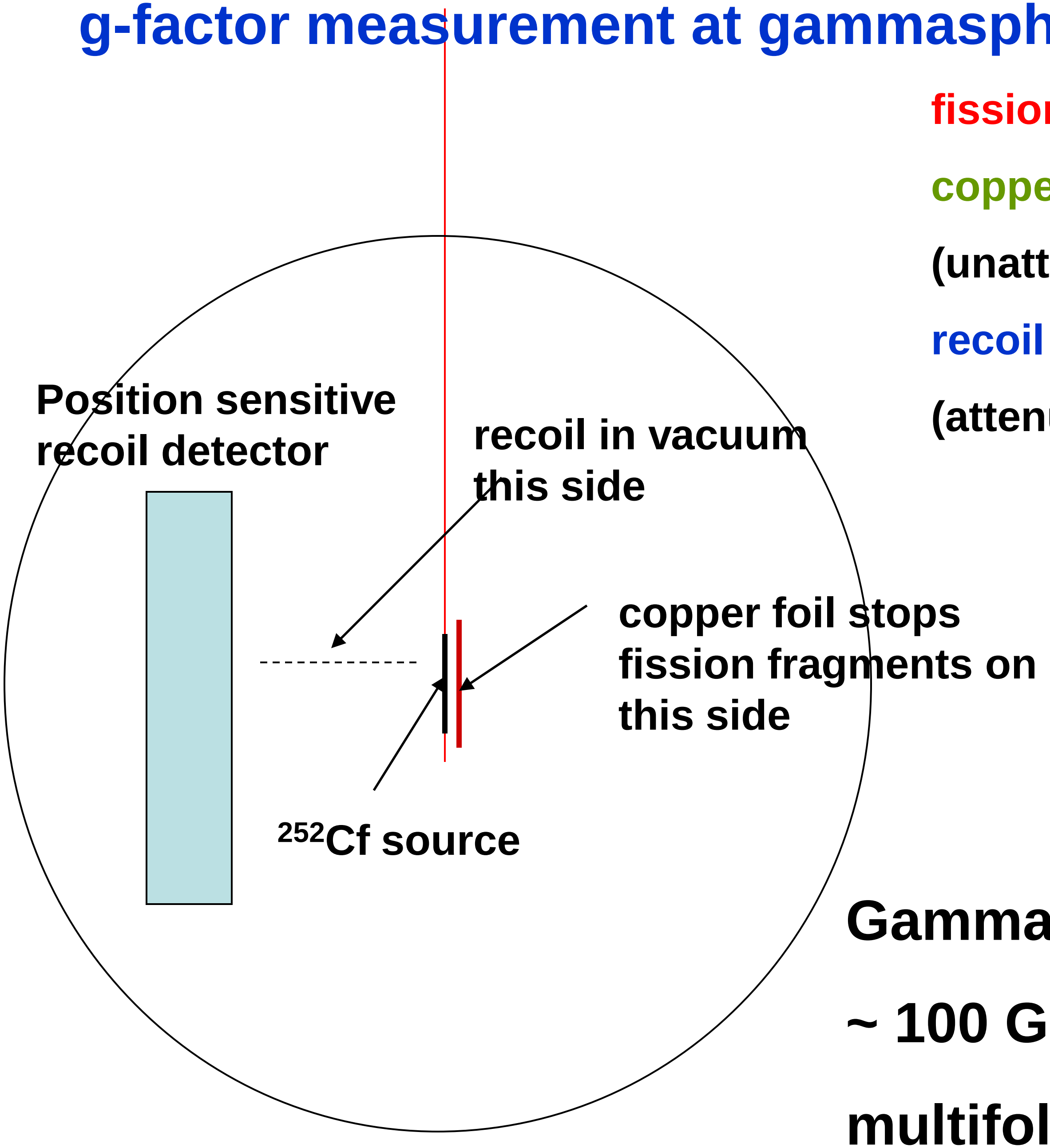
## Sources of aligned nuclei states

**In addition to Coulomb excitation, many other nuclear reactions give rise to aligned spin systems:**

**Deep inelastic scattering**

**Fission**

# g-factor measurement at gammasphere: ps states




fission recoils stopped in

copper foil on one side

(unattenuated distribution)

recoil in vacuum on other side

(attenuated distribution)

**Gammasphere**

**~ 100 Ge detectors: record**

**multifold coincidences**

**Given successful calibration,**
**Recoil-in-Vacuum**
**offers opportunities for g-factor**
**measurement for a wide range of nuclear states**
**with lifetimes in the ps range**
**produced by several nuclear reaction**
**and decay methods.**

**Thank you**