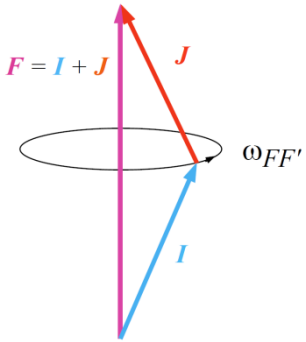
Australian National University

Gyromagnetic ratios in stable and neutron-rich semi-magic nuclei by the recoil in vacuum method



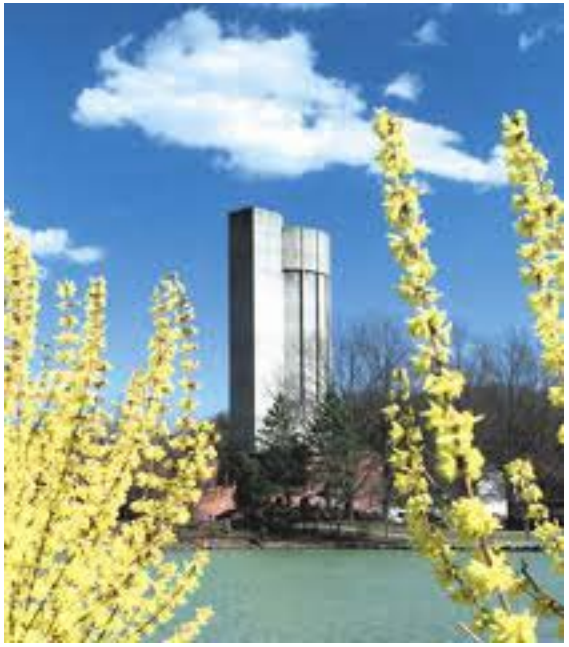
Holifield Radioactive Ion Beam Facility
Oak Ridge National Laboratory

A.E. Stuchbery, J.M. Allmond, A. Galindo-Uribarri, E. Padilla-Rodal, D.C. Radford, J.C. Batchelder, J.R. Beene, N. Benczer-Koller, C.R. Bingham, M.E. Howard, G.J. Kumbartzki, J.F. Liang, B. Manning, S.D. Pain, N.J. Stone, R.L. Varner, C.-H. Yu

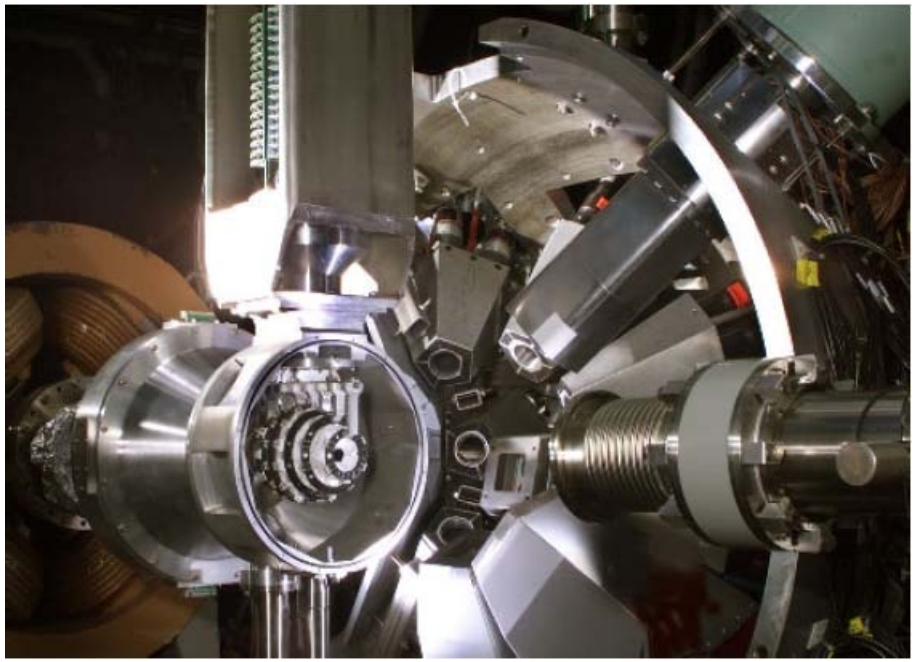
Recoil in Vacuum @ HRIBF

- ^{134}Te
- $^{112\text{-}126}$Sn

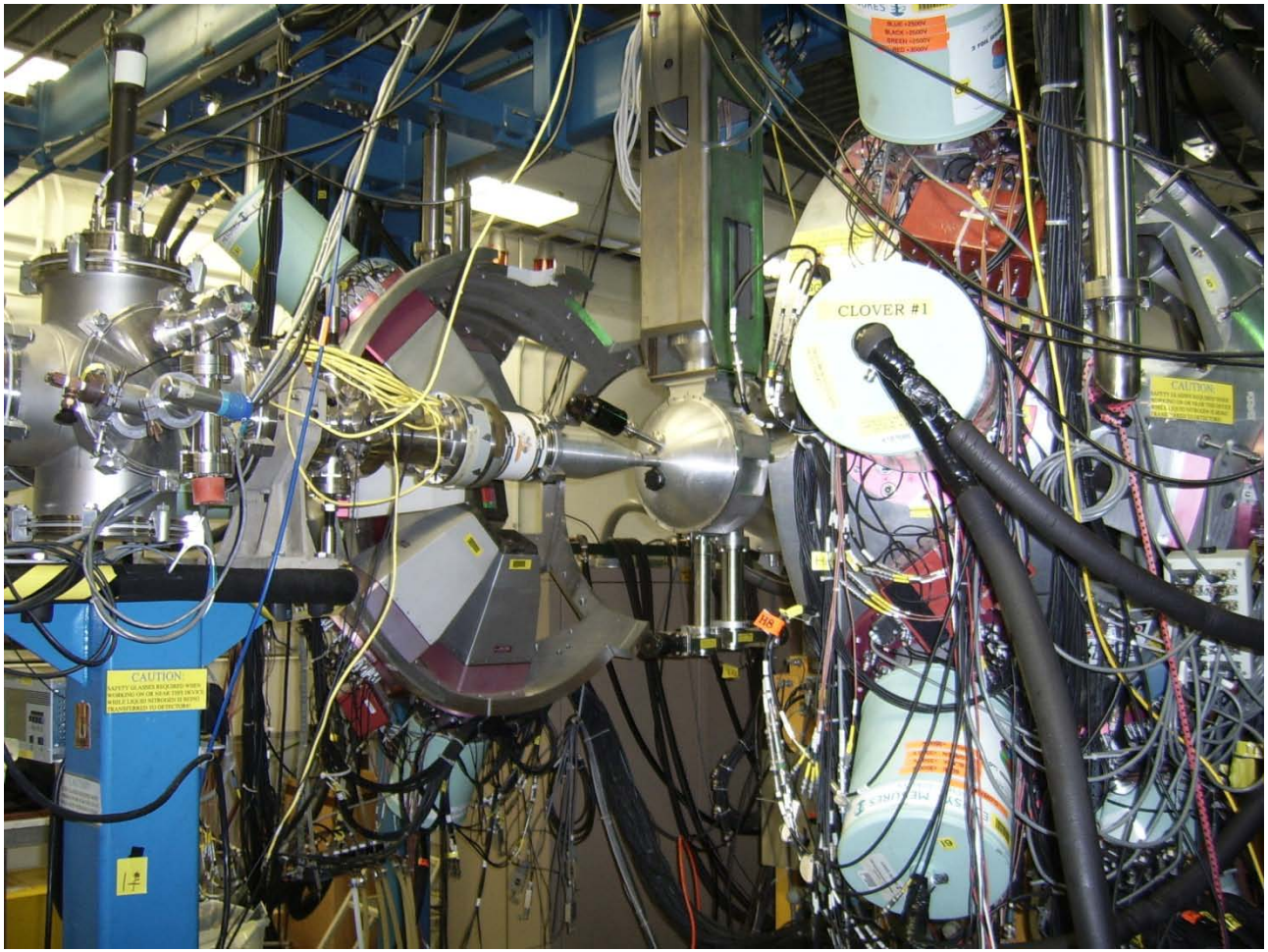
Holifield Radioactive Ion Beam Facility



Clarion + Hyball Arrays

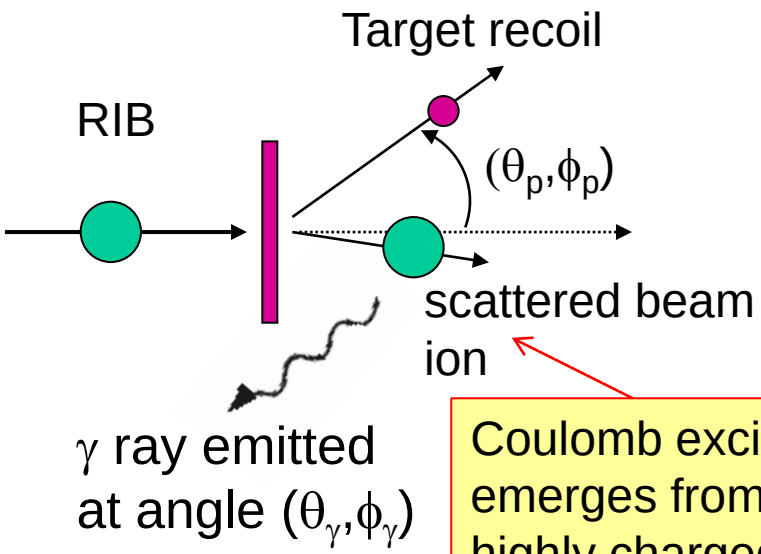


CLARION + HyBall



^{134}Te RIV g-factor measurement February 2012

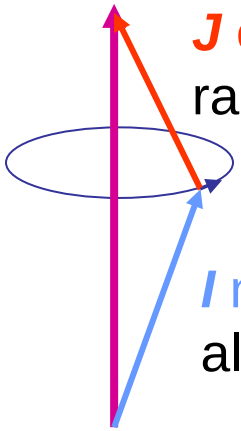
RIV *g*-factor measurements: rationale



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

Coulomb excited beam emerges from target as highly charged ion

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



J electron spin randomly oriented

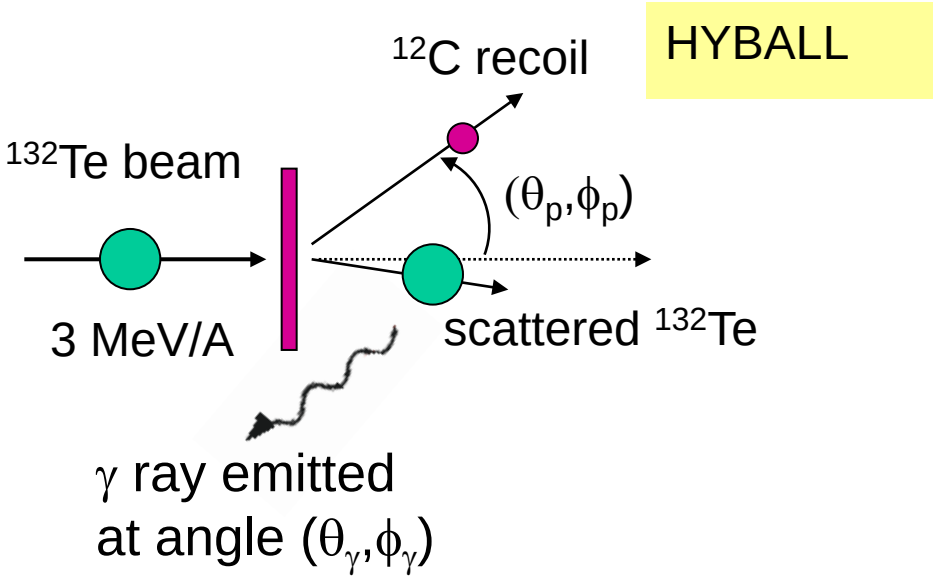
$\omega_{FF'} \propto |g|$

I nuclear spin aligned by reaction

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

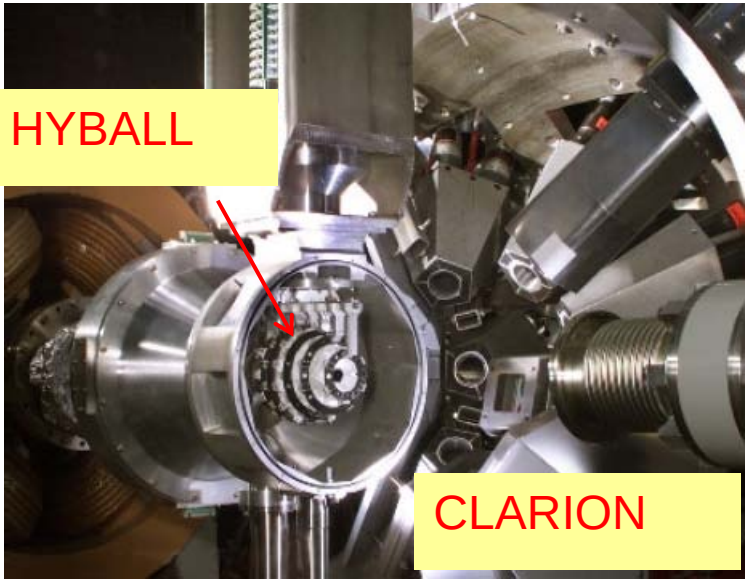
$$W(\theta_p,\theta_\gamma) = \sum_{k,q} \sqrt{2k+1}\,\rho_{kq}(\theta_p) G_k F_k Q_k D^{k*}_{q0}(\phi_\gamma - \phi_p, \theta_\gamma, 0)$$

Angles in the arrays

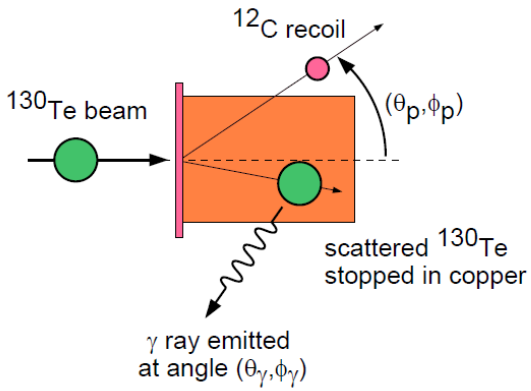


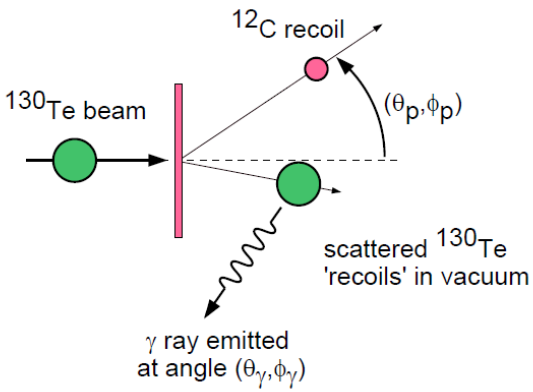
HYBALL

CLARION



Azimuthal angular correlations

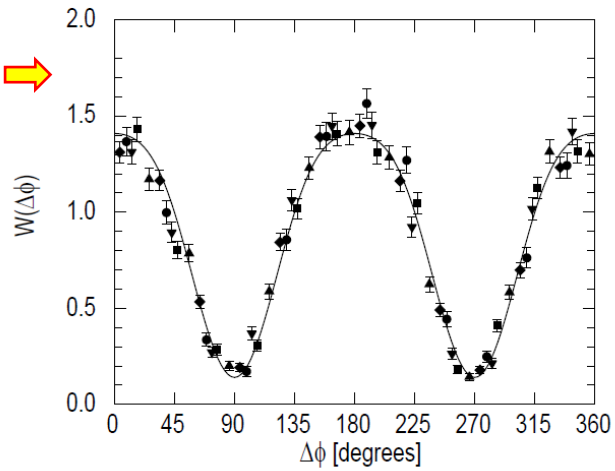


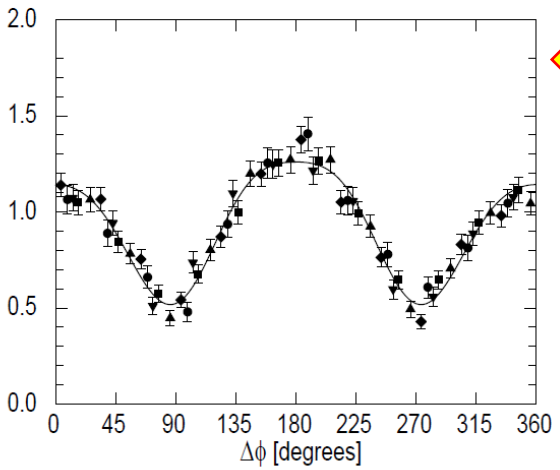


unperturbed

$G_k = 1$

(k = 2,4)

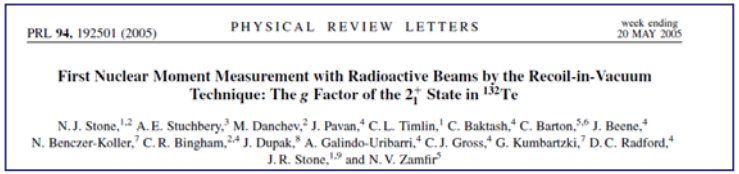




perturbed

$G_k < 1$

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

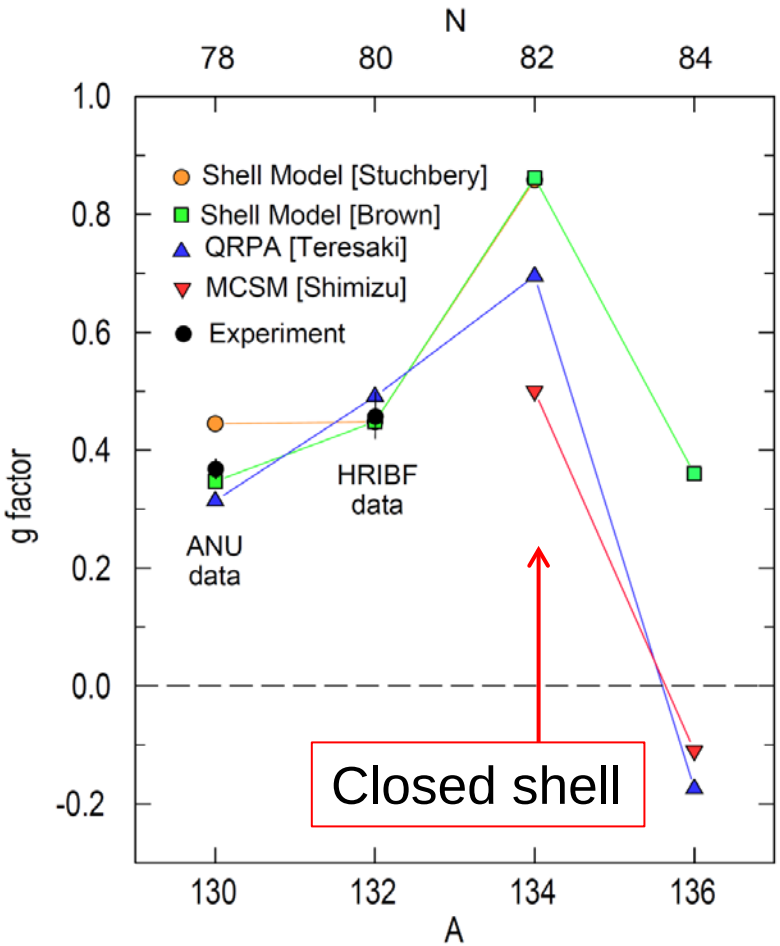

PRL 94, 192501 (2005) PHYSICAL REVIEW LETTERS week ending 20 MAY 2005

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

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

Data from PRL 94, 192501 (2005)

g(2+) predictions in Te isotopes



Conflicting theoretical predictions for ^{134,136}Te

Differences stem from:

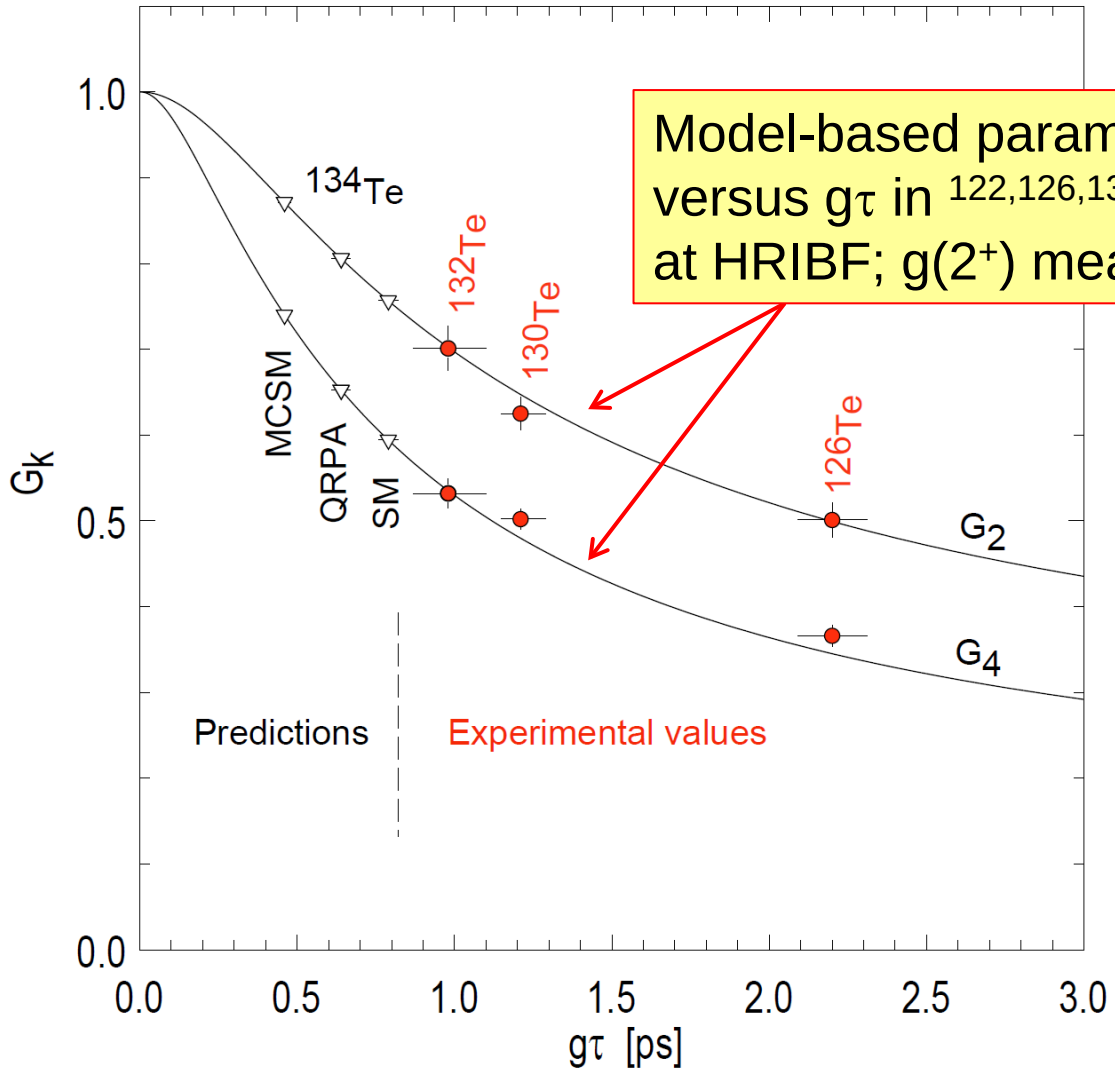
- the wave function
  (→ proton-neutron interactions)

- effective M1 operator
  (→ core polarization and meson exchange; tensor term and nucleon g factors: g_p, g_l and g_s)

[SM] G. Jakob et al. PRC 65, 024316 (2002);
[SM] B. A. Brown et al., PRC 71, 044317 (2005)
[QRPA] J. Terasaki, et al., PRC 66, 054313 (2002) ;
[MCSM] N. Shimizu et al., PRC 70, 054313 (2004).

Attenuation coefficient G_k to g factor

Vacuum attenuation coefficient



Model-based parametrization of G_k versus gτ in ^{122,126,130}Te. (G_k measured at HRIBF; g(2^+) measured at ANU)

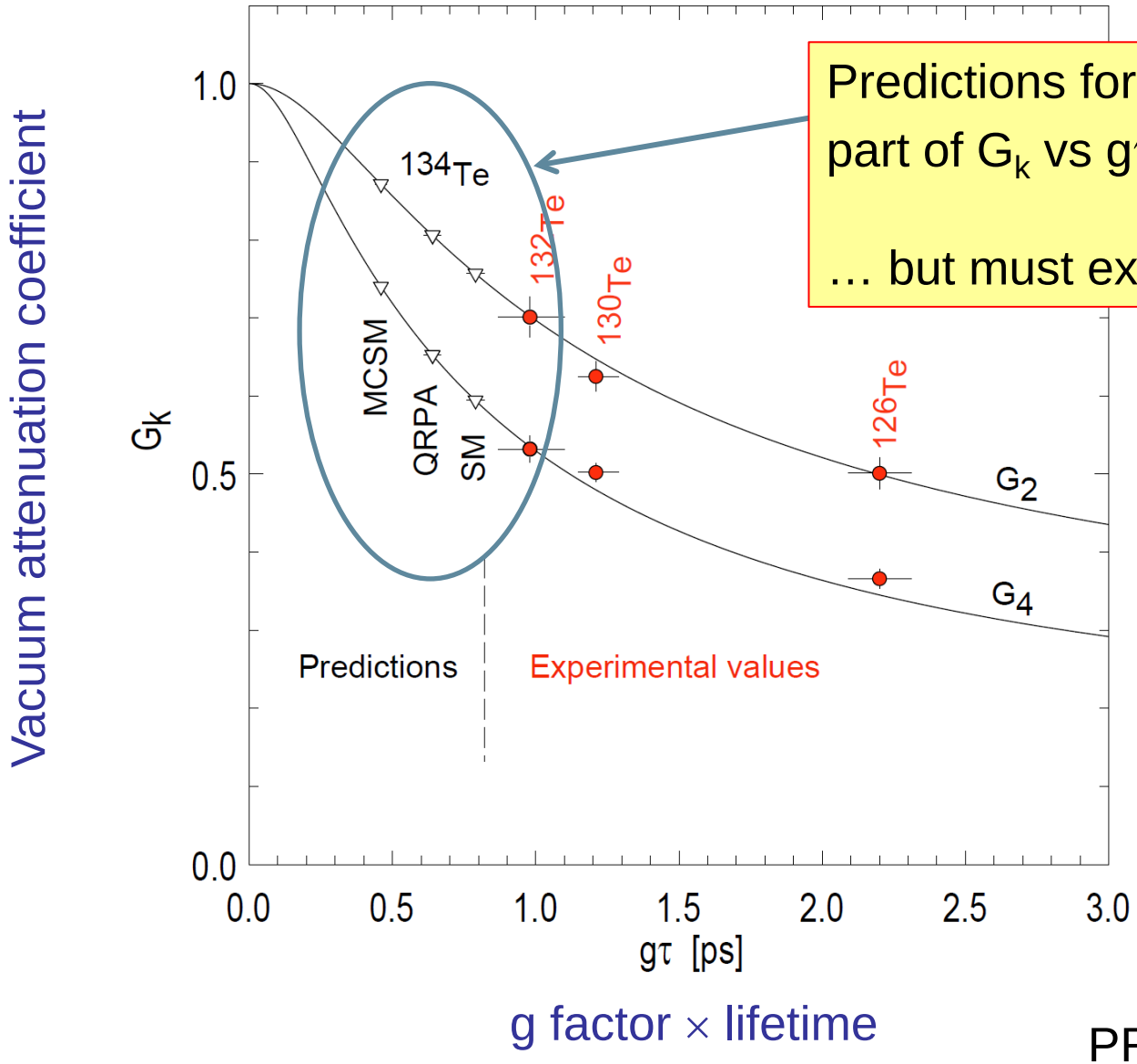
g factor × lifetime

PRC **76**, 034307 (2007)

Attenuation coefficient G_k to g factor

Predictions for ^{134}Te in sensitive part of G_k vs $g\tau$ curve

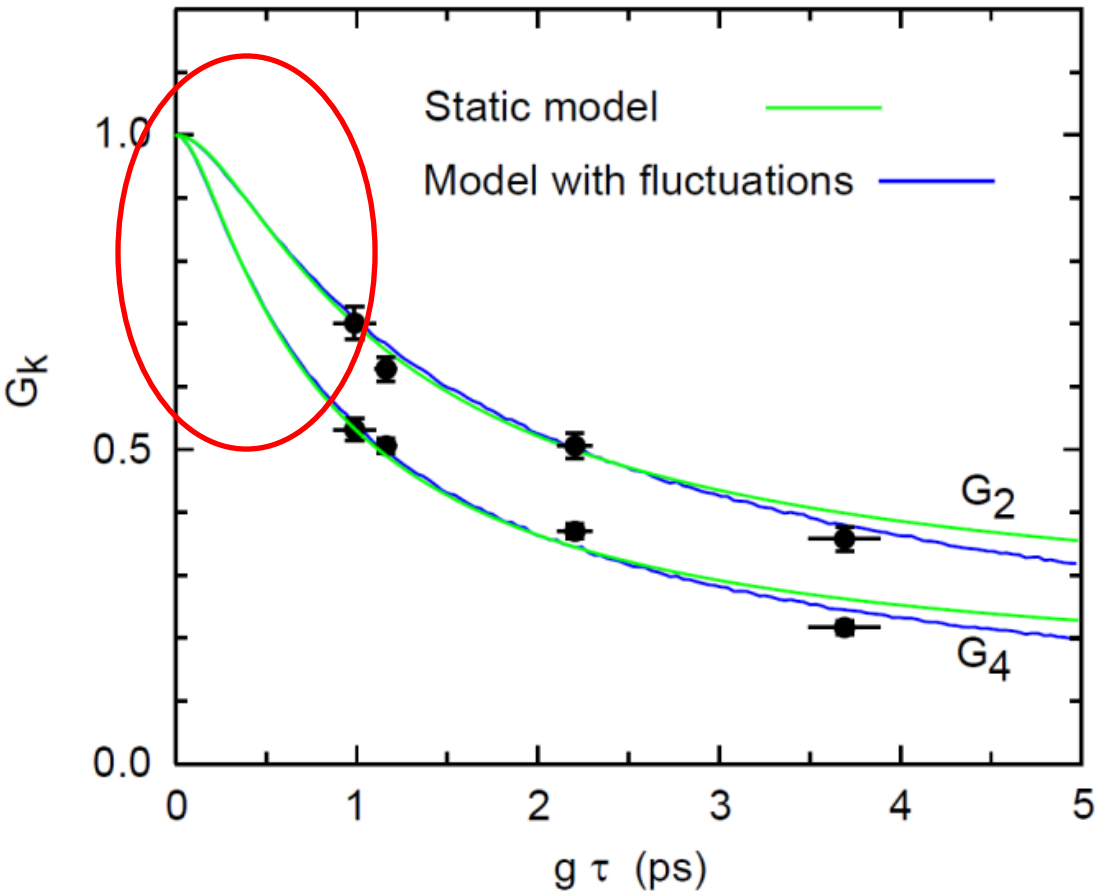
… but must extrapolate



PRC **76**, 034307 (2007)

Confidence in RIV calibration

1. Extensive characterization and modeling
   - see Stuchbery and Stone, PRC 76, 034307 (2007)



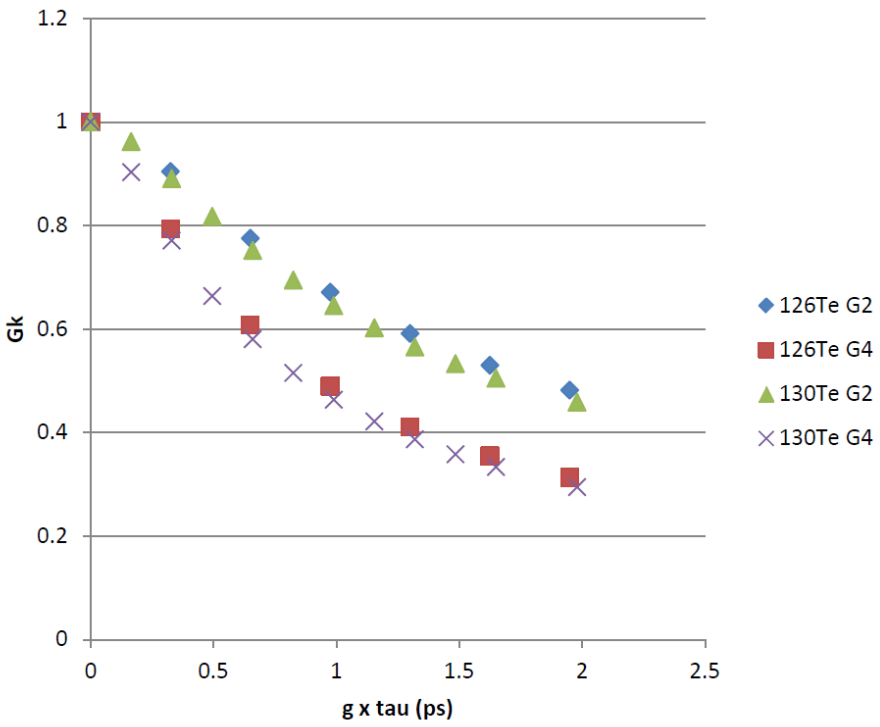
Robust extrapolation in region of interest

Confidence in RIV calibration

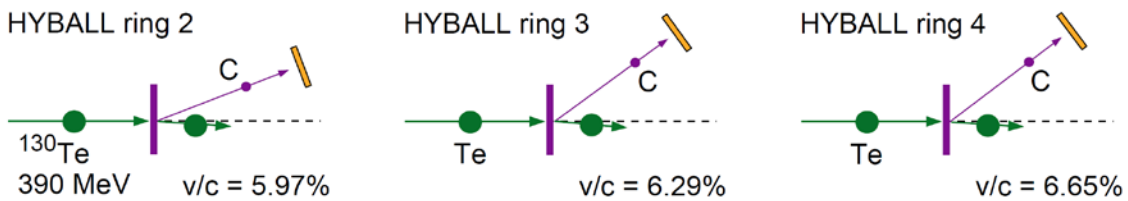
2. Ab Initio Atomic Model - see poster by Xinfeng Chen et al.

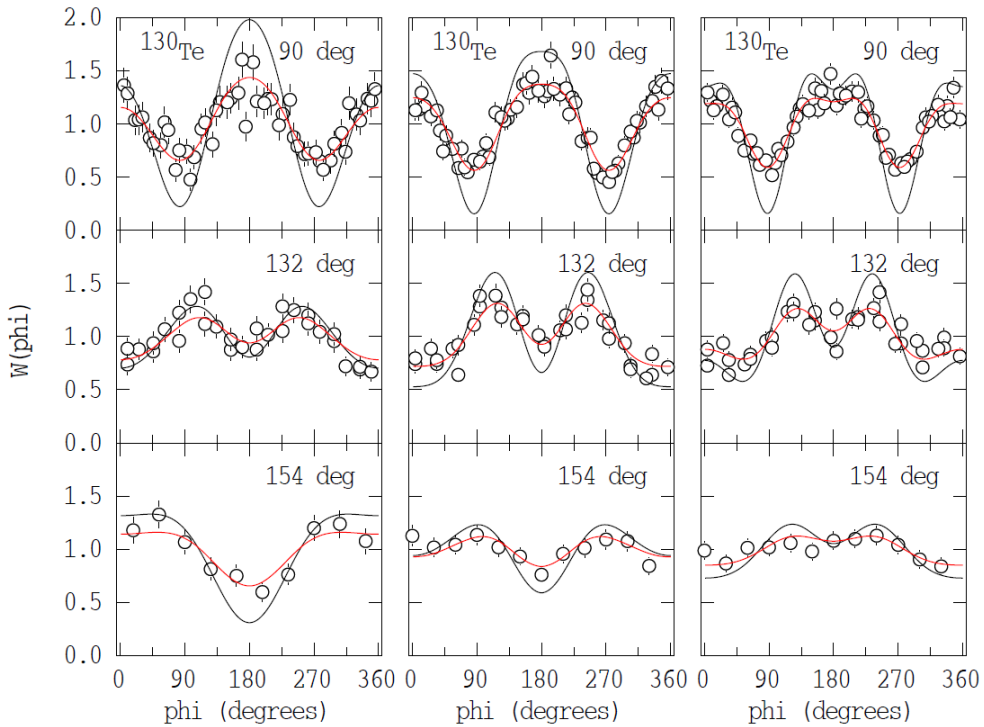
- Calculations of hyperfine fields and atomic lifetimes with GRASP2K (Multiconfiguration Dirac Fock code)

- Monte Carlo evaluation of the effect of atomic decays



^{130}Te data (Feb 2012 run)





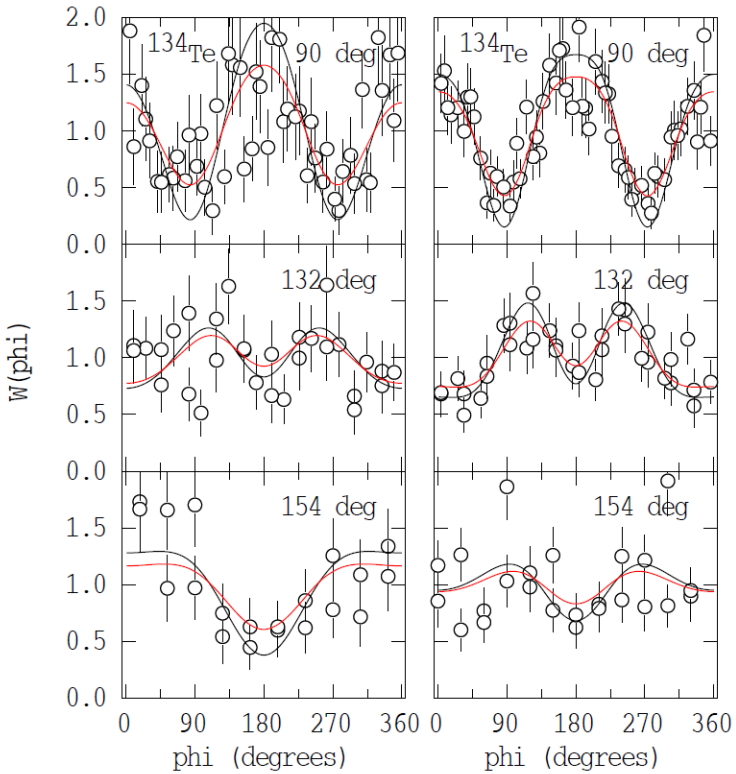
$\chi^2_\nu = 1.1$

Stable beam

Sanity check & calibration

Agrees with previous measurements

^{134}Te data & extracted g factor

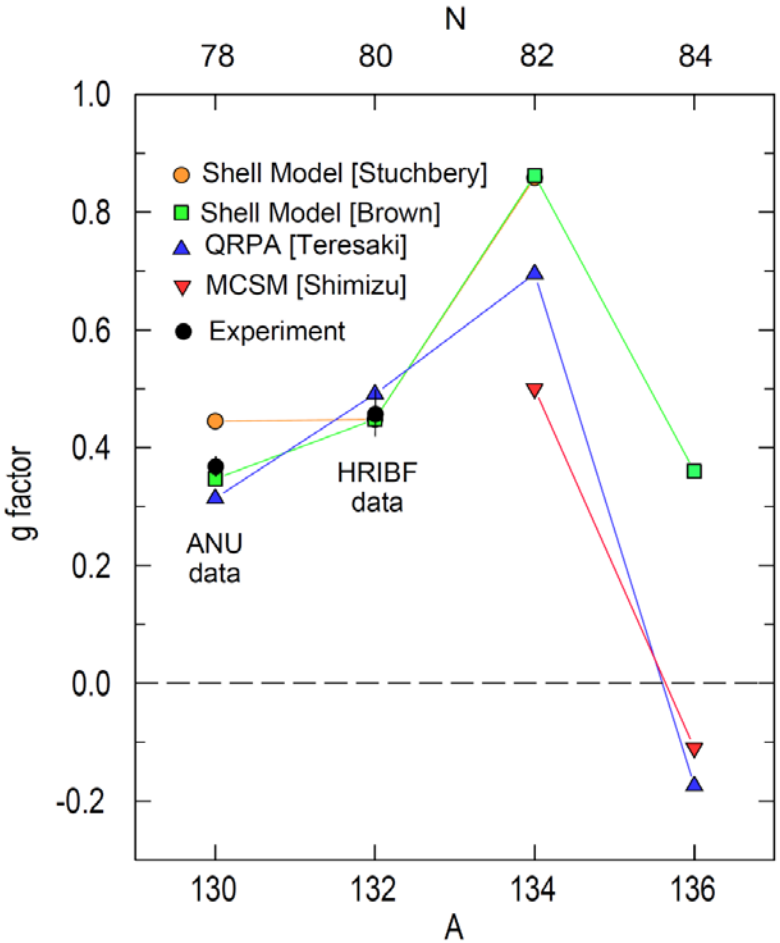


Radioactive beam

~ 3 days @ 10^7 pps

Preliminary result from Hyball rings 2 and 3 (χ^2_ν = 1.02):

^{134}Te comparison with theory



Preliminary result

Agrees best with QRPA,

BUT…

^{134}Te & corrections to M1 operator

- expect mainly $\pi(g_{7/2})^2$ configuration
- shell model wavefunction: 95.8% $\pi(g_{7/2})^2$
- sensitivity g factor to M1 operator (core polarization and meson exchange)

$$\mu = (g_l + \delta g_l)l + (g_s + \delta g_s)s + g_p[Y_2, s]$$

orbit	Schmidt	δg_l=0; δg_s=-1.68	Empirical (δg_l=0.13; δg_s=-1.55)
$d_{5/2}$	+1.917	+1.582	+1.540
$g_{7/2}$	+0.490	+0.677	+0.803

QRPA & MCSM

Shell Model PRC 65, 024316

cf. Brown et al PRC 71, 044317
δg_l~0.1; δg_s~-2; g_p~1.6
(orbit dependent)

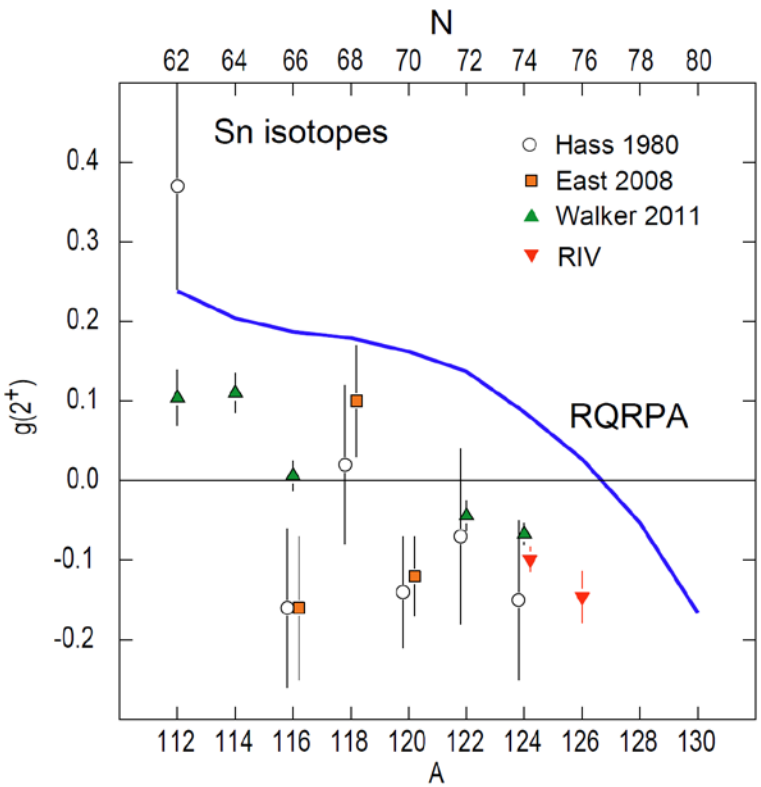
^{131}Sb $7/2^+$ g.s. has g=0.826(3)

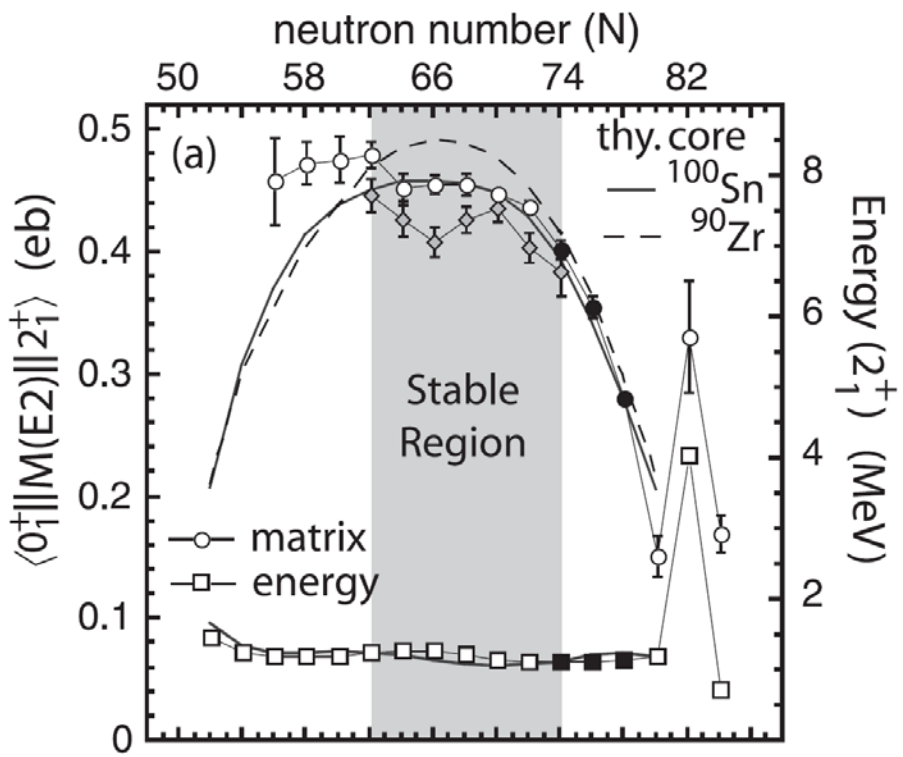
^{134}Te summary

1. Analysis to be completed
2. Have a result that tests theory
3. Corrections to the M1 operator are important, along with the wavefunction
4. RIV method works well for g(2^+) measurements on ~3 MeV/u radioactive beams of heavy nuclei

g(2⁺) and B(E2) in Sn isotopes

Status January 2012



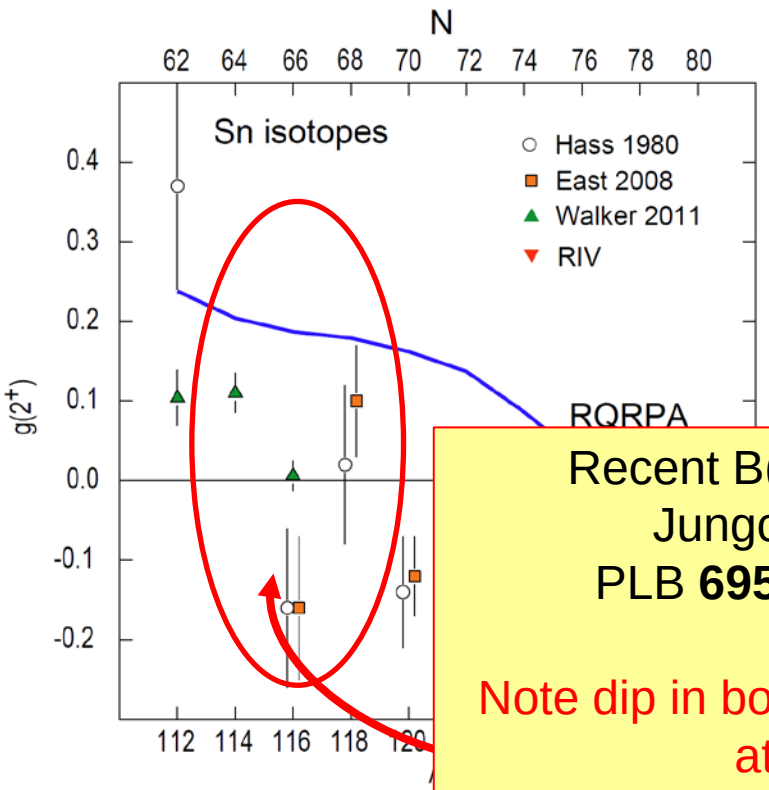


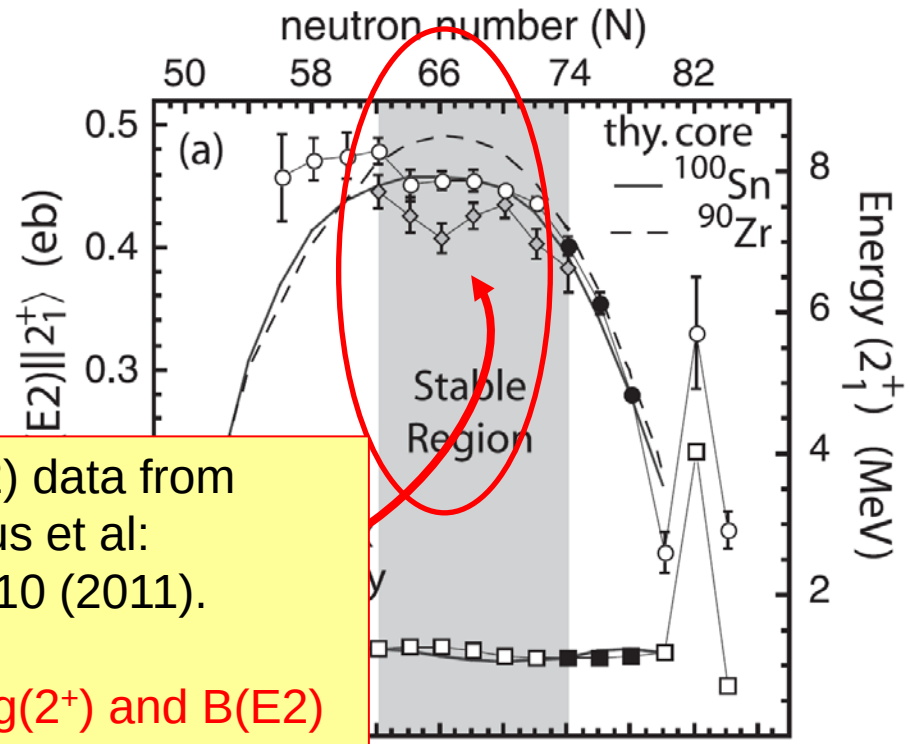
RQRPA: Ansari and Ring
PLB 649 , 128 (2007) .

From Allmond et al,
PRC C **84**, 061303(R) (2011)

g(2⁺) and B(E2) in Sn isotopes

Status January 2012





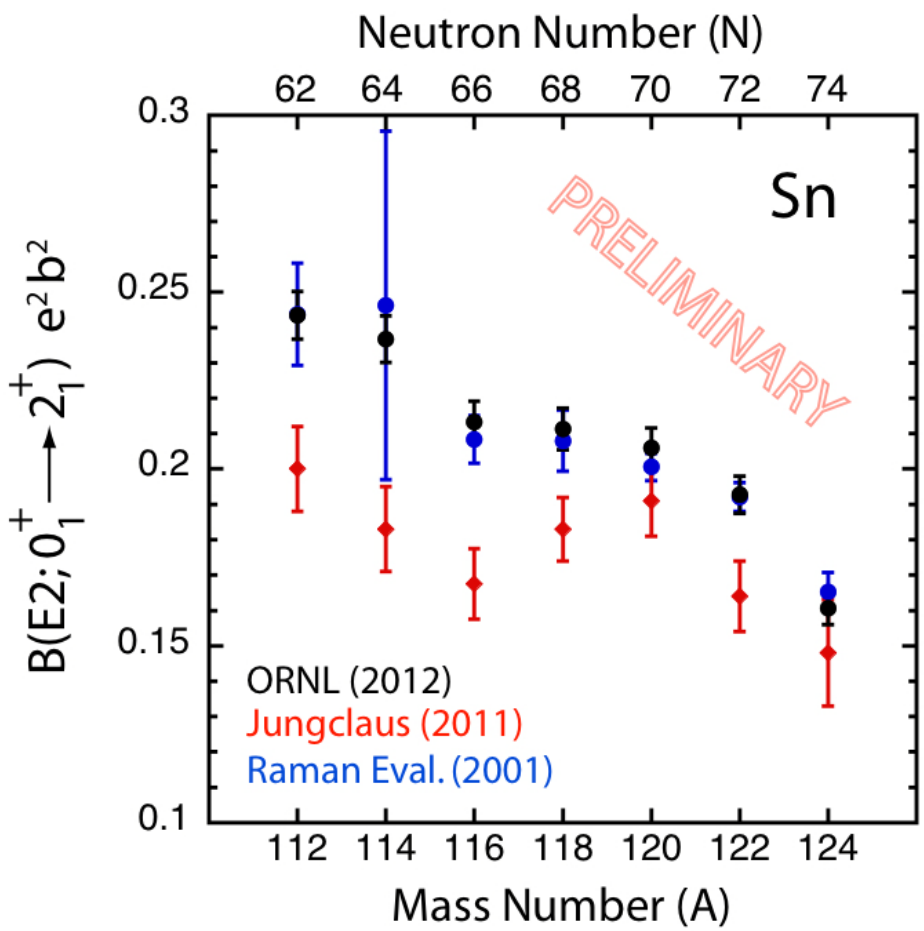
Recent B(E2) data from Jungclaus et al:
PLB **695**, 110 (2011).

Note dip in both g(2⁺) and B(E2) at N=66

RQRPA: Ansari
PLB 649 , 128 (2007) .

mond et al,
PRC C **84**, 061303(R) (2011)

New B(E2) values in Sn isotopes



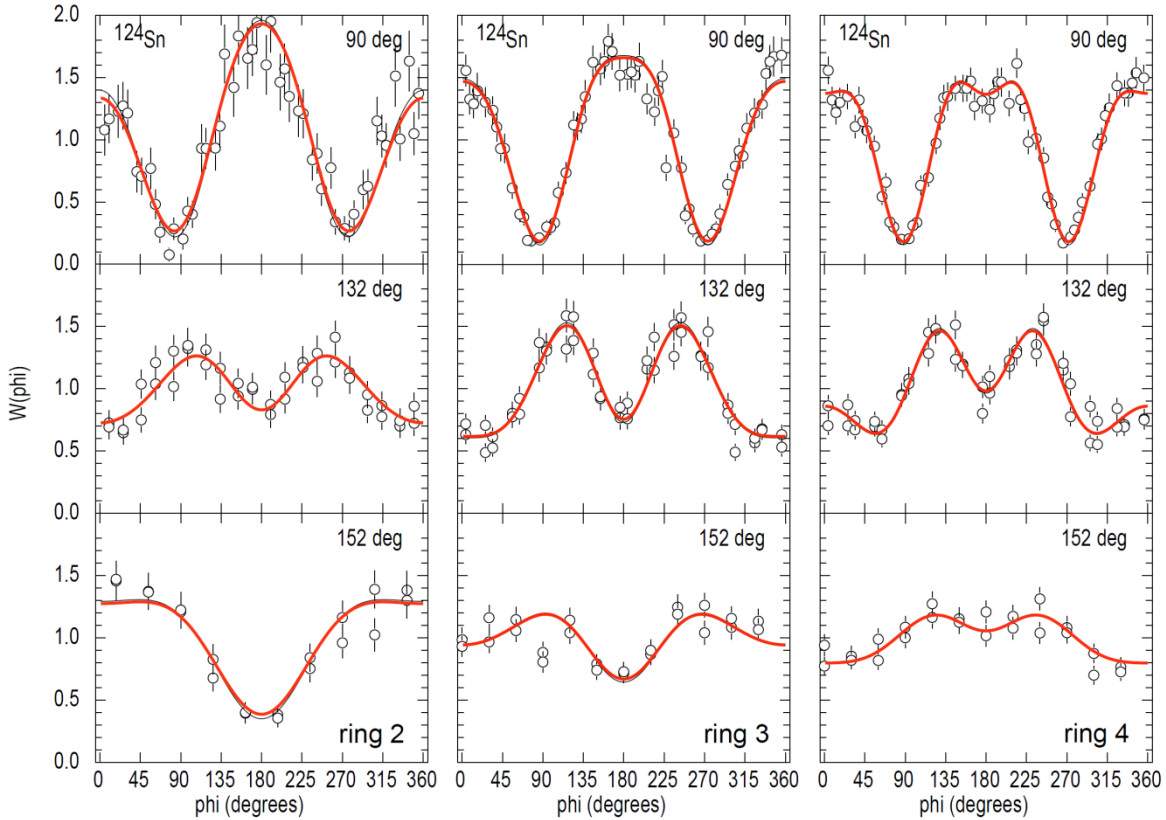
- Improved precision
- Confirms ENSDF
- Drop in B(E2) at N=66
- No dip at N=66

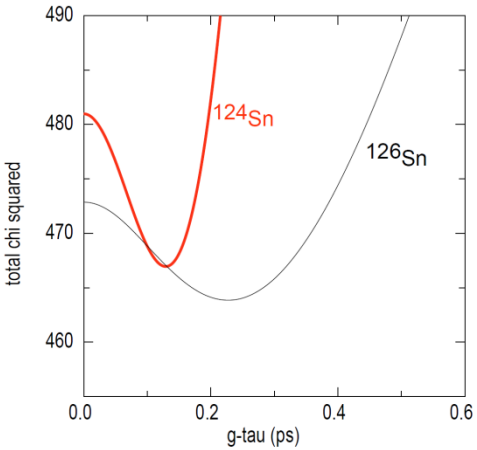
What about g factors?

From Mitch Allmond et al.

^{124}Sn angular correlations

3 MeV/u ^{124}Sn on ^{12}C



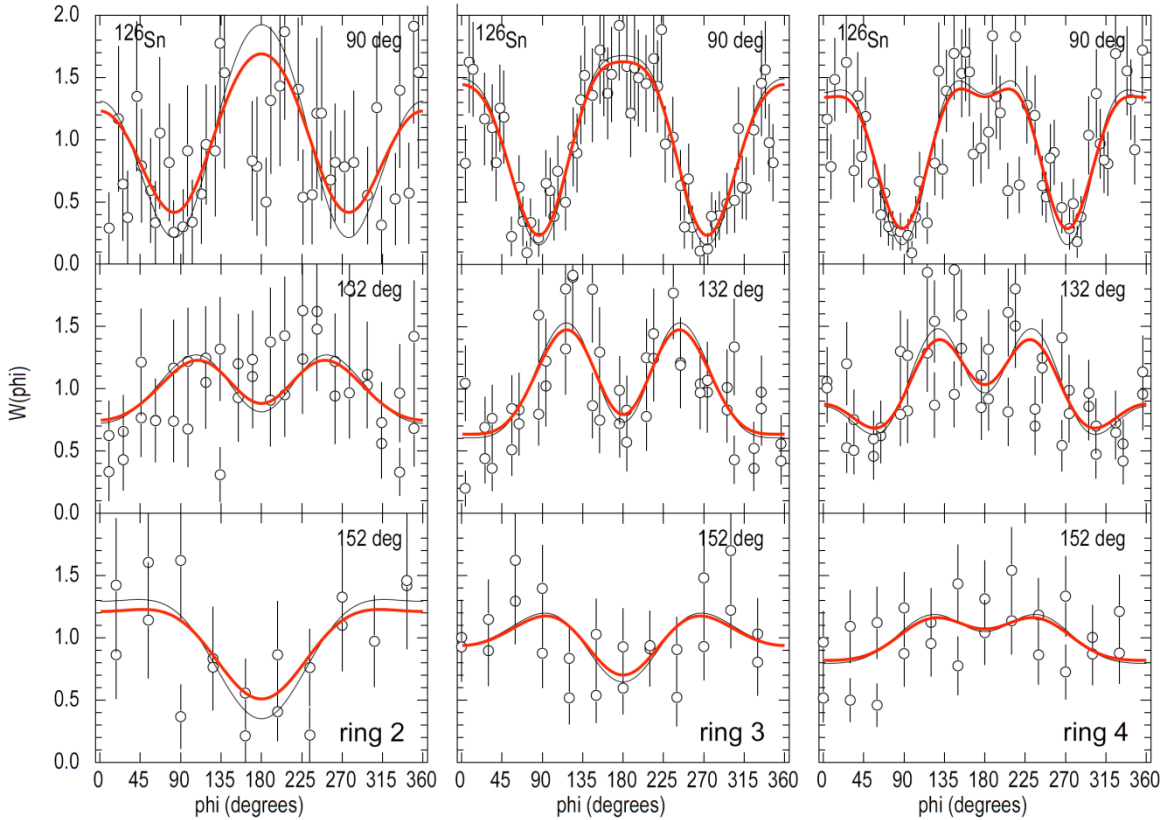


Stable beam

See J.M. Allmond et al. PRC C **84**, 061303(R) (2011)

^{126}Sn angular correlations

3 MeV/u ^{126}Sn on ^{12}C



Radioactive beam

See J.M. Allmond et al. PRC C **84**, 061303(R) (2011)

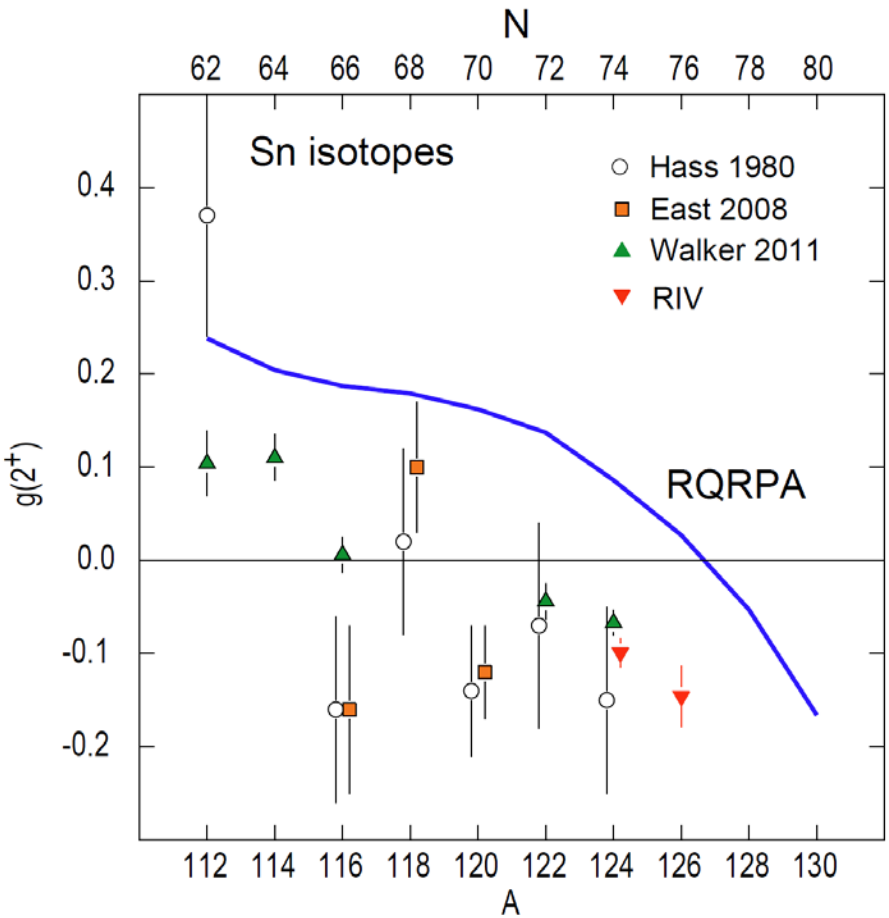
RIV g factors in Sn isotopes

PRELIMINARY

1. Good agreement with previous measurements (Transient Field)
2. Better precision for radioactive beam ^{126}Sn than transient field (Kumbartzki et al)
3. ^{112,114}Sn have $\tau \sim 0.5$ ps

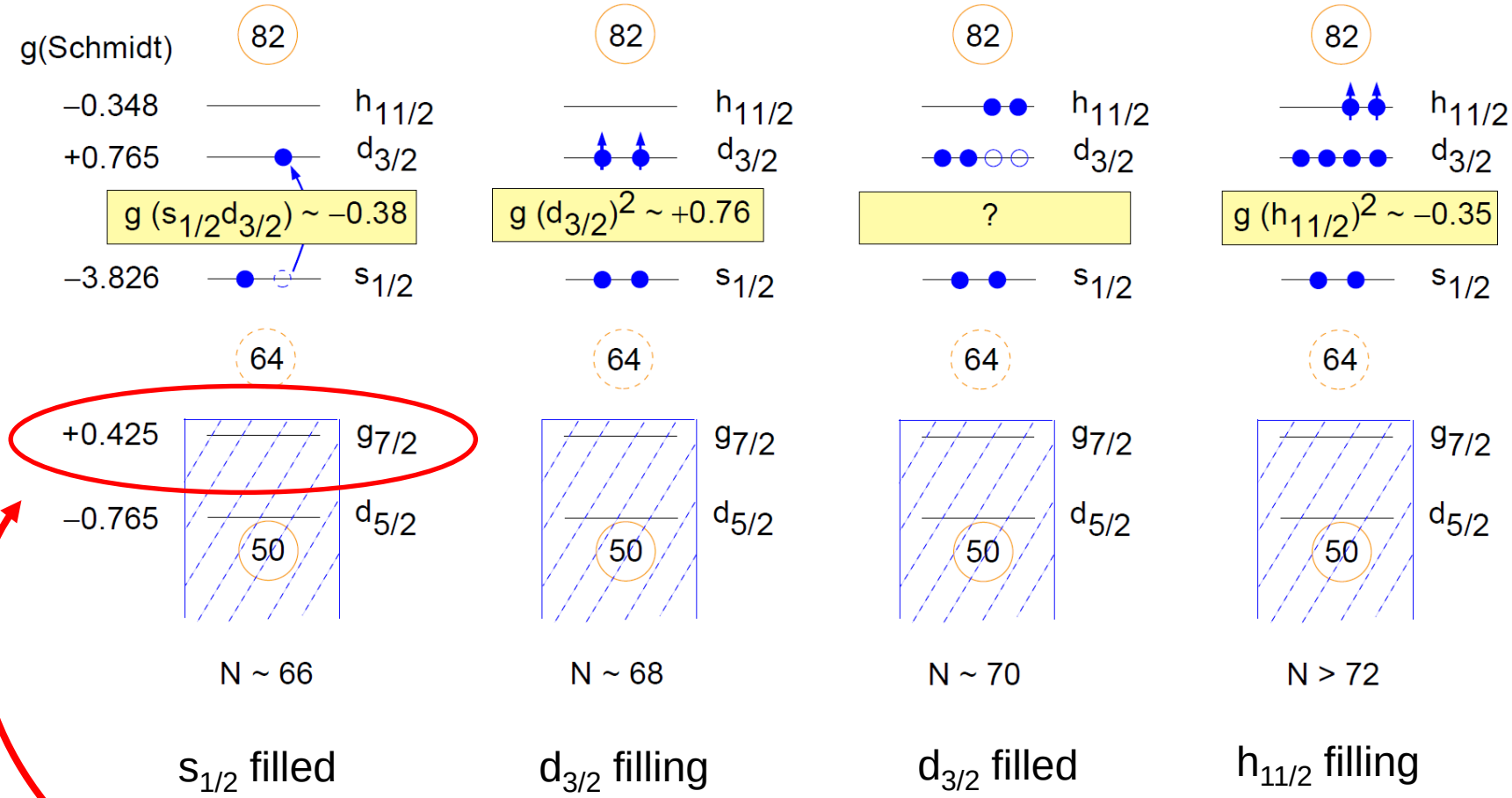
Amazing !

RIV g factors in Sn isotopes



1. $g(2^+) > 0$ for N =62,64
2. Like B(E2), $g(2^+)$ drops at N=66
3. $g(2^+) \sim 0$ for $66 \leq N \leq 72$
4. $g(2^+) < 0$ for $N > 74$
5. dip at N = 70??

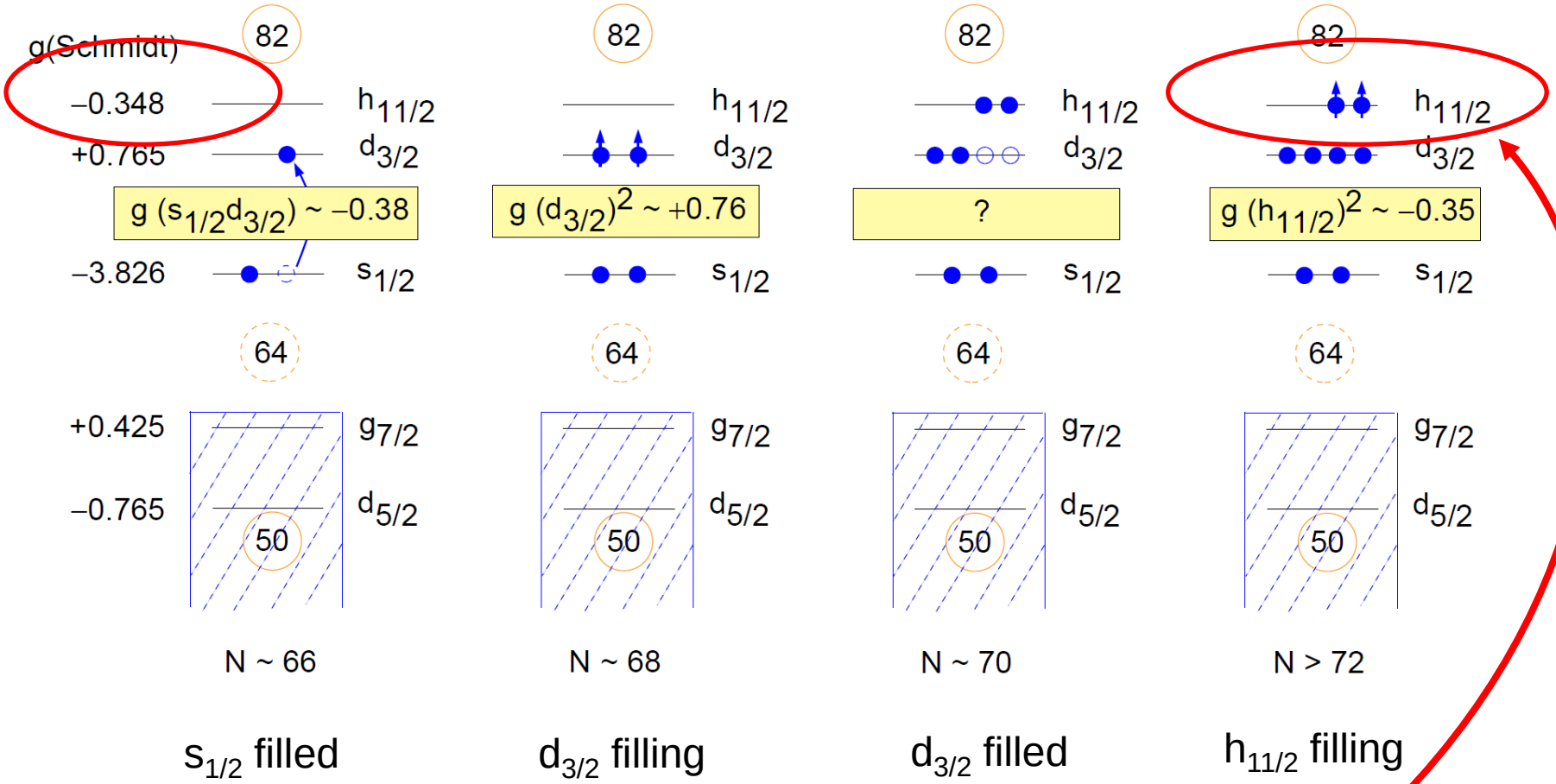
Configurations near Fermi surface



$s_{1/2}$ filled | $d_{3/2}$ filling | $d_{3/2}$ filled | $h_{11/2}$ filling

For N = 62, 64: $g_{7/2}$ neutron gives positive $g(2^+)$

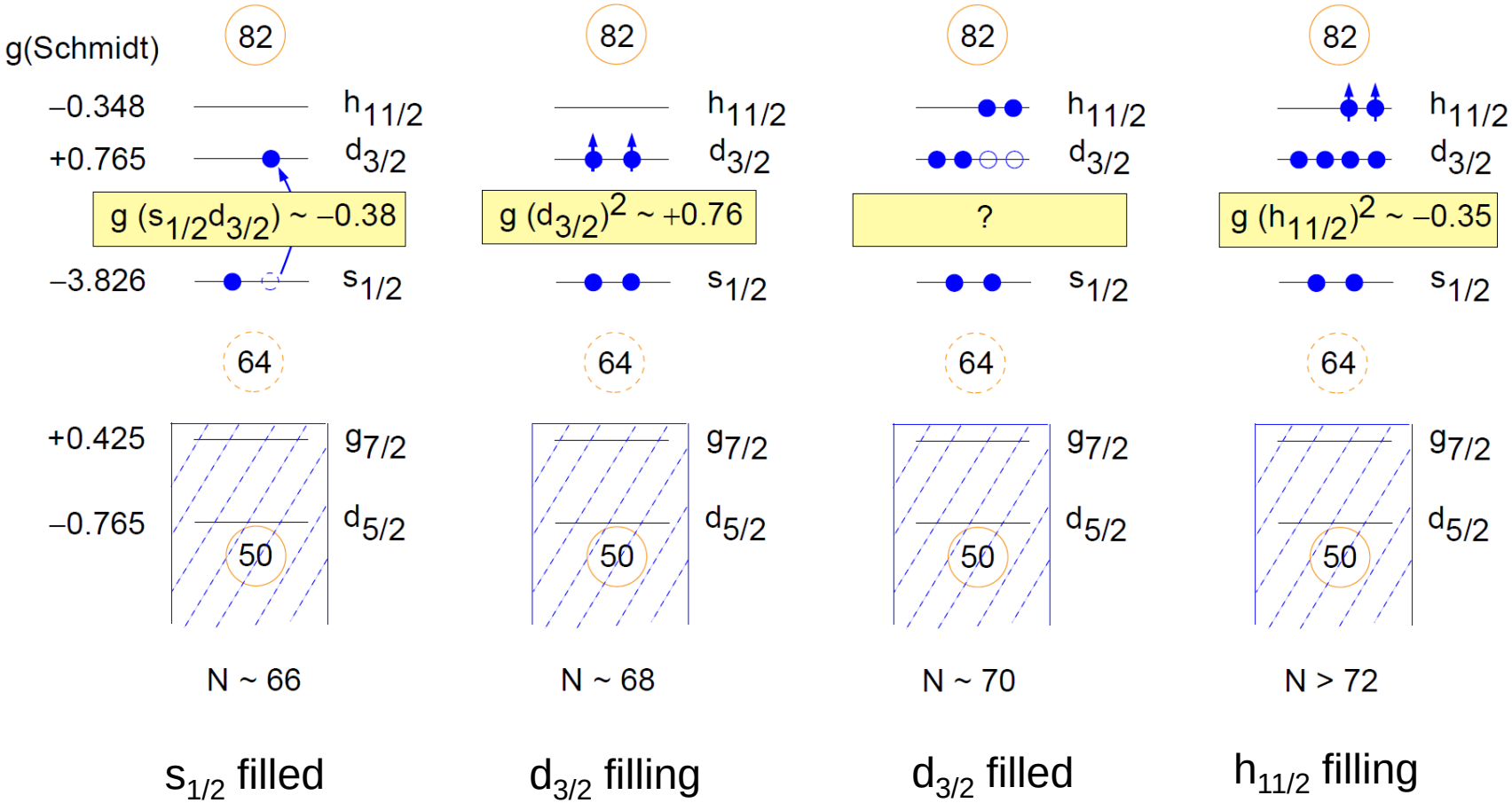
Configurations near Fermi surface



$s_{1/2}$ filled | $d_{3/2}$ filling | $d_{3/2}$ filled | $h_{11/2}$ filling

For N > 72: $h_{11/2}$ neutron gives negative $g(2^+)$

Configurations near Fermi surface



$s_{1/2}$ filled $d_{3/2}$ filling $d_{3/2}$ filled $h_{11/2}$ filling

For N = 66 -70 competing configurations give $g(2^+) \sim 0$

g factors in Sn isotopes: Summary

1. Trends in B(E2) and g factor reflect orbit occupation

2. $g(2^+)$ is very sensitive to fine details of the wavefunction for N=66-70

3. Need precise transient-field g-factor measurements on ^{118,120}Sn (stable)

4. Future RIB measurements toward ^{100}Sn? Feasibility demonstrated.

Future directions: Summary

RIV g factor measurements well proved for A~130 radioactive beams with 2^+ lifetimes of a few picoseconds

1. Time differential (plunger) measurements
   - Yale group (Volker Werner et al.) A~100 stable beams
   - Low-Z RIBs & H-like ions
     Method proposed :AES, Paul Mantica, Anna Wilson PRC 71, 047302
     Test @ Orsay in November: Georgi Georgiev, Deyan Yordinov, AES

2. Ab initio modeling & atomic effects in lower-Z ions
   - N.J. Stone et al Hyperfine Interact. 197, 29 (2010)
   - Xinfeng Chen – poster ** great progress**

3. Lower-Z semimagic nuclei:
   - Ni isotopes NSCL LOI, Paul Mantica and AES (200 MeV Ni+Ag $\Rightarrow$ v/c ~ 7.6% $\Rightarrow$ N-like ions & larger hyperfine fields than seen here)

4. g factors of s.p. levels via transfer reactions? ^{133}Sn, ^{135}Te, ^{137}Xe, ^{209}Pb
   - angular correlations – can we go beyond spin assignments to g factors?

A.E. Stuchbery, J.M. Allmond, A. Galindo Uribarri, E. Padilla-Rodal, D.C. Radford, J.C. Batchelder, J.R. Beene, N. Benczer-Koller, C.R. Bingham, M.E. Howard, G.J. Kumbartzki, J.F. Liang, B. Manning, S.D. Pain, N.J. Stone, R.L. Varner, C.-H. Yu