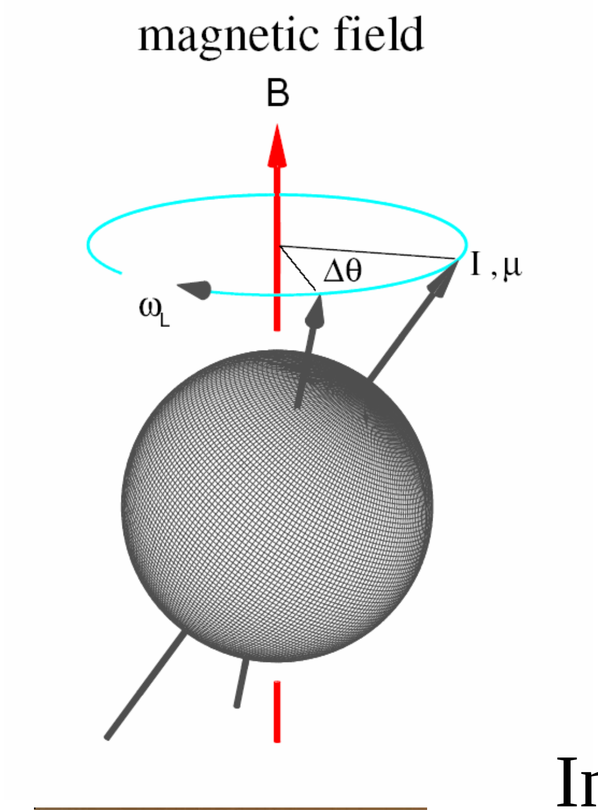
Recent developments in *g*-factor measurements on exotic nuclei and their relation to nuclear structure

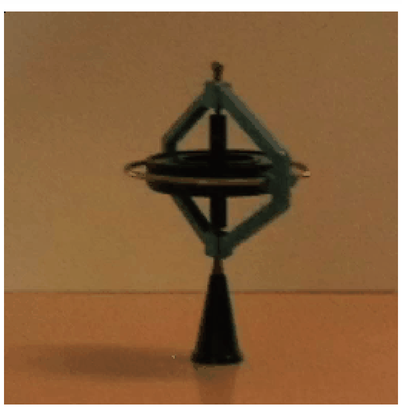
Andrew E Stuchbery

THE AUSTRALIAN NATIONAL UNIVERSITY

Department of Nuclear Physics, The Australian National University
Canberra, ACT 0200, Australia

Magnetic moment measurements: ps states





g factor / gyromagnetic ratio: $g = \mu / I$

$$\Delta\theta \sim - \; g \, (\mu_N / \hbar) \, B \, \Delta t$$

$\Delta\theta \sim$ few degrees

$B \sim 10^3$ Tesla $\Delta t \sim$ few ps

Need hyperfine fields

Internal fields in ferromagnets:

- Static IPAC
- Transient HVTF

Free ion in vacuum: RIV

Outline

- Fission fragments: A ~ 100 – 120 “IPAC”
  - are these neutron-rich nuclei ‘exotic’?
- Fast fragmentation: Z ~ 16 – 26 “HVTF”
  - shell closures in n-rich S, Ar, Fe
- Reaccelerated beams: ~ ^{132}Sn “RIV”
  - novel nuclear structure near ^{132}Sn

Measurements on fission fragments

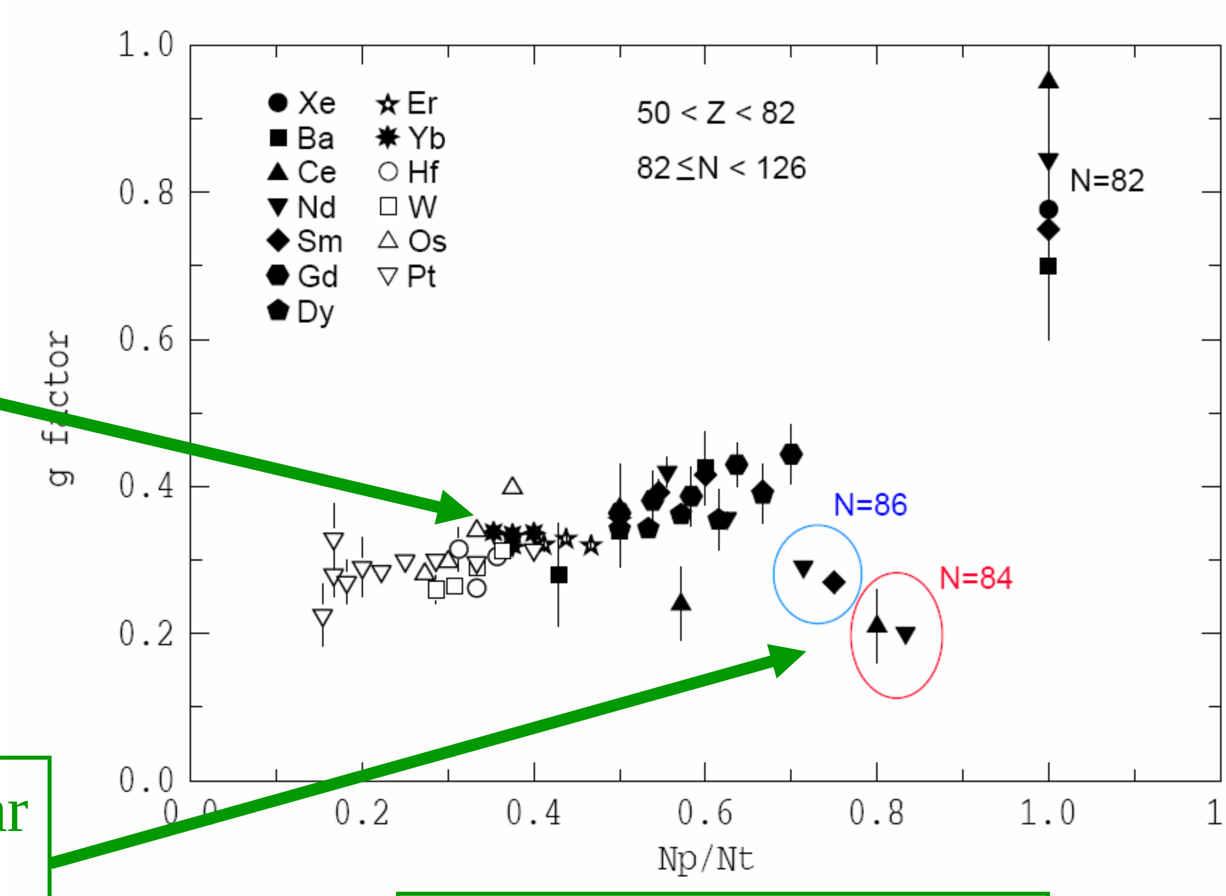
Show ‘Exotic’ behavior – or do they?

Rare earth region: 50 < Z < 82 ; 82 < N < 126

g(2^+) systematics

$$g \approx \frac{L_p}{L_p + L_n}$$

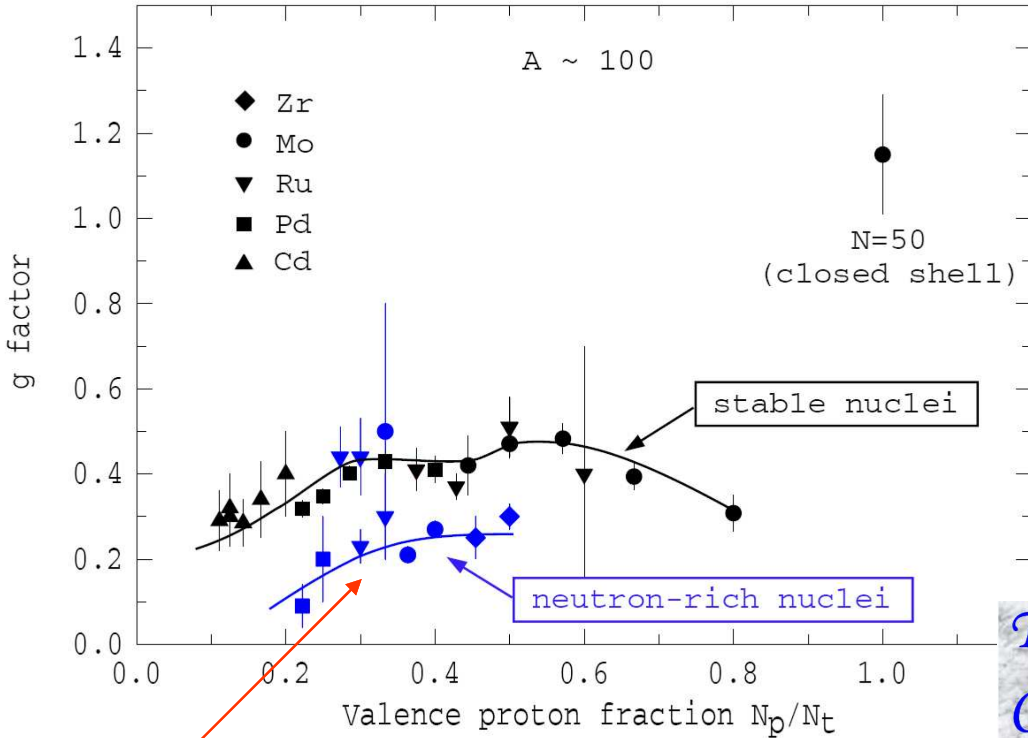
g factors well correlated with $N_p/(N_p+N_n) = N_p/N_t$



Deviations occur near closed shells

Valence proton fraction

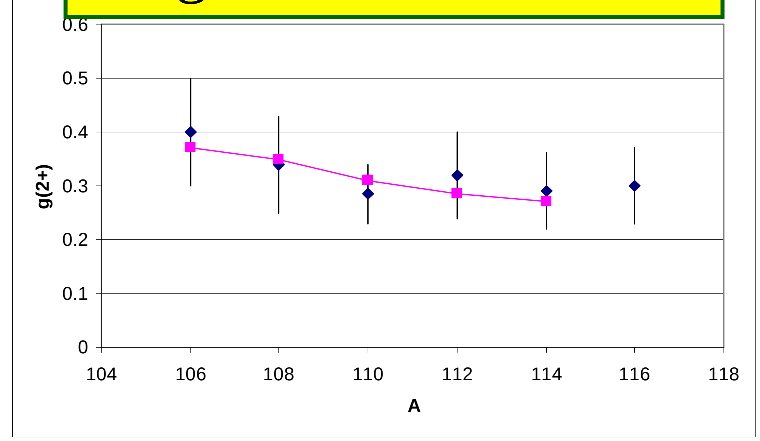
40 < Z <50 ; 50 < N <82

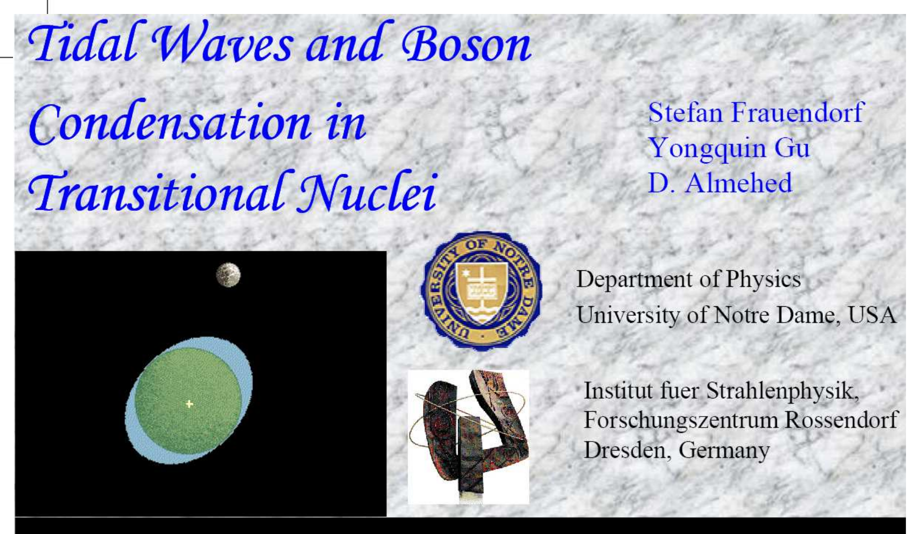


^{252}Cf + Gammasphere
A.G. Smith *et al.* PLB **591**, 55 (2004)

Behavior of neutron-rich *g* factors

Large errors on old data



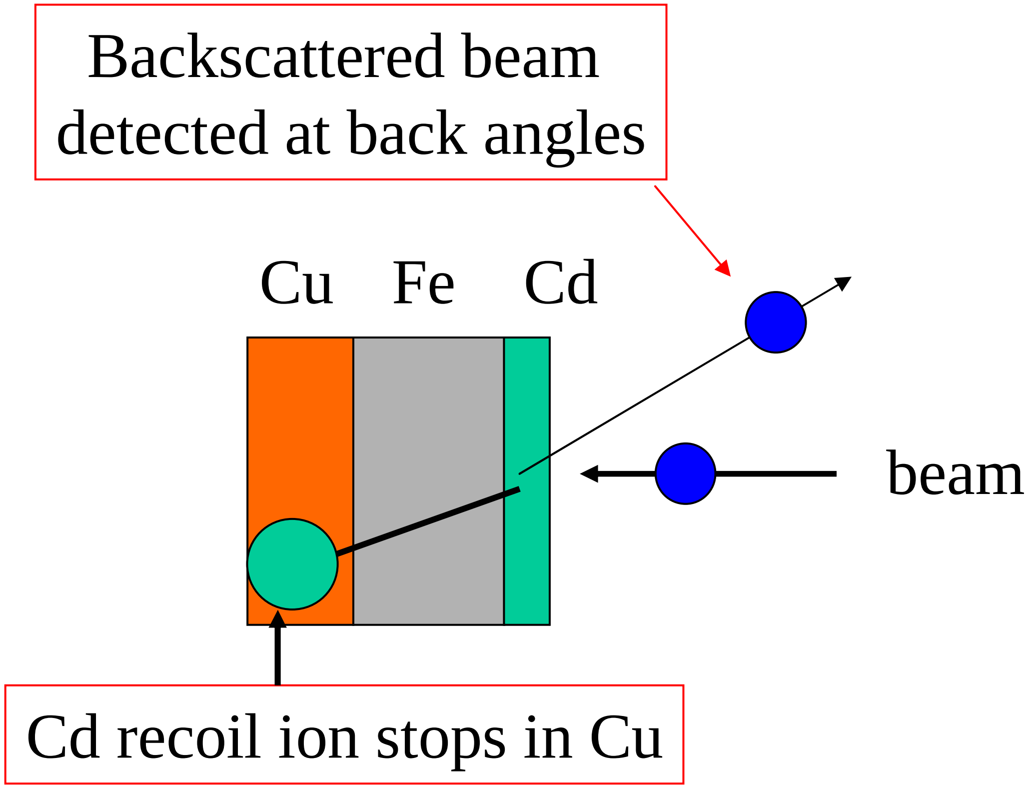


New cranking model for region

Transient-field *g*-factor measurements @ ANU

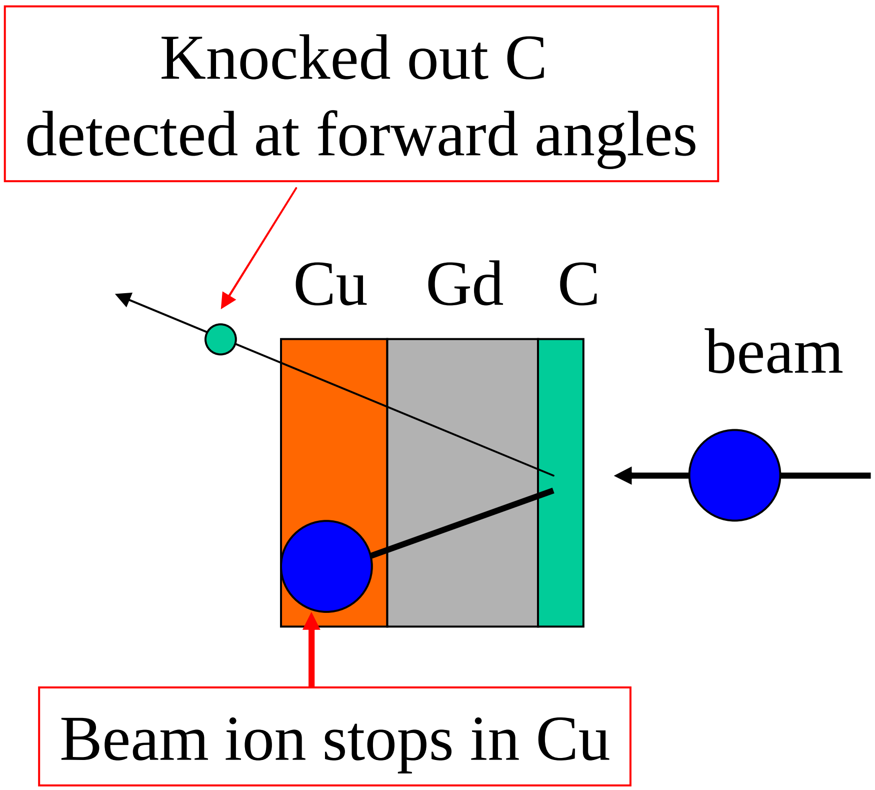
A. Conventional kinematics:

- ^{110,111,112,113,114,116}Cd via 95 MeV ^{32}S on ^{nat}Cd



Target Layer:	Ag	Cd	Fe	Cu	(+ Cu)
Thickness (mg/cm^2)	0.05	0.98	2.64	5.5	~ 20

Transient-field *g*-factor measurements @ ANU



B. Inverse kinematics:

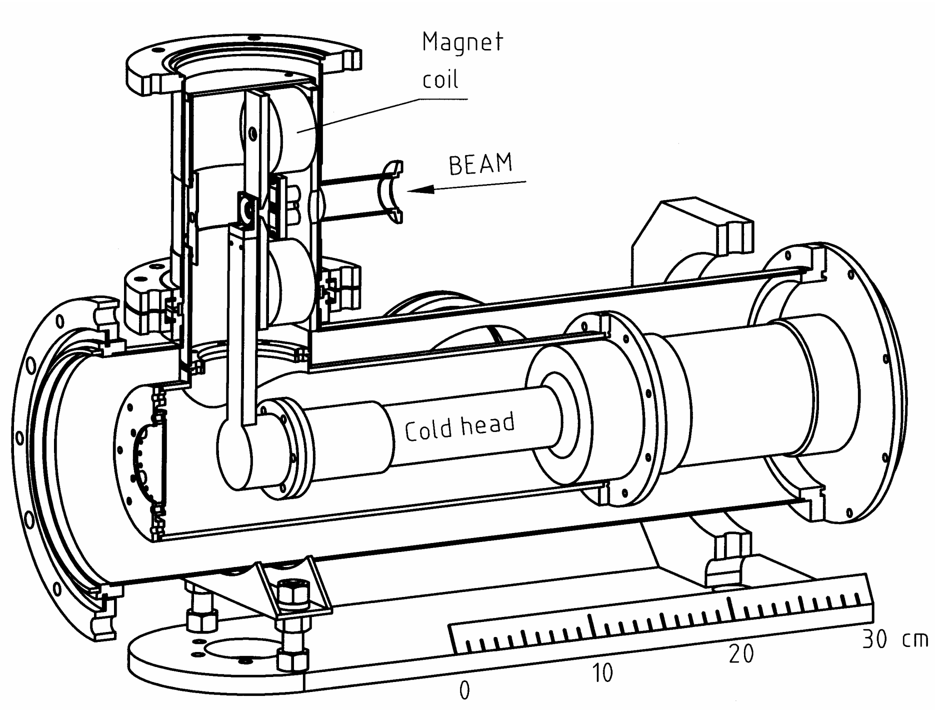
- 240 MeV ^{96,98,100,102,104}Ru
- 245 MeV ^{102,104,106,108,110}Pd
- 240 MeV ^{106,108,112,114}Cd *
- 230, 245, 260 MeV ^{108}Pd

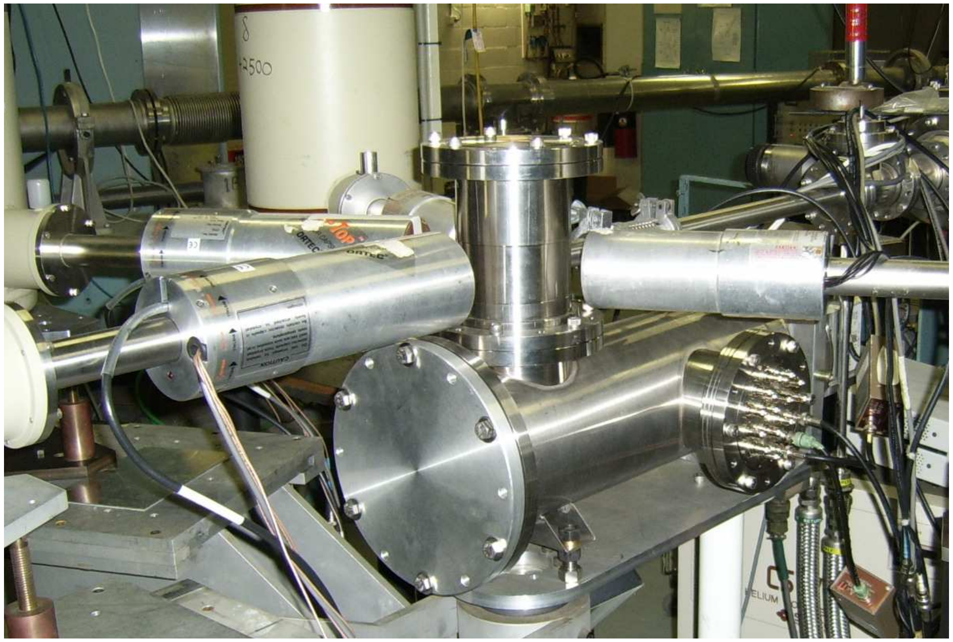
* Partially enriched ^{106,108}CdO in ion source

Target Layer:	C	Cu	Gd	Cu	(+ Cu)
Thickness (mg/cm^2)	0.42	0.04	6.12	5.5	~ 4.5

Hyperfine Spectrometer: Hyperion

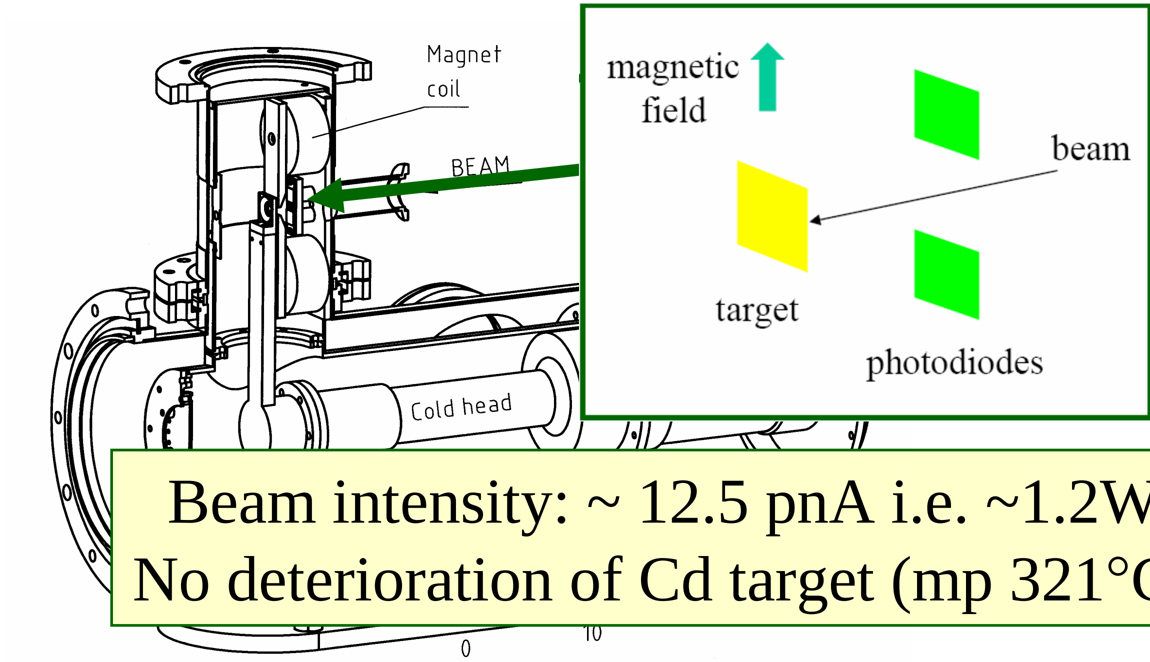
HYPERfine Interactions ON line.
Low temperature capability





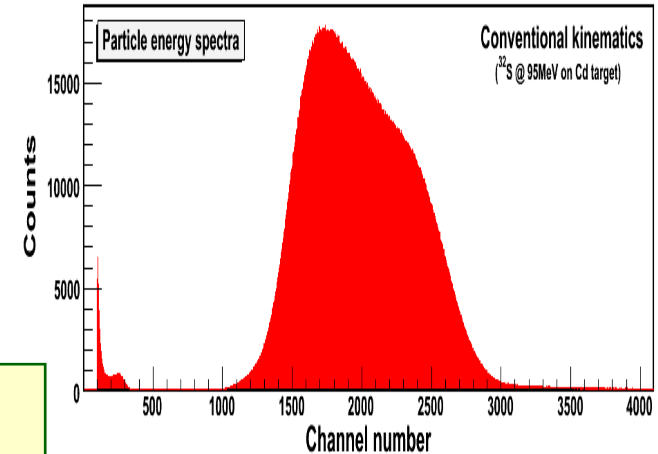
- 1 W cooling power at 4K (~10 W at 10 K) Sumitomo RDK 408D
- No target current reading – use particle rate
- Photodiodes as particle detectors (separate electronics channels)
- LakeShore temperature controller and temperature sensors
- Compact electromagnet: polarizing field ~ 0.09 tesla

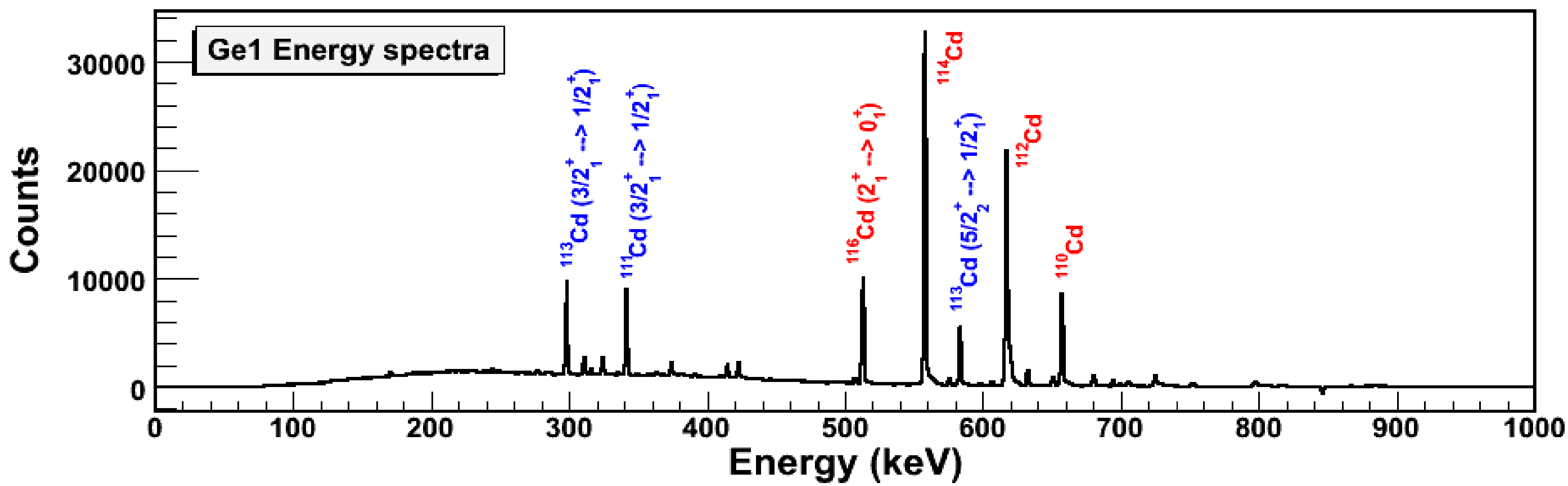
Conventional kinematics: 95 MeV ^{32}S on ^{nat}Cd



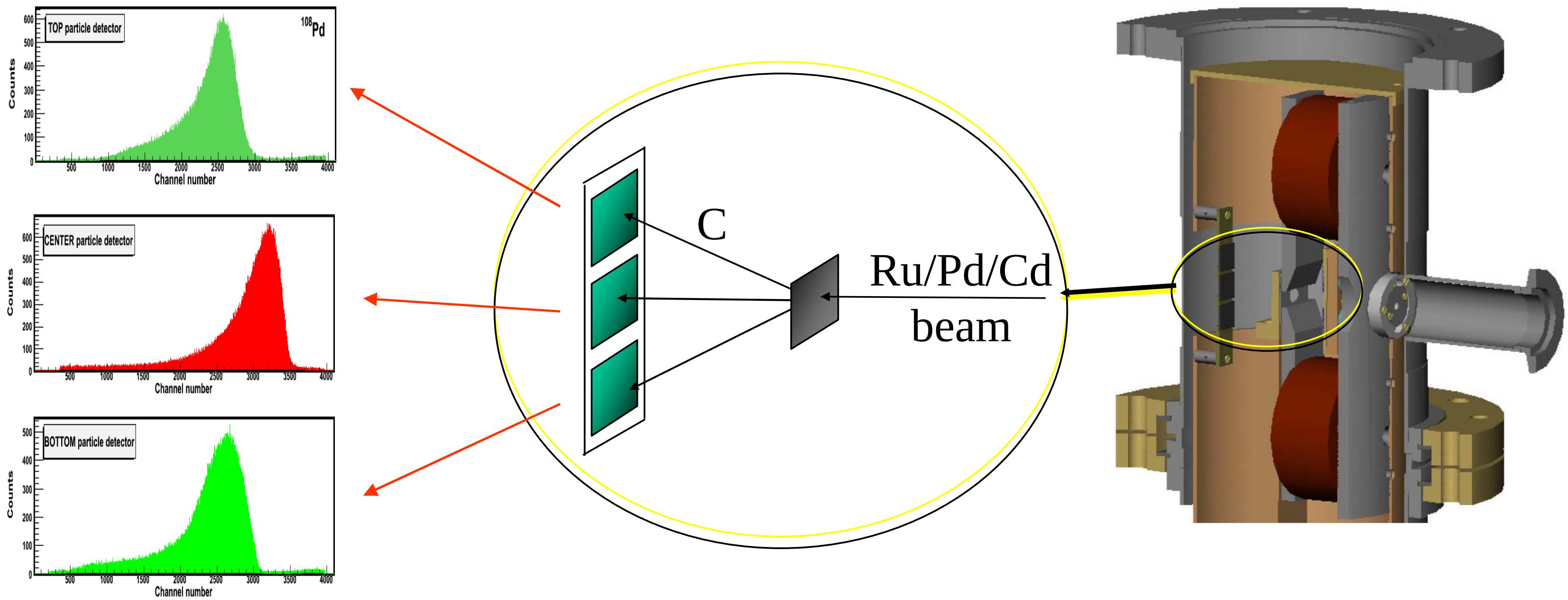
Beam intensity: ~ 12.5 pnA i.e. ~1.2W
No deterioration of Cd target (mp 321°C)

Backscattered ^{32}S spectrum





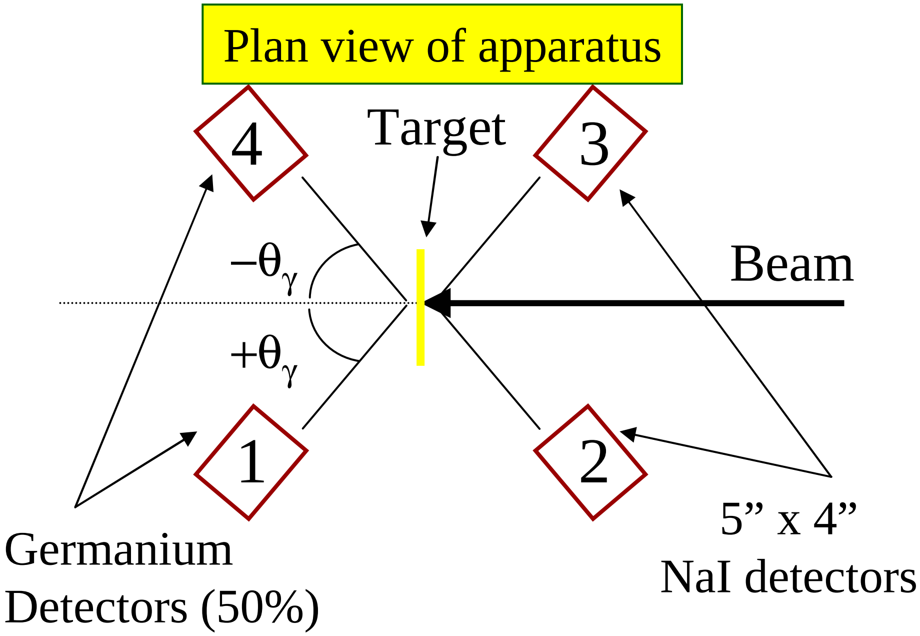
Inverse kinematics ~ 240 MeV Ru, Pd and Cd beams

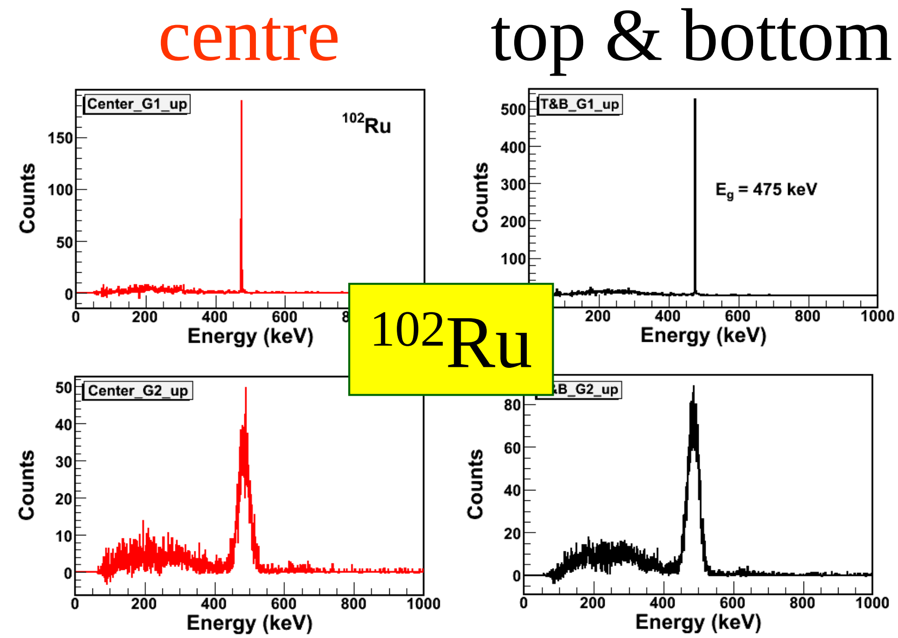


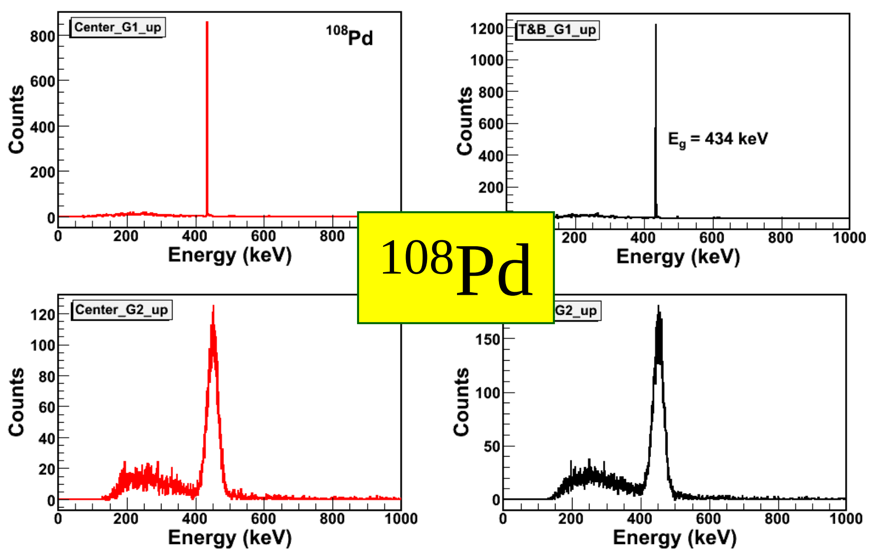
Beam energy is ~ 2.3 MeV/nucleon

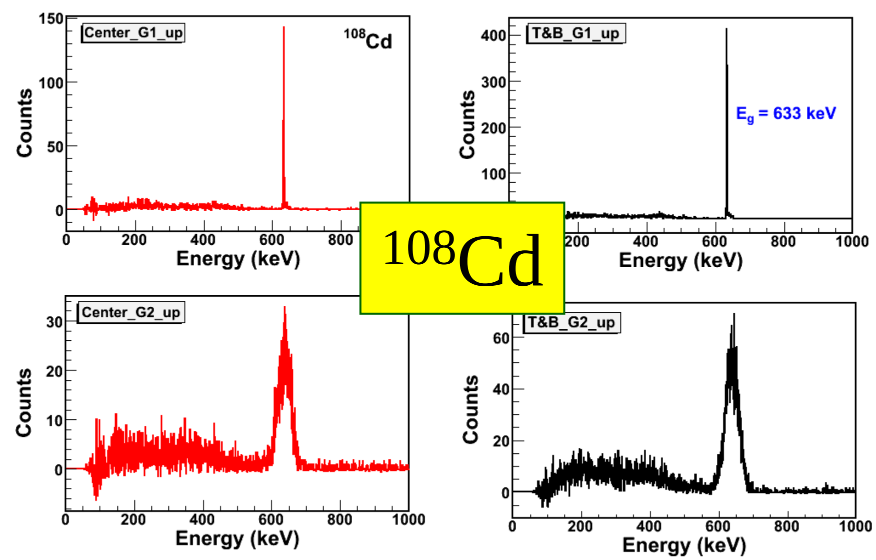
Beam intensity: from ~ 0.5 pnA for ^{106}Pd to ~ 0.05 pnA for ^{102}Pd

Inverse kinematics: coincidence γ-ray spectra



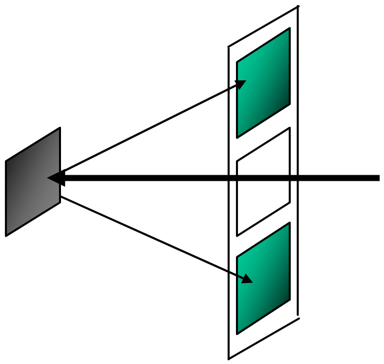


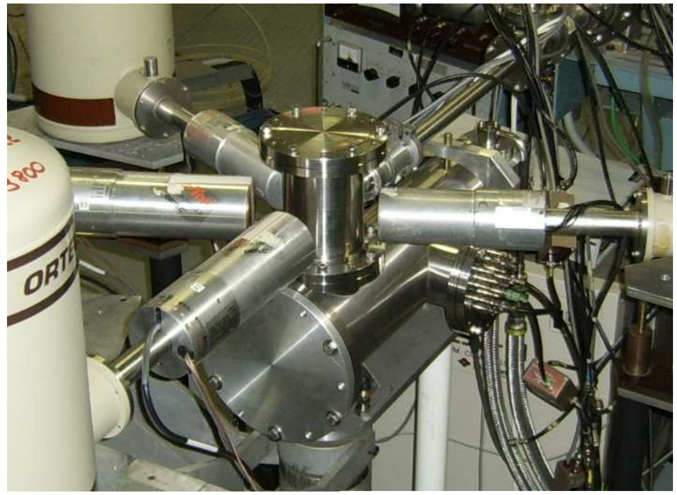




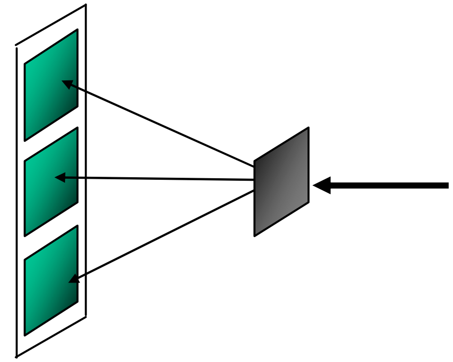
Angular correlations: calculated and measured

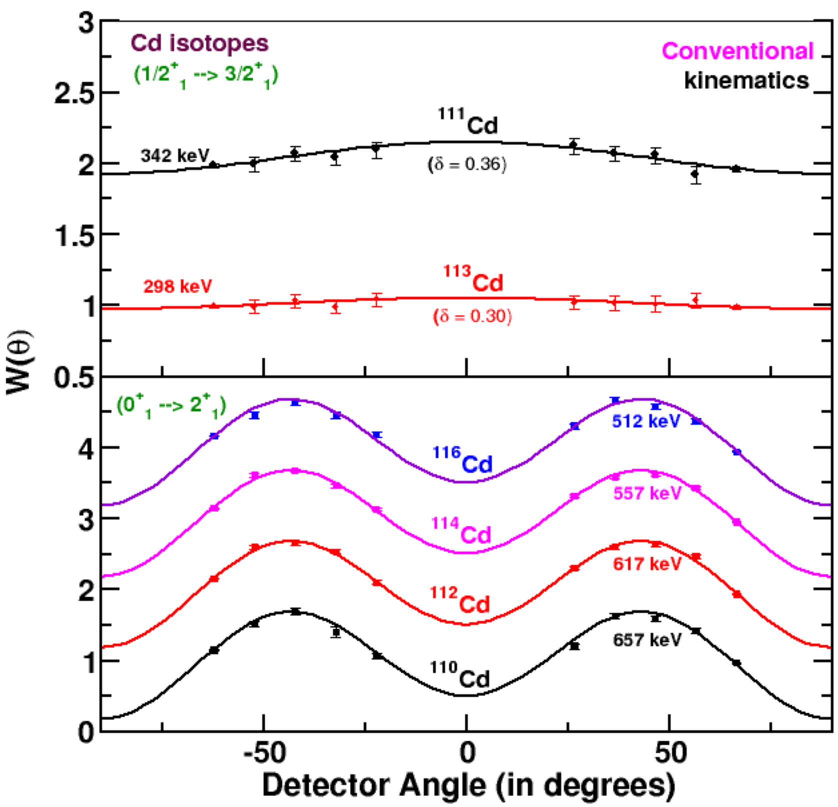
conventional

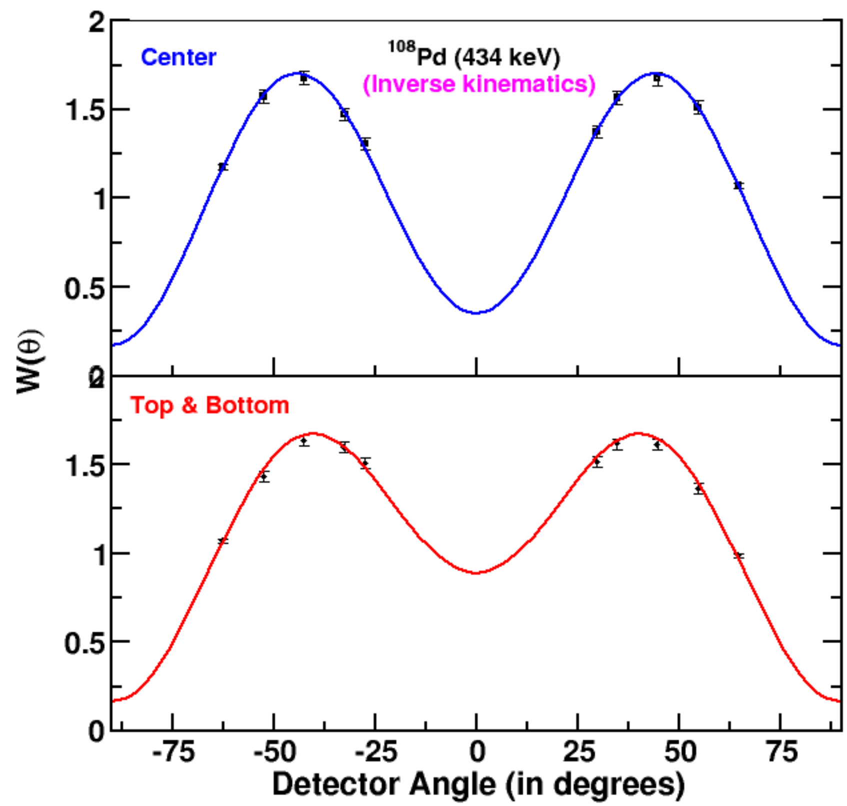




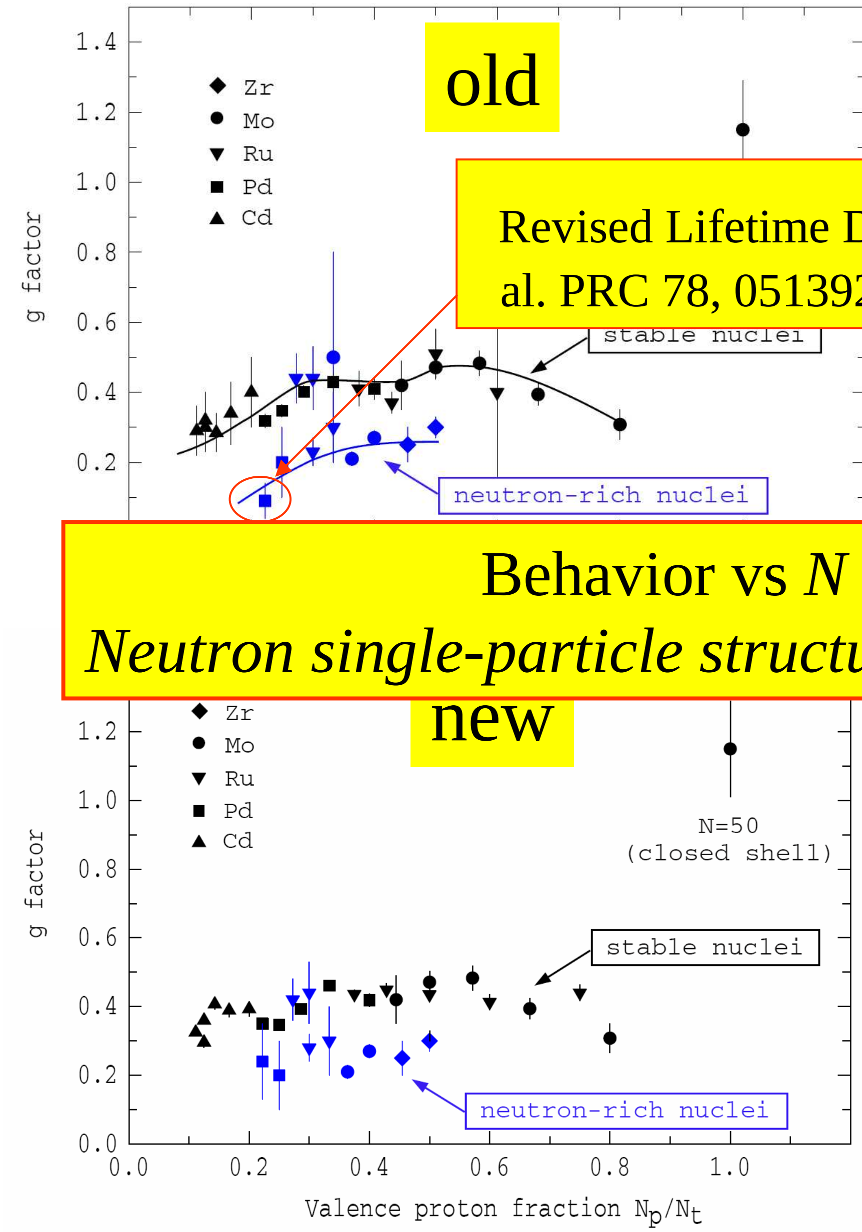
inverse



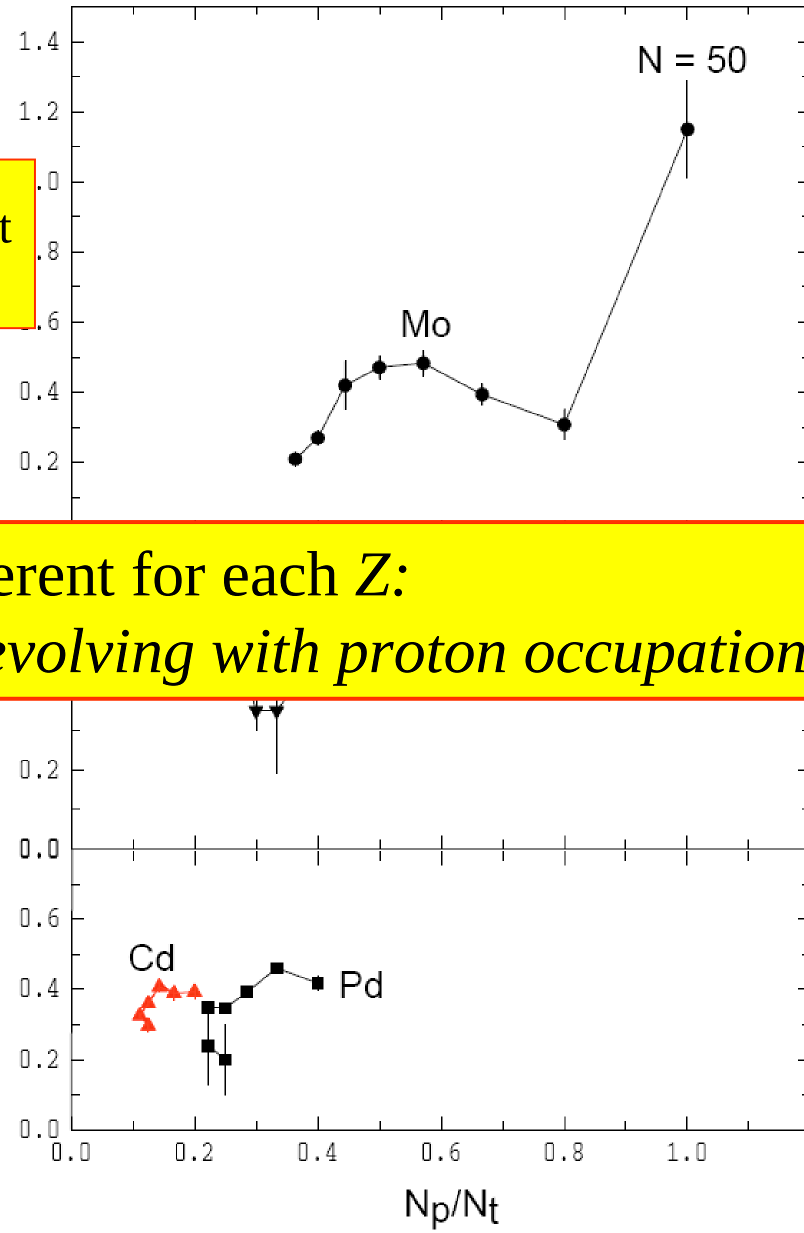




Summary of the data



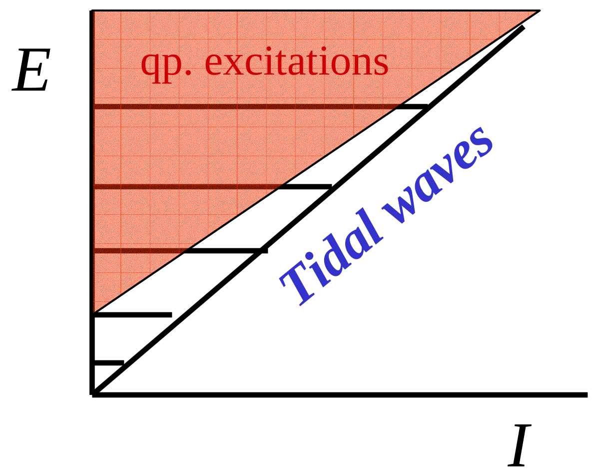
Revised Lifetime Dewald et al. PRC 78, 051392 (2008)

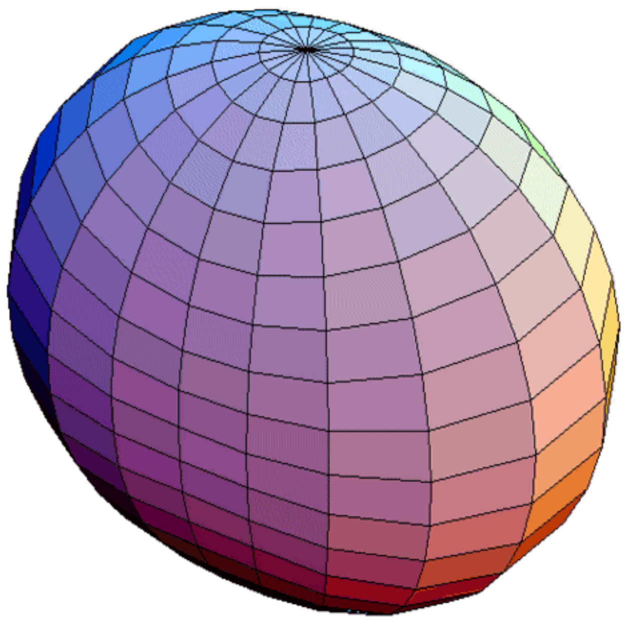


Behavior vs *N* is different for each *Z:*

Neutron single-particle structure is evolving with proton occupation

Quadrupole Tidal Waves





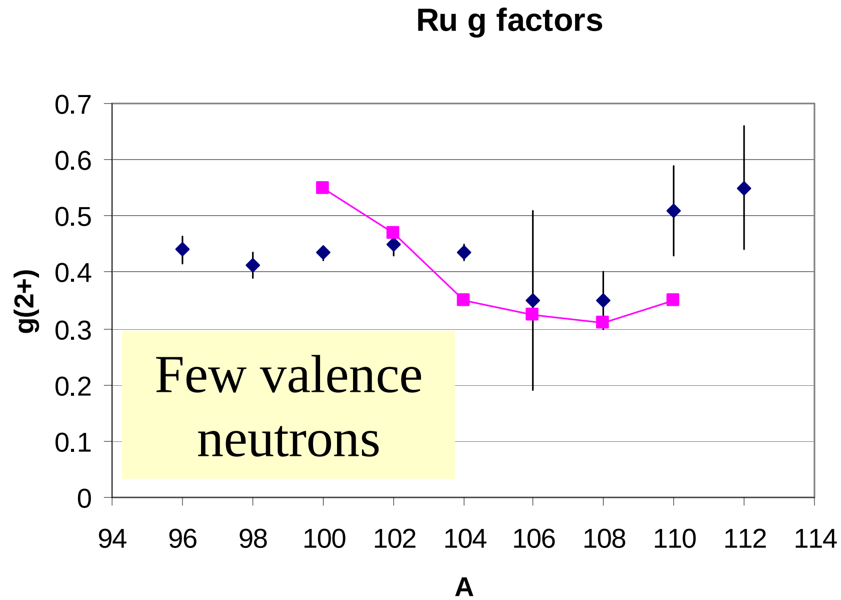
Yrast states of vibrational and transitional nuclei can be considered as “tidal” waves traveling the nuclear surface.

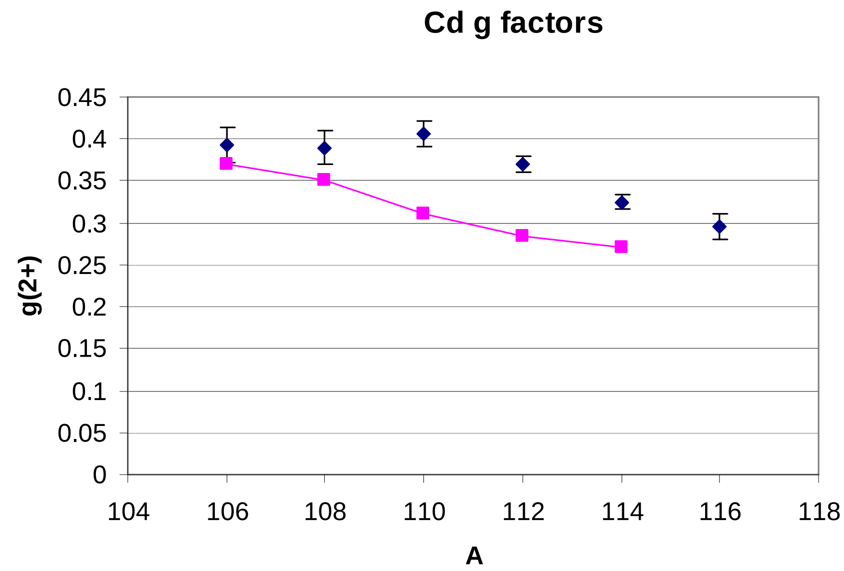
$$\omega = \frac{\Omega}{2} \qquad E = \omega L_z$$

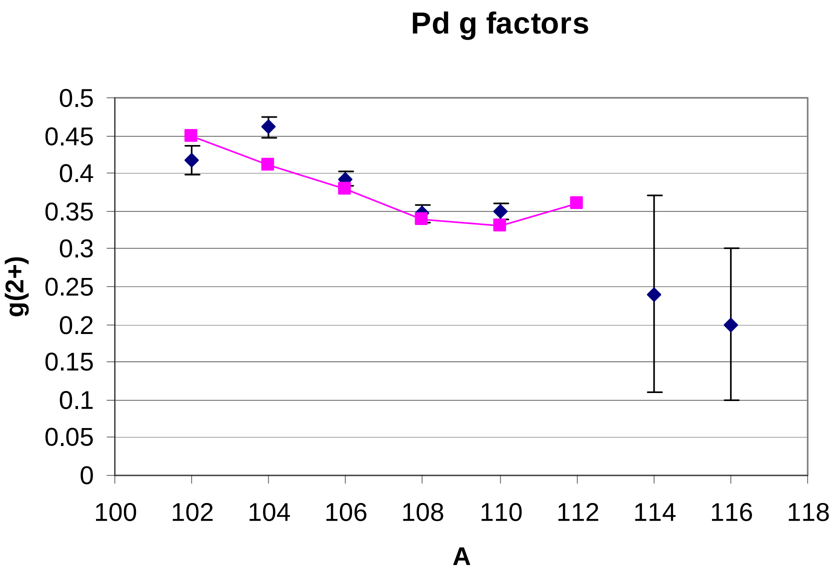
In the rotating frame they correspond to a static deformation → Cranking model

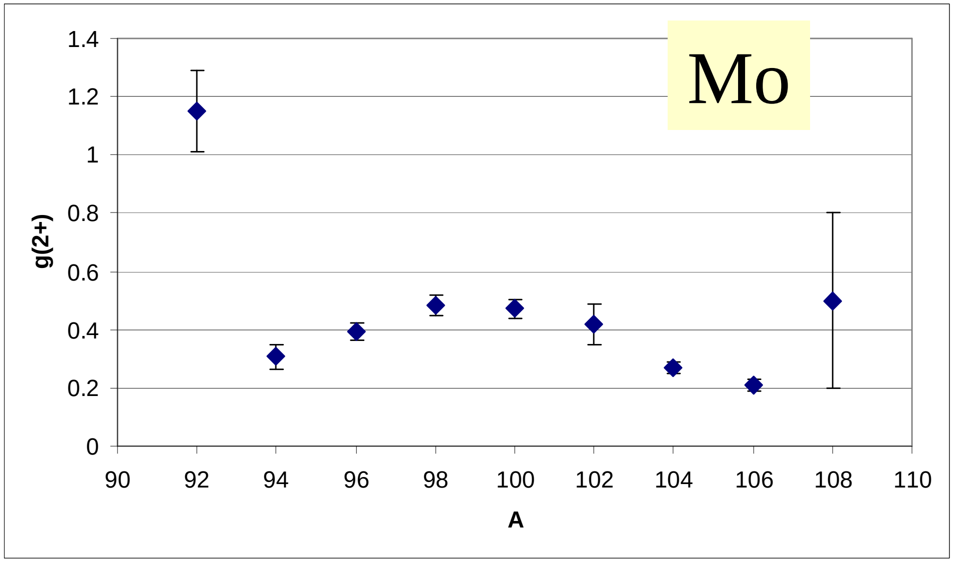
$$R(\vartheta, \varphi, t) =$$
$$R_0[1 + 2a_2 \cos(2\varphi - \Omega t) Y_{22}(\vartheta, \varphi = 0)]$$

Comparison of *g* factors with the ‘tidal’ wave model









Conclusions & Outlook A ~ 100

- *g*(2^+) behavior vs *N* changes with *Z*
  - probably reflects changes in single particle structure

- trends in neutron-rich nuclei continue trends in stable isotopes

We still need stable-beam measurements!

- basis for future measurements: odd-*A* nuclei; fission products, RIB, RIV, etc
  - towards both ^{100}Sn and ^{132}Sn

Measurements on fast fragments: High Velocity Transient Field

Nuclear structure near closed shells

- neutron rich S, Ar, Fe isotopes

High velocity transient fields

First measurements: NSCL 2004, $^{38,40}S$

Experiments in 2008

Nuclide(s)	Lab	Date Run	Spokesperson
^{72}Zn	GANIL	April 2008	Georgiev, Jungclaus
$^{60,62}Fe$	NSCL	October 2008	AES
$^{42,44,46}Ar$	NSCL	October 2008	AES

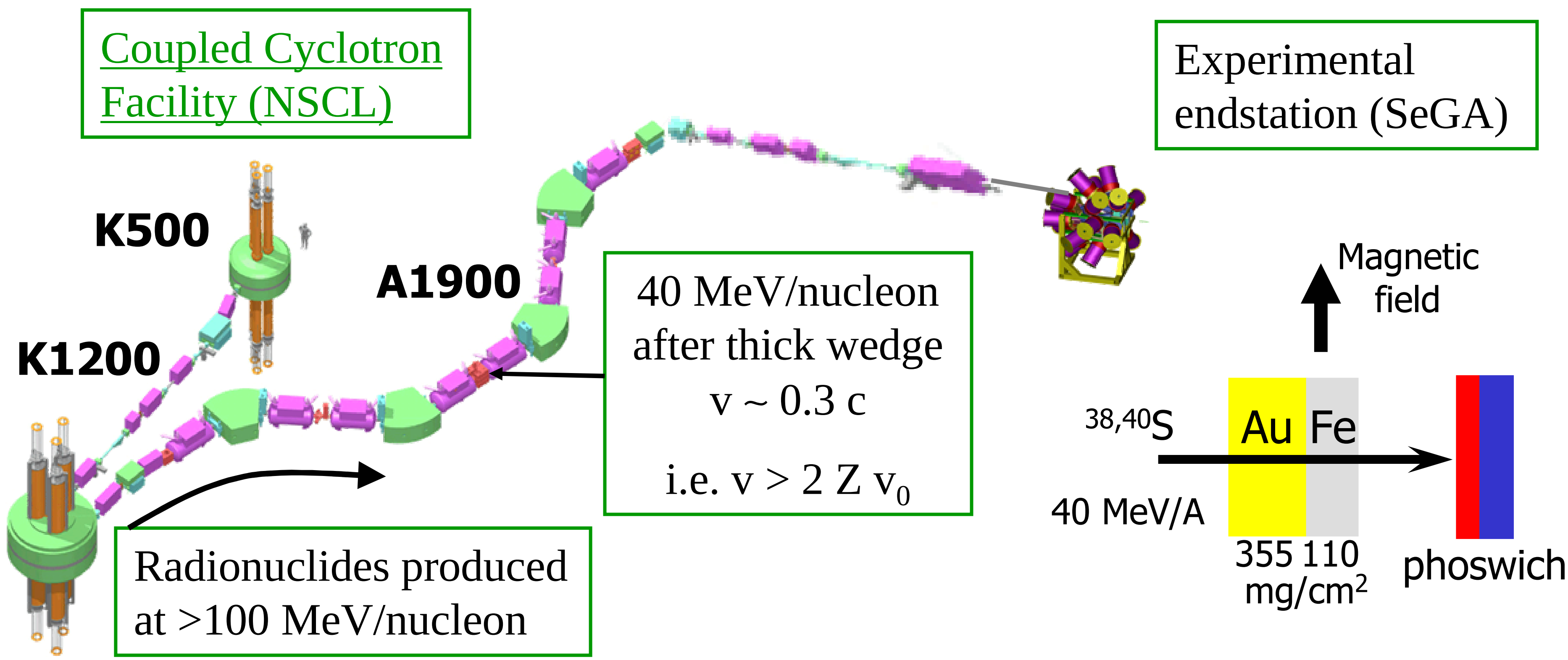
Aim: probe shell structure in neutron-rich nuclei

Fast beam production of $^{38,40}S$, $^{42,44,46}Ar$

140 MeV/A

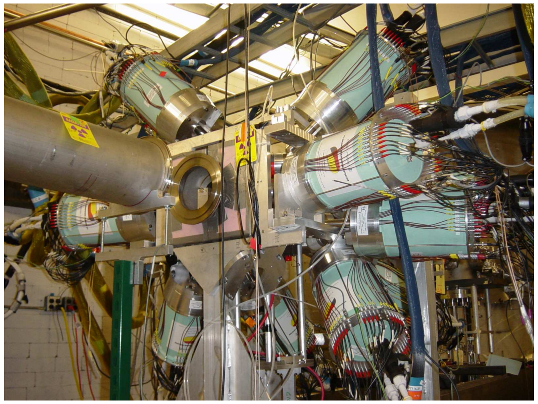
$^{40}Ar \rightarrow {}^{38}S$, 10^5 pps
$^{48}Ca \rightarrow {}^{40}S$, 10^4 pps
$^{48}Ca \rightarrow {}^{42,44,46}Ar$, 10^5 pps

(^{48}Ti as fragments from Kr for field calibration)

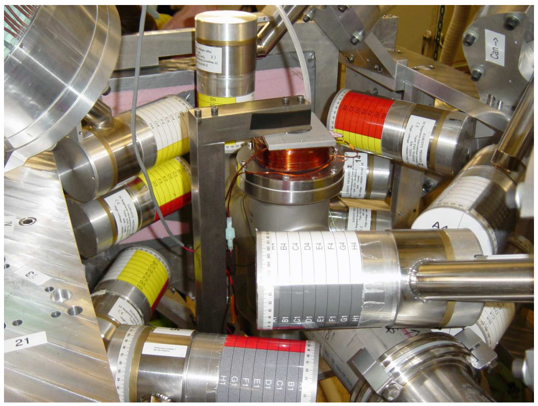


TF endstation: Segmented Ge Array (SeGA)

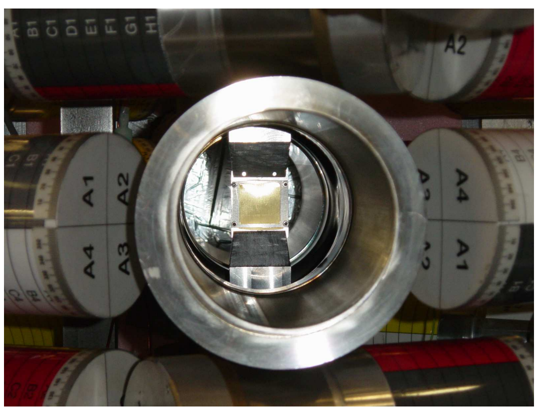
1

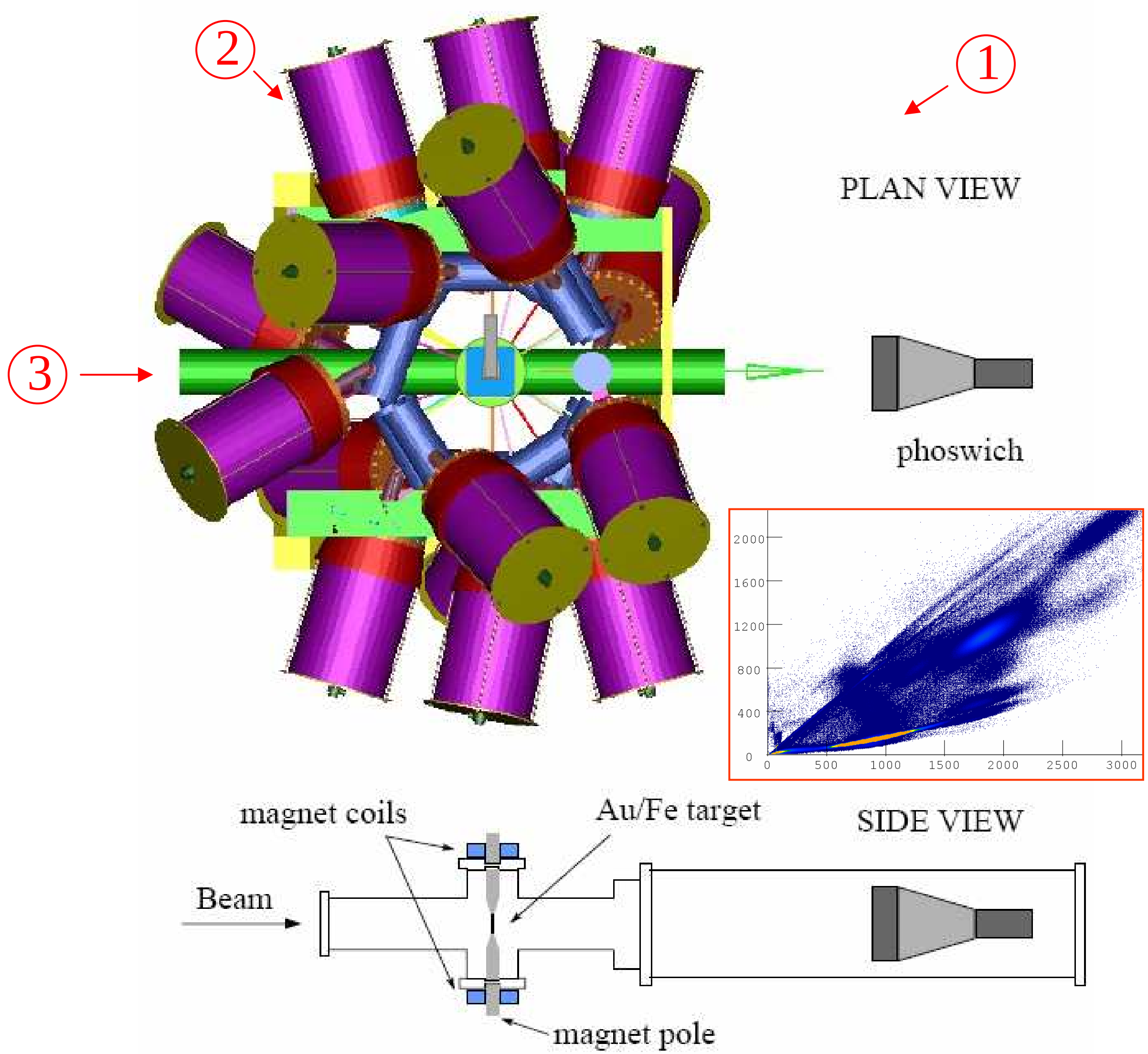


2

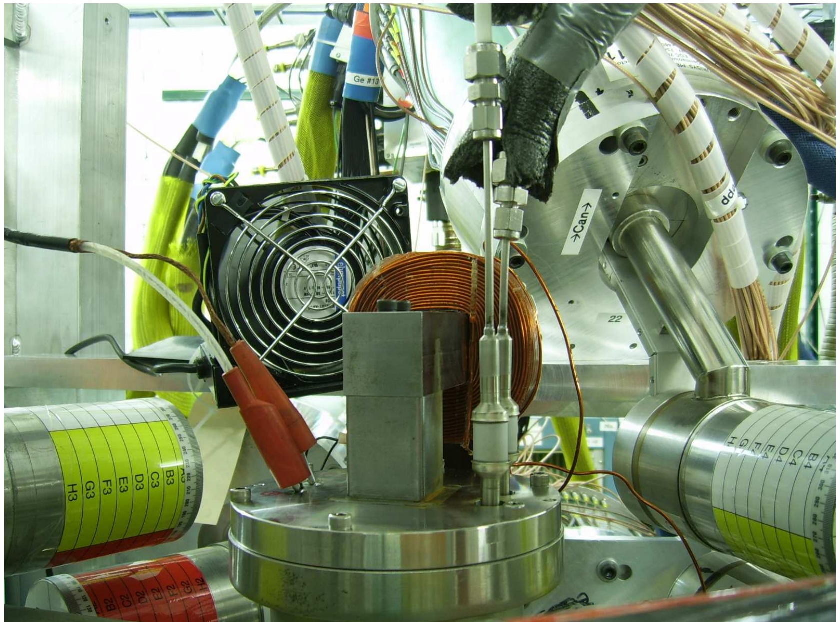


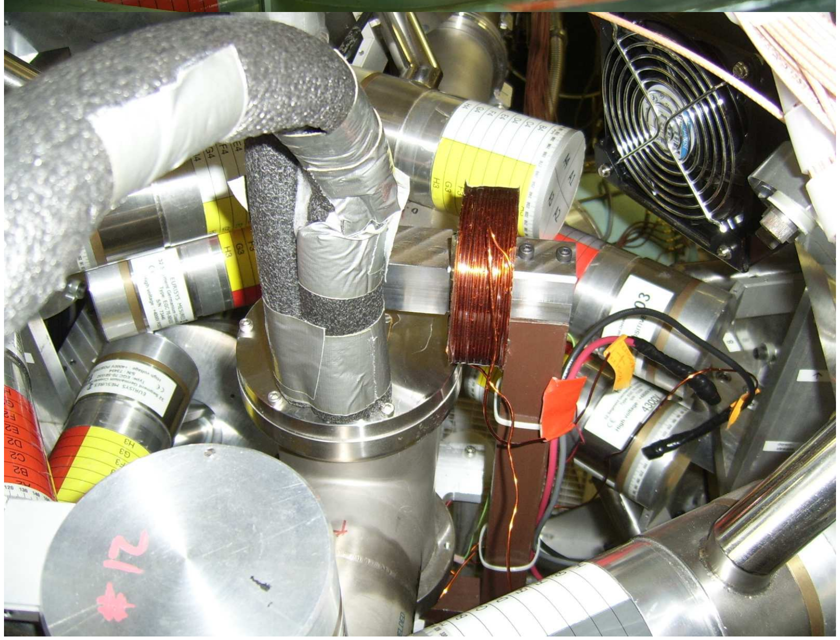
3

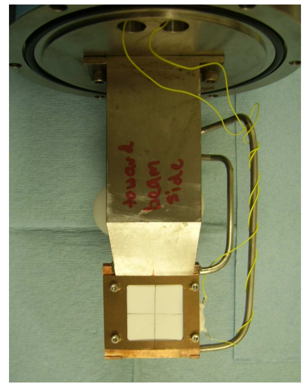


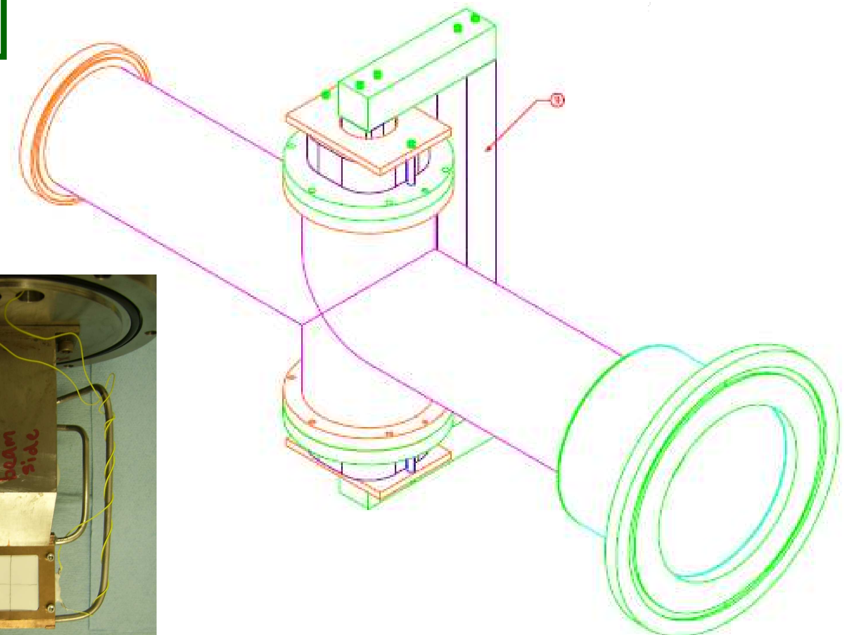


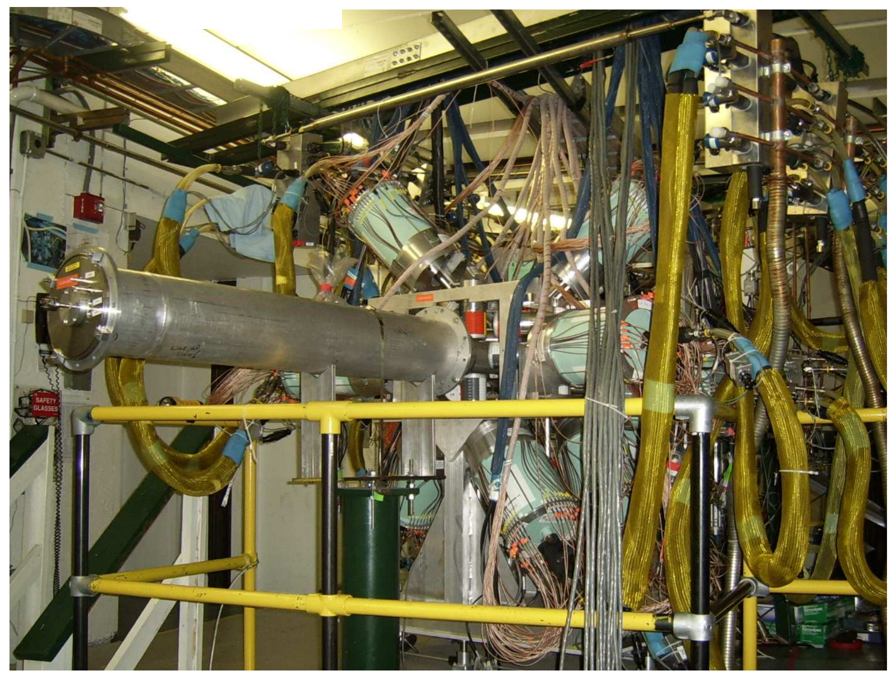
Cooled target for 2008 campaign



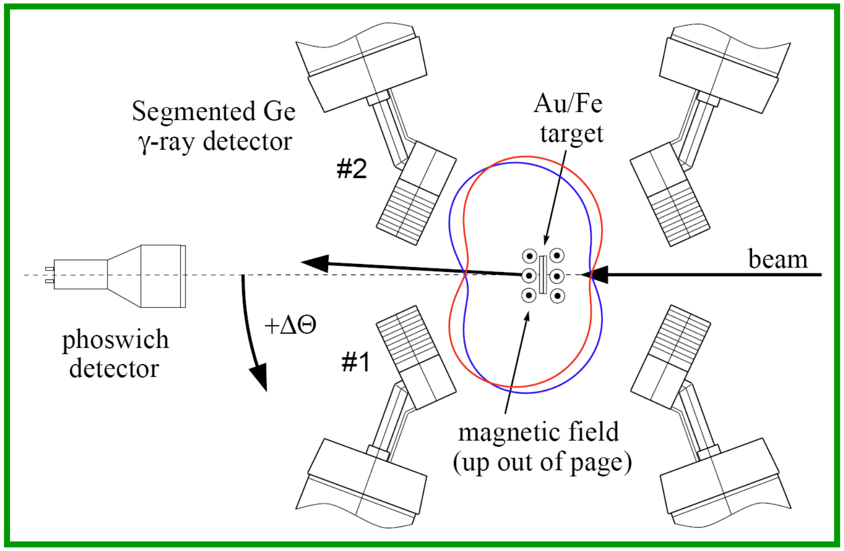


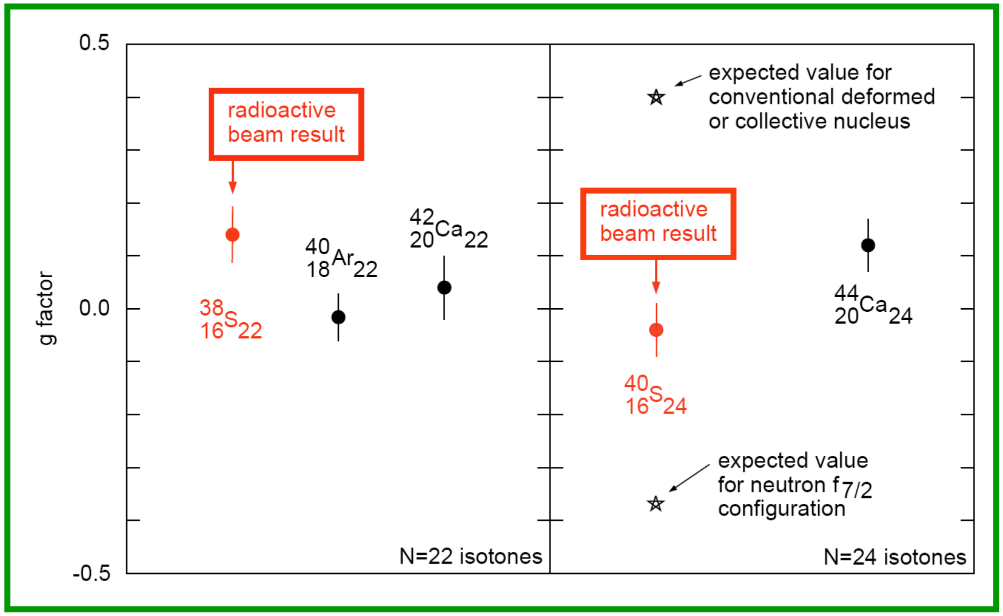




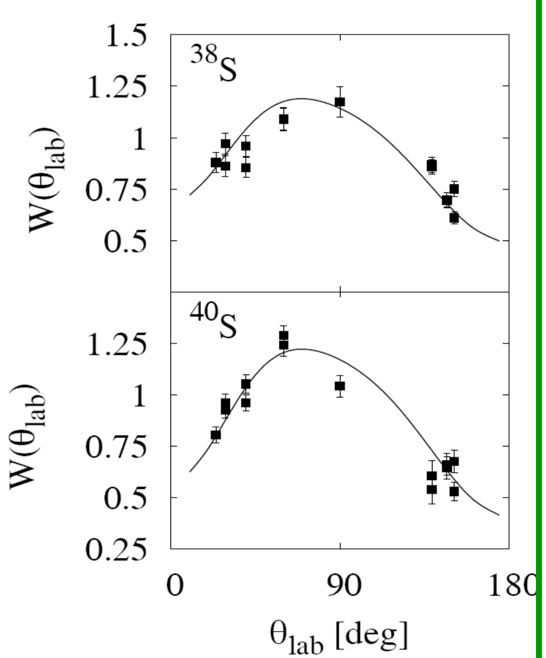


Angular correlations and *g* factors $^{38,40}S$





Lab frame angular correlation



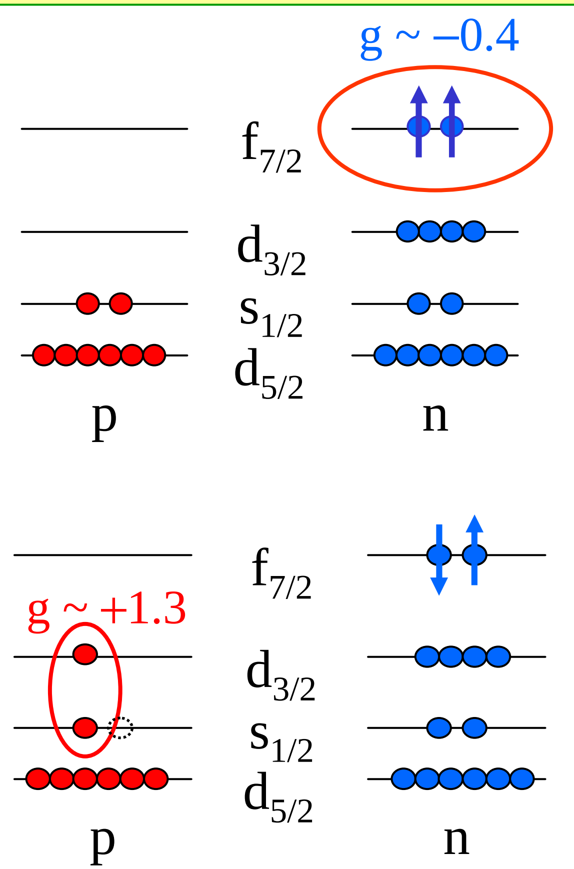
High velocities ⇒Large fields
Experimental uncertainties rival stable-beam measurements

Stable-beam data: Rutgers: Phys Rev C **72**, 014309; Bonn: Phys Lett B **571**, 29.

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

Two surprises in the *g* factors of ^{38,40}S

g(2^+) in ^{38}S is clearly *positive*



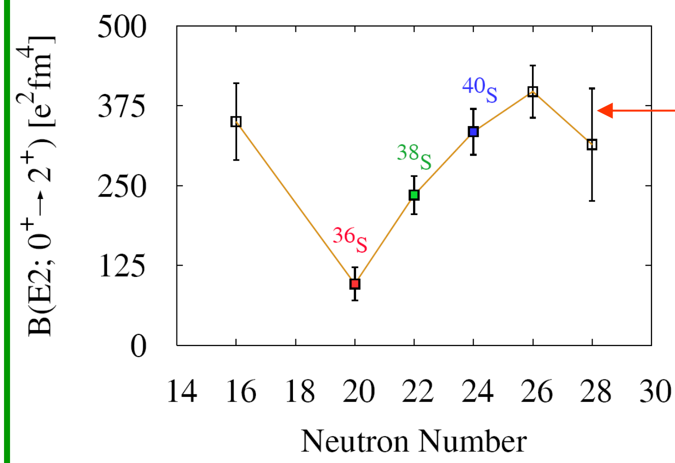
Neutron excitation

versus

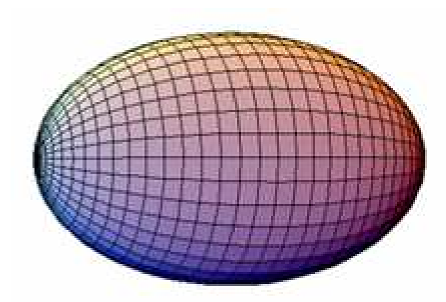
Proton excitation

Block excitations across N=28:
$g_{th} = 0 \rightarrow -0.36$
Neutron configuration affects protons
-very sensitive to $\nu p_{3/2}$ occupation

g(2^+) ≠ Z/A in 'prolate' ^{40}S



$\beta_2 \approx 0.3$

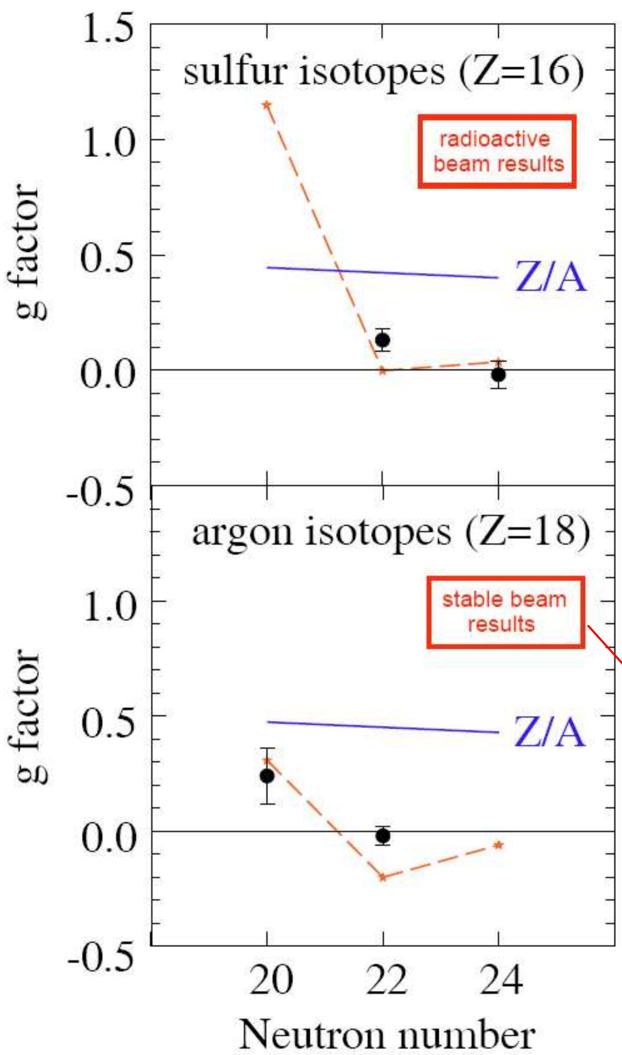


^{40}S

?

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

^{38,40}S Interpretation: Shell model calculations



Oxbash: *sdpf* space; *sdpf-NR* interaction
protons in *sd* shell; neutrons in *pf* shell

Nuclide	E(2^+) (keV)		β		
	th	exp	Q^{th}	$B(E2)^{th}$	$B(E2)^{exp}$
^{38}S	1531	1292	+0.17	0.26	0.25(2)
^{40}S	980	904	+0.33	0.34	0.28(2)

^{38}Ar: Bonn,
PLB **632**, 207 (2006)

^{40}Ar: Rutgers,
PRC **72**, 014309 (2005)

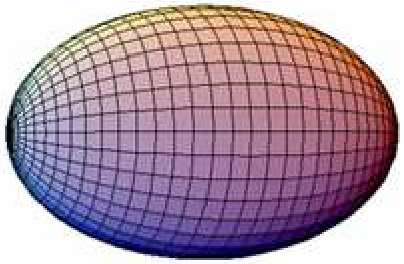
^{40}S: consistent deformation β from Q and B(E2)

Prolate deformed ^{40}S: why is $g \neq Z/A$?

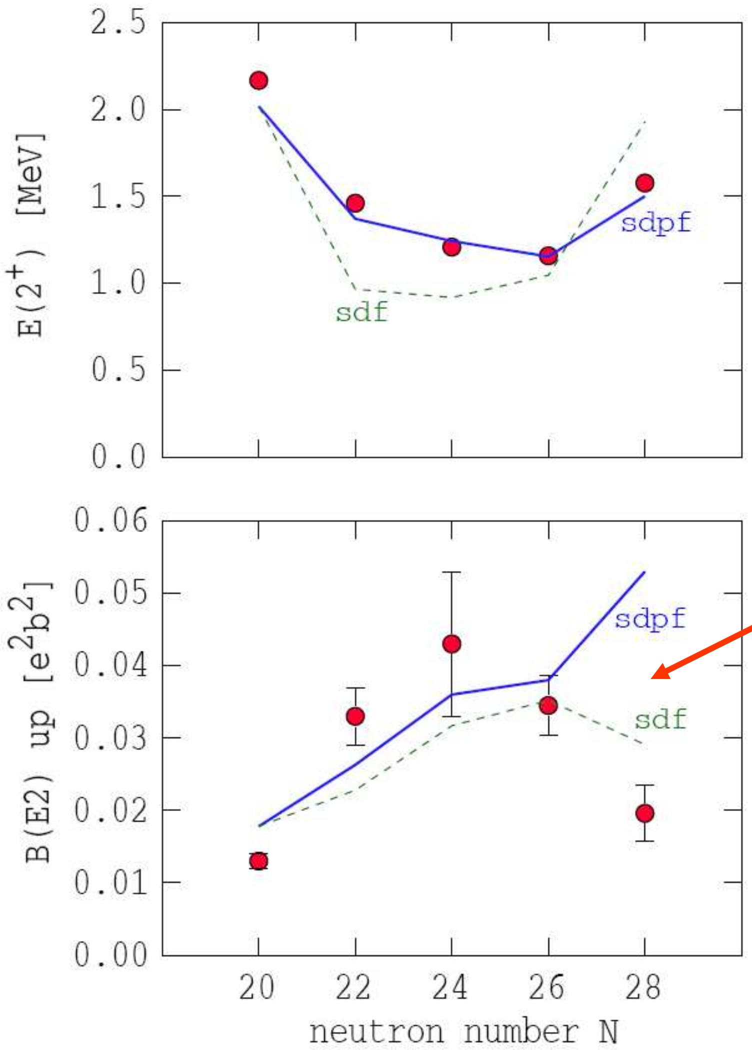
g^{th}(proton)			g^{th}(neutron)	g^{th}	g^{exp}
orbital	spin	total	spin = total		
0.225	0.051	0.276	-0.241	0.035	-0.01(6)

- spin contributions to *g* factor do not cancel
- $f_{7/2}$ neutrons still have a distinct contribution to $g(2^+)$
- few particles contribute to the collectivity
- understand quadrupole collectivity in terms of symmetries:
  - quasi SU(3) for $\nu\ f_{7/2} - p_{3/2}$
  - pseudo SU(3) for $\pi\ d_{3/2} - s_{1/2}$

Retamosa *et al.* PRC **55**, 1266 (1997)



^{42,44,46}Ar measurements NSCL October 2008



Oxbash: *sdpf* space; *sdpf-NR* interaction
protons in *sd* shell; neutrons in *pf* shell

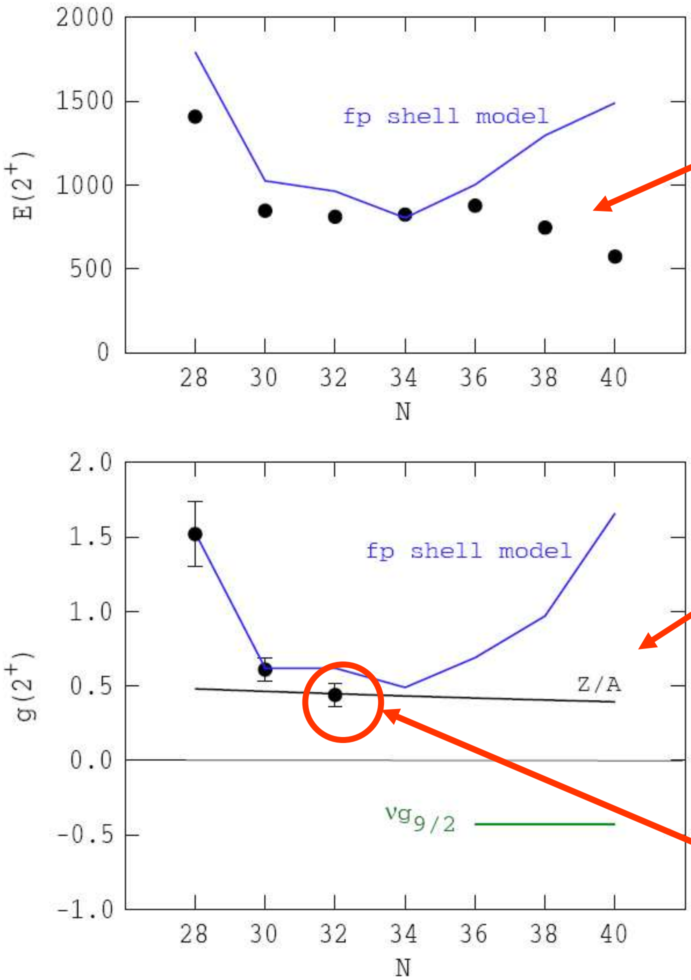
Discrepancy between theory and experiment for the N=28 nucleus ^{46}Ar

Preliminary: DBLS from *g* factor measurement confirms experimental B(E2)

g factors for 2^+ states in ^{42,44,46}Ar under analysis

H. Scheit *et al.*, Phys Rev Lett **77**, 3967 (1996)
J. Retamosa *et al.*, Phys Rev C **55**, 1266 (1997)
A. Gade *et al.*, Phys Rev C **68**, 014302 (2003)

$^{58,60,62,(64)}$Fe *g*-factor measurements



Schematic shell model calculations

Evidence for quenching the shell gap at N=40

The *g* factor near N=40 could be ~ Z/A

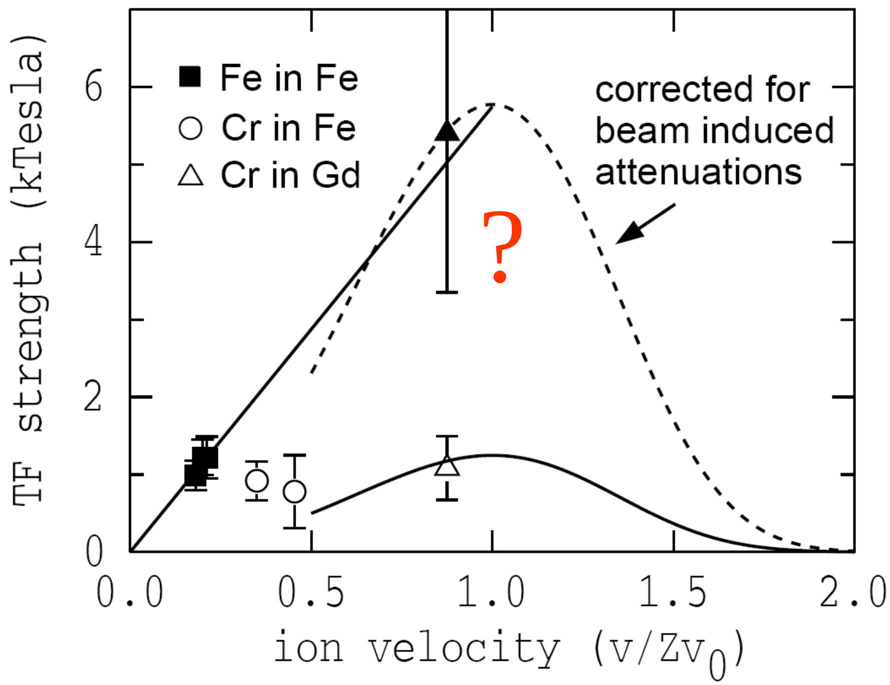
or

range from ~ –0.5 to ~ 1.5 if a particular configuration is dominant

^{58}Fe used to calibrate TF

Existing data had ≈ 30% errors

$^{58,60,62}Fe$ transient field calibration



- The TF strength at high velocity for Z > 20 is uncertain
- Use ^{58}Fe to calibrate

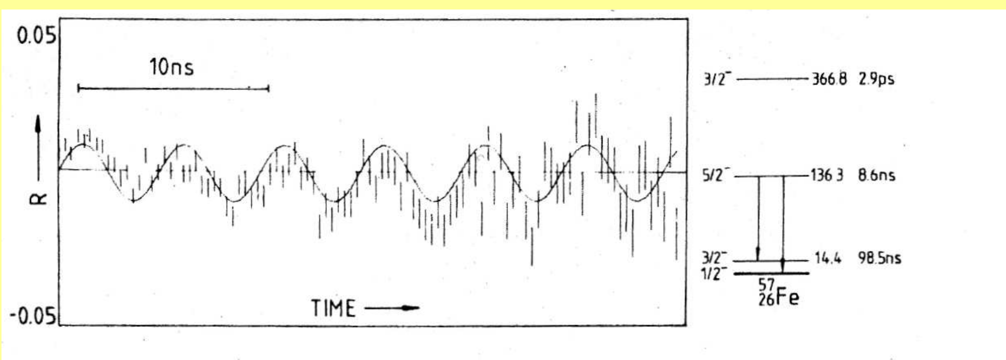


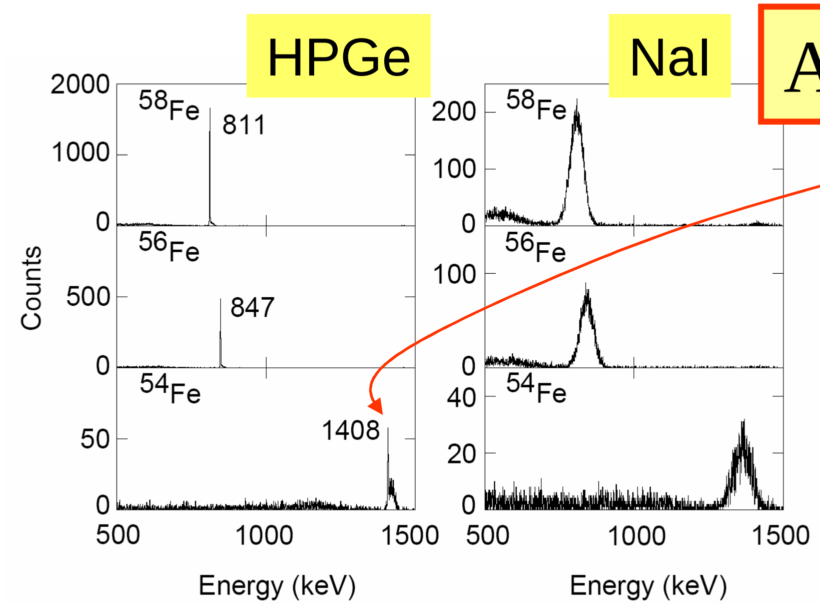
Fig. 2. Reduced time spectrum for ^{57}Fe implanted into ferromagnetic Fe.

Fahlander *et al.* Physica Scripta **20**, 163 (1979).

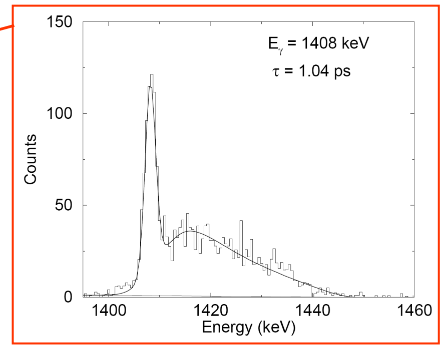
At ANU remeasured *g* factors in $^{56,58}Fe$ relative to ^{57}Fe $5/2^{-}$

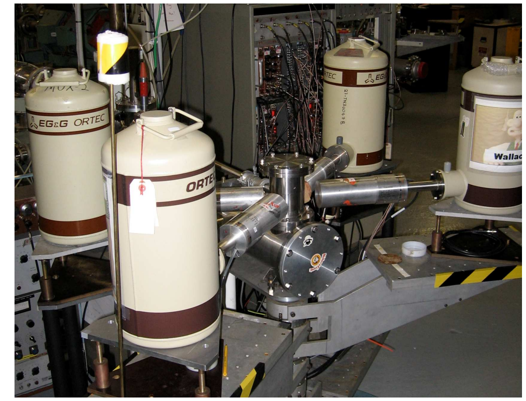
Inverse kinematics with 110 MeV $^{54,56,57,58}Fe$ beams

Stable Fe isotopes: spectra and angular correlations

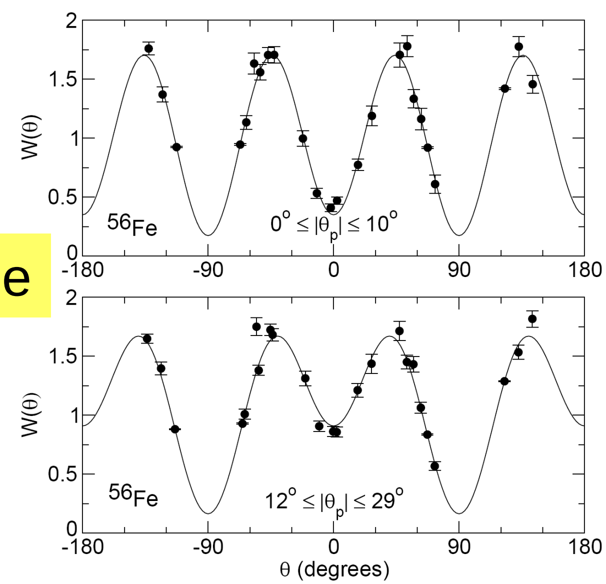


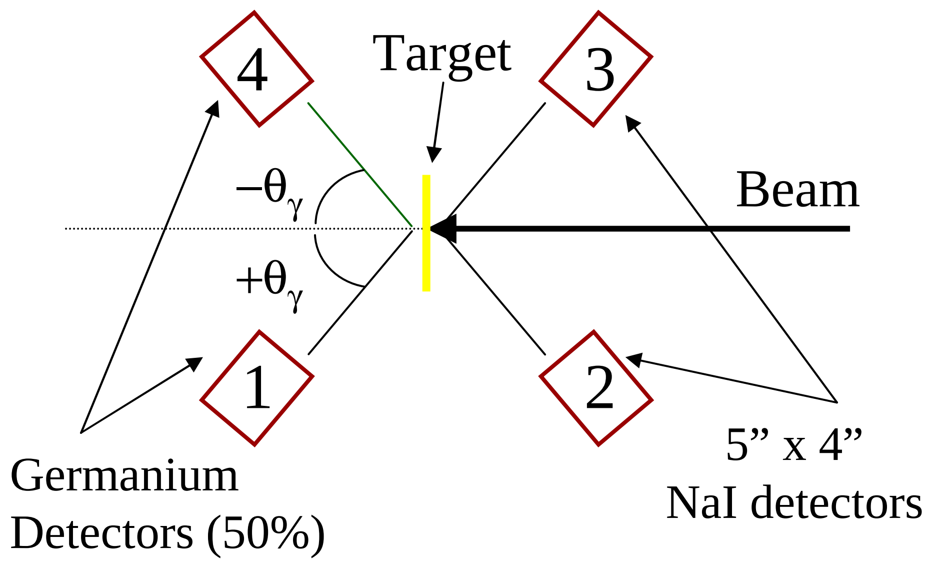
ANU experiments



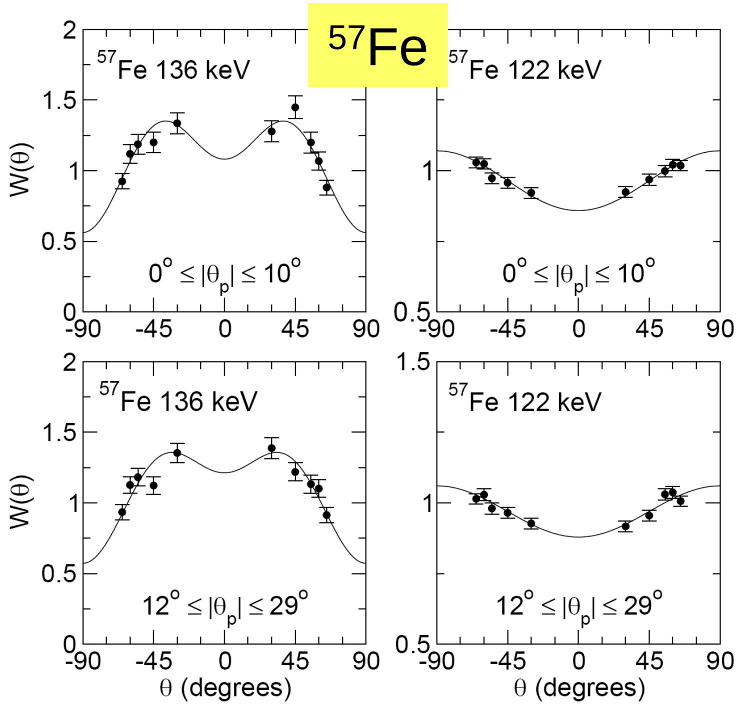


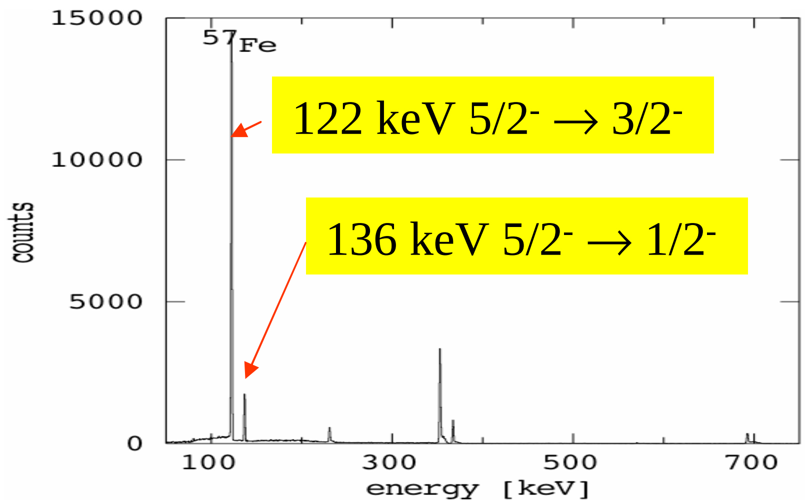
^{56}Fe

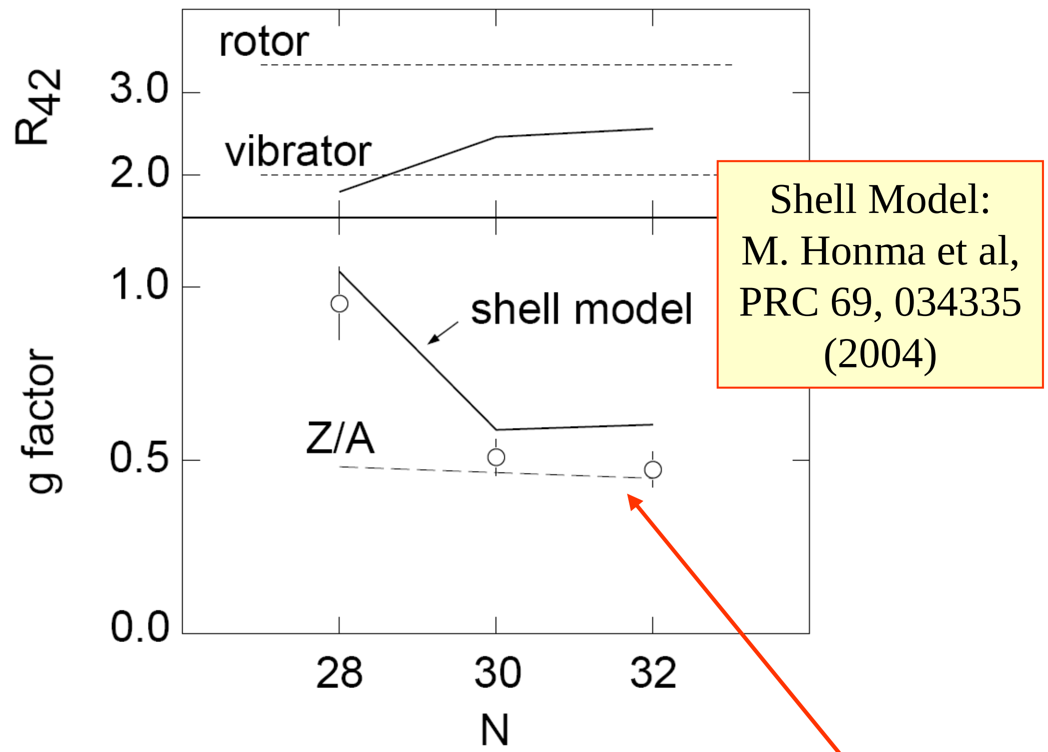




g factors in the stable Fe isotopes (PRC, submitted)







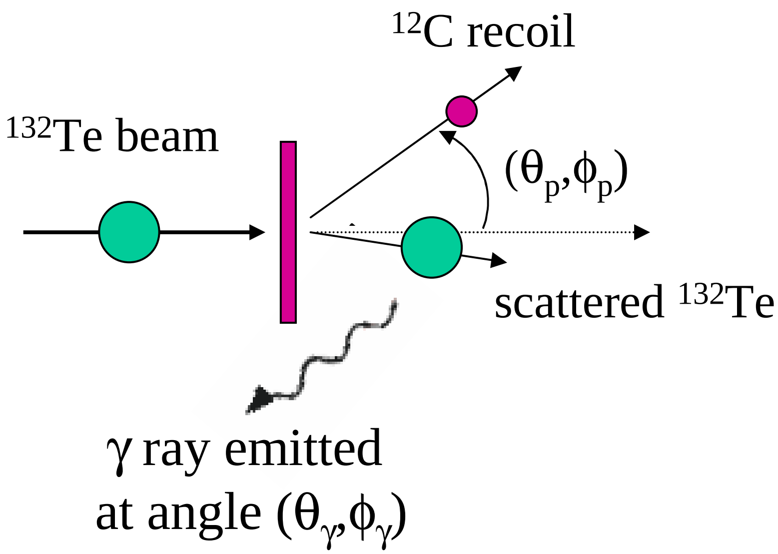
^{56,58}Fe *g* factors approach Z/A

Analysis of ^{62}Fe is in progress

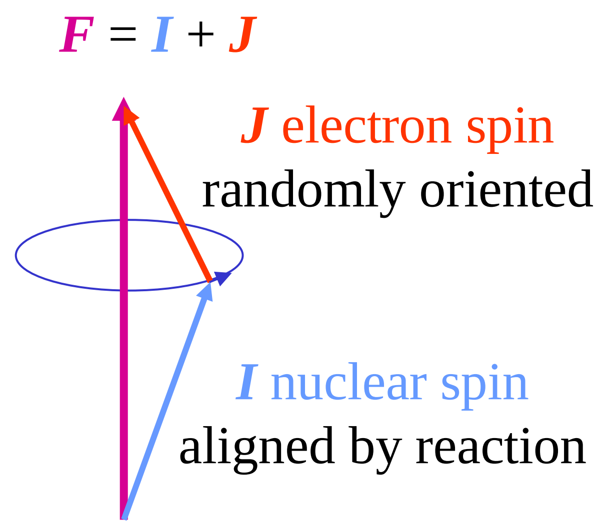
Measurements on reaccelerated beams: Recoil in Vacuum

Nuclear structure near ^{132}Sn

RIV *g* factor measurements with ISOL-type beams



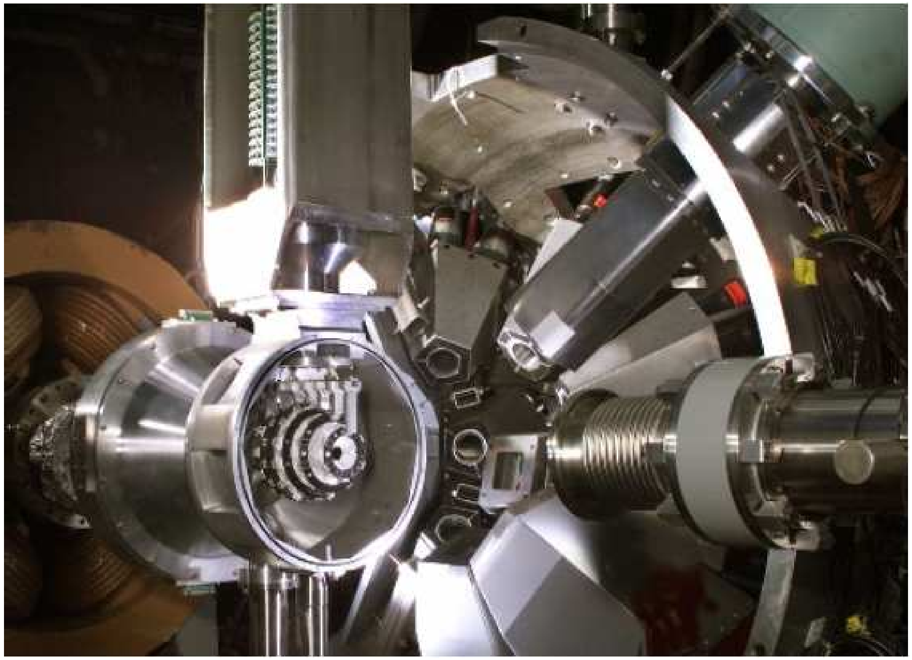
- Slow beams: v/c ~ 6%
- Measure azimuthal angular correlations

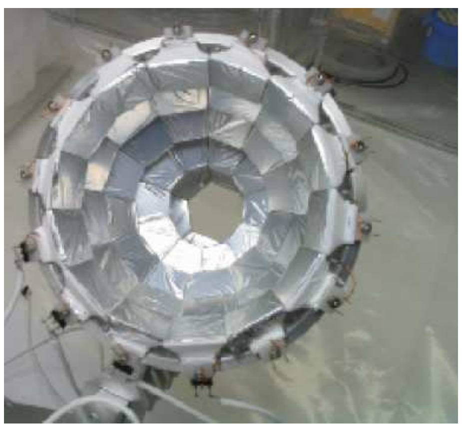


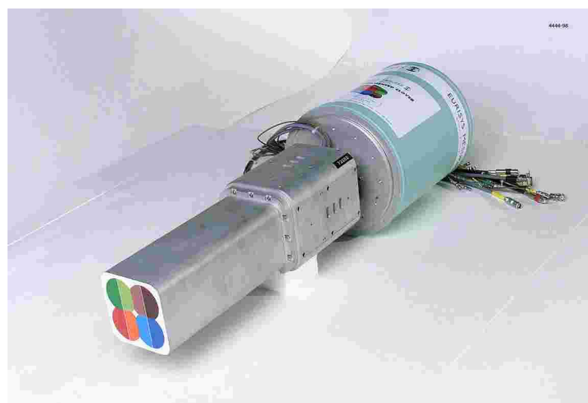
Attenuation coefficient due to RIV: contains information about the nuclear moment

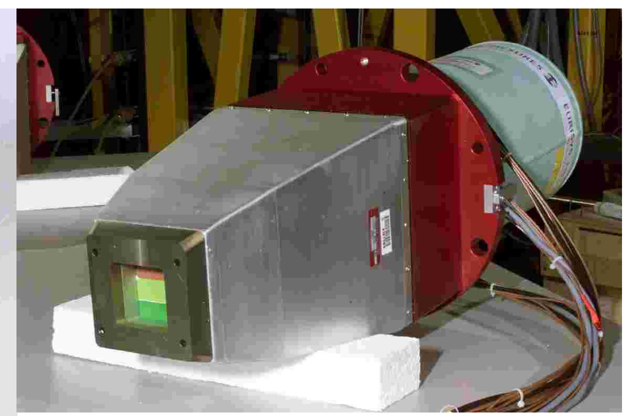
$$W(\theta_\gamma,\phi_p-\phi_\gamma) = \sum_{kq} \sqrt{(2k+1)}\, \rho_{kq}(\theta_p)\, G_k\, F_k\, Q_k\, D^{k*}_{q0}(\phi_p-\phi_\gamma,\theta_\gamma,0)$$

Clarion and Hyball at Holifield RIB Facility









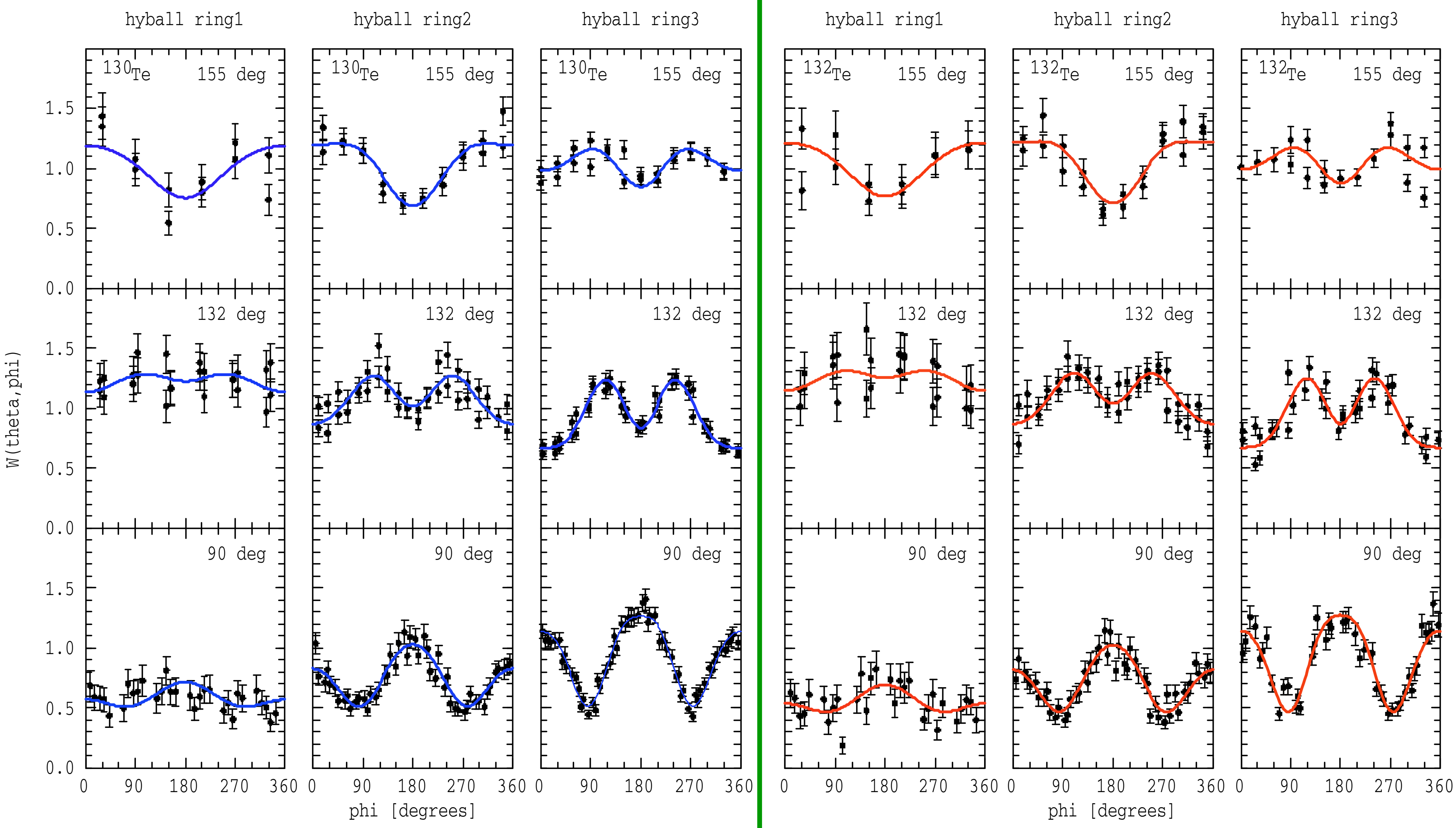
HyBall

95 CsI detectors with photodiodes

CLARION

11 segmented clover Ge detectors

Perturbed azimuthal angular correlations



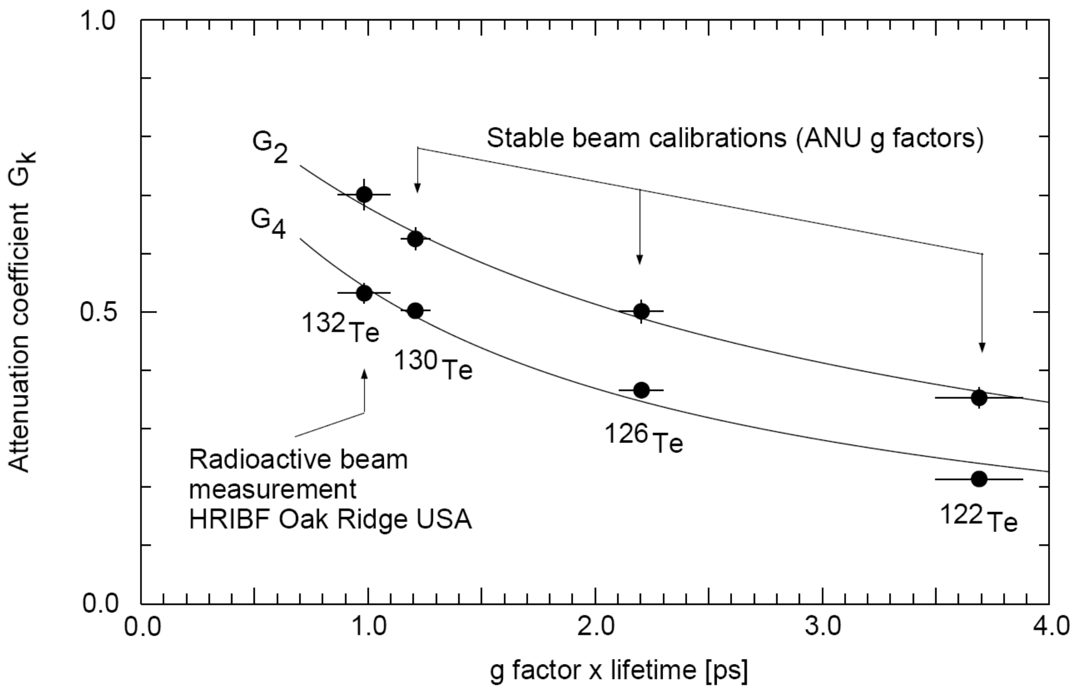
^{130}Te stable beam

^{132}Te Radioactive Beam

From attenuation coefficient G_k to g factor

Assume $G_k(t) = \alpha_k + (1-\alpha_k)\mathrm{e}^{-(t-t_0)/\tau_k}$ with $\tau_k = C_k/g^n$

$G_k(\infty) = \dfrac{C_k}{C_k + |g|\tau}$ proves adequate



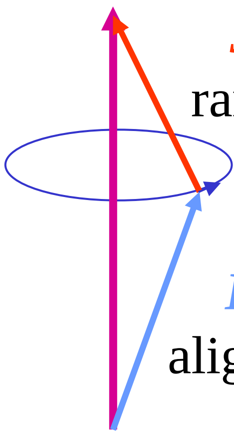
3 parameters:
C_2, C_4, $g(^{132}\mathrm{Te})$

$g(2^+;^{132}\mathrm{Te}) = 0.382(34)$

AES and NJ Stone,
PRC **76**, 034307 (2007)

Static model of the RIV interaction

$$G_k(J,B) = \sum_{F,F'} \frac{(2F+1)(2F'+1)}{(2J+1)} \begin{Bmatrix} F & F' & k \\ I & I & J \end{Bmatrix}^2 \frac{1}{1+[\omega_{F,F'}(B)\tau]^2}$$



Superimpose a distribution of time-invariant frequencies:

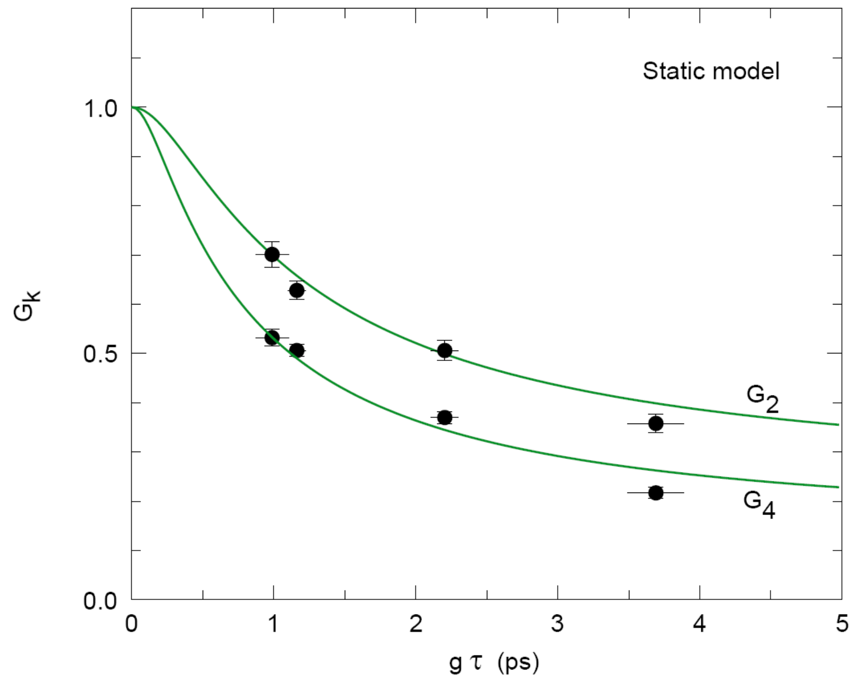
$$G_k = \sum_{i,j} w_J(J_i)\, w_B(B_J)\, G_k(J_i, B_j)$$

Gaussian distributions

Parameters:

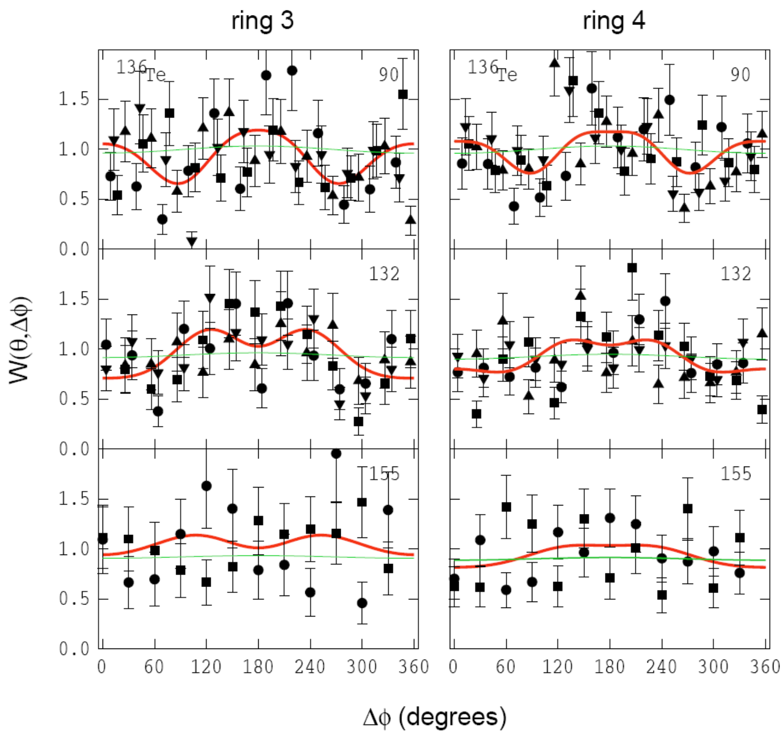
$\sigma_B = \overline{B} = 8.8$ kTesla

$\overline{J} = 4.5\hbar \quad \sigma_J = 1$



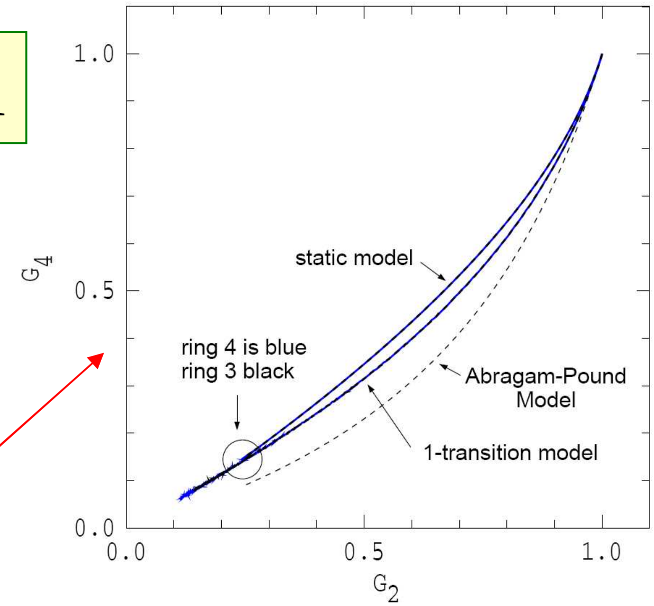
⇒The RIV interaction is mainly 'static'

Analyzing data with weaker beams

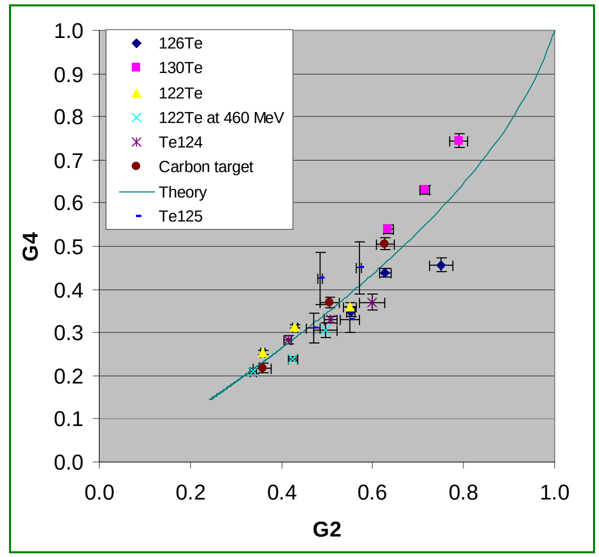


$^{136}Te + ^{50}Ti$

models



preliminary data



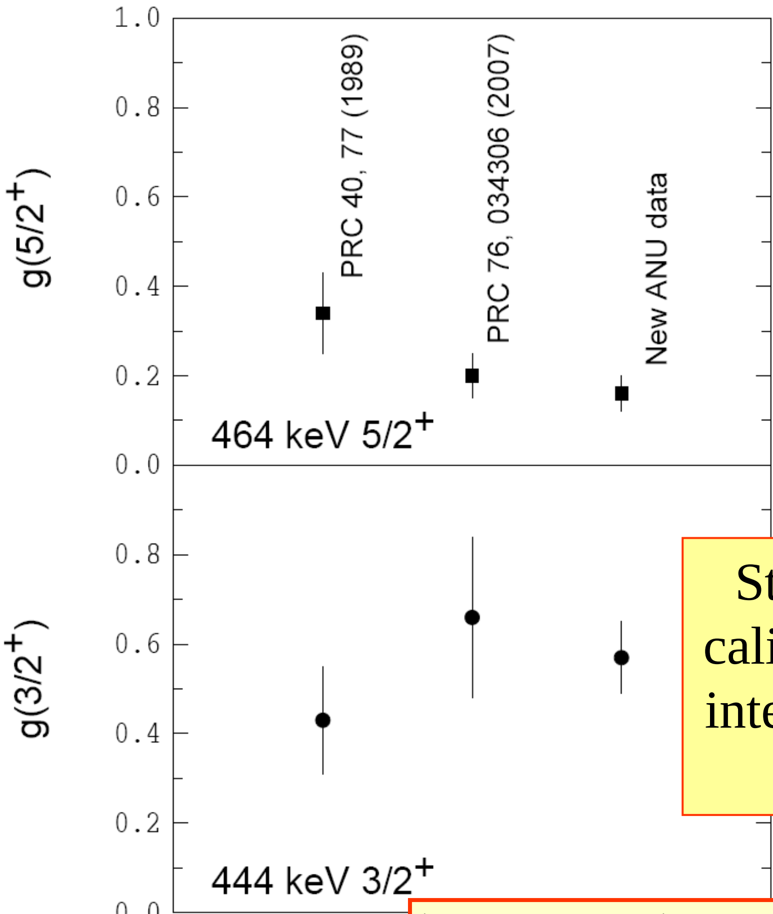
If we can constrain G_2 and G_4:

$$G_4 = f(G_2)$$

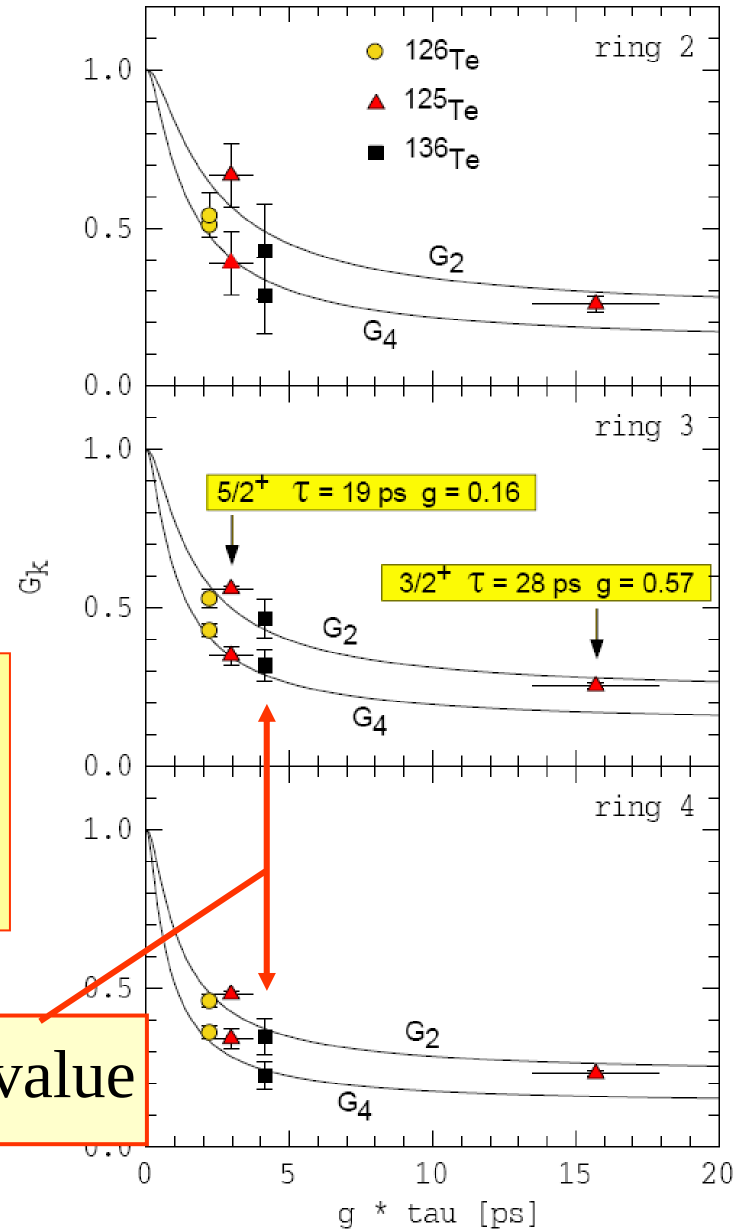
Can fit with a *single* parameter!

Preliminary: ^{136}Te

New *g* factor results in ^{125}Te @ ANU



States in ^{125}Te calibrate the RIV interaction out to ~ 30 ps



$|g(^{136}\text{Te})|$ = preliminary value

Summary and conclusions

- We need precise stable beam measurements with and for RIB work

- HVTF@NSCL: Analysis of ^{42,44,46}Ar and ^{58,62}Fe in progress

- ^{136}Te: RIV has been calibrated to ~ 30 ps
  - *g* factor suggests weakly coupled p and n configurations

The future

HVTF: ^{32}Mg (?); *N*~40 Ti,Cr,Fe isotopes

RIV: Re accelerated beams – CARIBU; MSU, etc

Acknowledgments

ANU

Michael East
Anna Wilson
Paul Davidson
Tibor Kibedi
Sanjay Chamoli

Rutgers

Noemie Koller
Gerfried Kumbartzki

MSU (2004)

Andrew Davies
Paul Mantica
Alex Brown
The β/NMR Group
The Gamma Group
Andreas Stolz
A1900 Beam Physicists

HRIBF

Nick Stone
Miro Danchev
John Pavan
Irena Stone
Claire Timlin
Jim Beene
Cyrus Baktash
Dave Radford
Carrol Bingham
Alfredo Gallindo-Uribarri
Chang-Hong Yu
Carl Gross

Participants in the HVTF runs @ NSCL Oct 08:
Michael East, Paul Mantica, Heather Crawford, Georgi Georgiev, Radi Lozeva, Andrea Jungclaus, Kei Minamisono, Jill Pinter, Josh Stoker, Alexandra Gade, Dirk Weisshaar, Kris Starosta, Geoff Grinyer, Andrew Ratkiewicz, David Miller, Sean McDaniel, Travis Baugher, Phil Voss.

MSU: NSF support; HRIBF: DOE support
ARC Discovery and RIEF schemes

AES *et al.* Travel support:
ANSTO AMRF Programme