

Nuclear moments of short-lived isomeric states – experimental techniques, recent studies and ideas for future developments

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Overview

- Introduction
 - Key ingredients: **lifetimes** of the states of interest; necessary **fields**; **spin orientation**
- First steps at **GANIL**
 - 1999 - ^{67}Ni , ^{69}Cu
 - 2002 + ... - $^{61}\text{Fe} \rightarrow \mu$ and Q
- The g-RISING campaign at **GSI** (2005)
 - Fission of $^{238}\text{U} - ^{126}\text{Sn}$ and ^{192}Pb
 - Fragmentation of $^{136}\text{Xe} - ^{127,128}\text{Sn}$
- ^{68}Ni region – revisited at **NSCL** (2005)
 - ^{67}Ni , ^{69}Ni and ^{70}Ni – K. Stoychev et al., submitted to PRC
- ^{132}Sn region – studies at **RIKEN**
 - ^{130}Sn (10^+) in TDPAD (2018 and 2024)
 - ^{132}Sn (6^+) in TDPAC (2024)
- Further **ideas for TDPAC** studies – advantages and difficulties
- A few take-home points

Nuclear structure and magnetic moments

Nuclei with non-zero spins have a magnetic dipole moment:

where g is the nuclear gyromagnetic ratio and I is the total angular momentum of the state.

$$\mu = gI [\mu_N]$$

Two sources of nuclear magnetism:

- orbital movement of charged particles;
- intrinsic spin of the nucleons.

Magnetic moment of a nucleus – contribution of all valence nucleons

$$\vec{\mu} = \sum_{k=1}^A g_{\ell}^{(k)} \vec{\ell}^{(k)} + \sum_{k=1}^A g_s^{(k)} \vec{s}^{(k)}$$

Sensitivity towards the nuclear structure:

- valence particle configuration;
- core polarization (M1 excitations);
- purity of the wave function (configuration mixing)

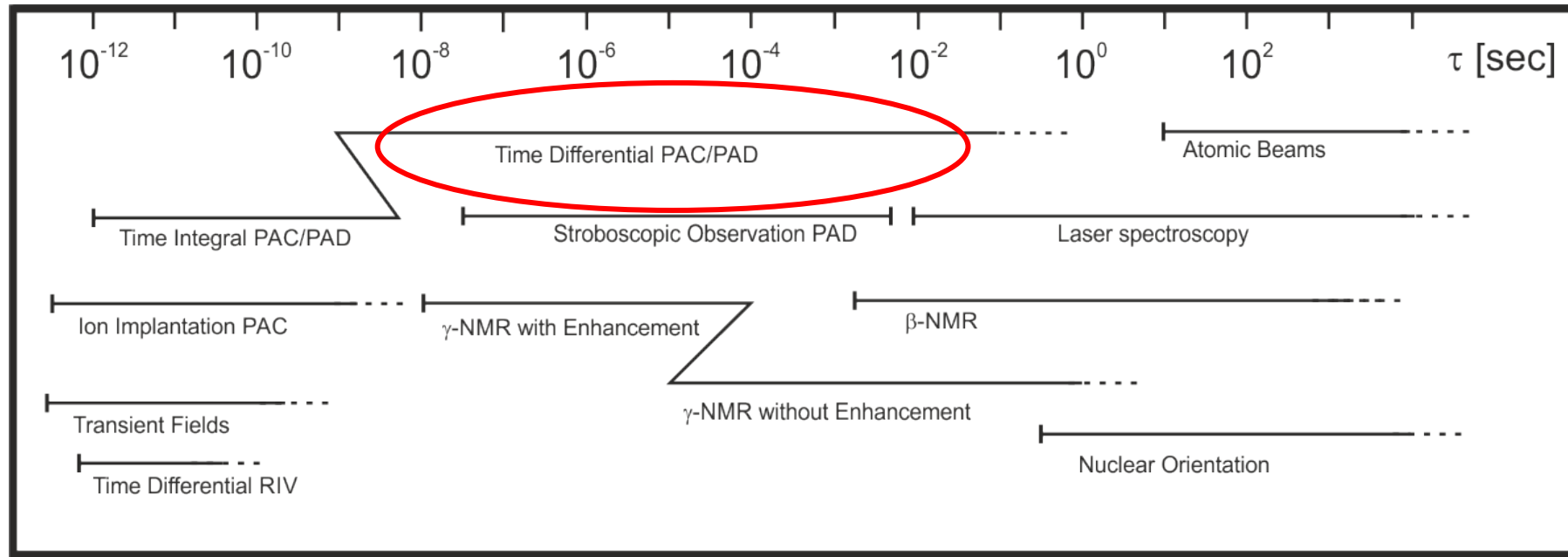
<i>free-nucleon</i>		<i>effective</i>	
$g_s^{\pi} = 5.58$	$g_{\ell}^{\pi} = 1$	$g_s^{\pi} = 0.7 * g_s^{\pi}$	$g_{\ell}^{\pi} = 1 + \Delta g^{\pi}$
$g_s^{\nu} = -3.28$	$g_{\ell}^{\nu} = 0$	$g_s^{\nu} = 0.7 * g_s^{\nu}$	$g_{\ell}^{\nu} = \Delta g^{\nu}$

Short-lived excited states (in even-even nuclei)

- any deviation from Z/A indicates (strong) shell effects

$$g = \frac{L_p}{L_p + L_n} \rightarrow g \approx \frac{Z}{A}$$

Moment measurements methods according to the lifetimes



Methods are strongly dependent on the *nuclear lifetimes* (>12 orders of magnitude) and they provide different level of *precision and accuracy*

Focusing on *Time Differential methods* (better control on the different experimental parameters)

- Time Dependent Perturbed Angular *Distribution* (TDPAD)
 - for *microsecond isomeric states* (in projectile fragmentation)
- Time Dependent Perturbed Angular *Correlations* (TDPAC)
 - down to (a few) *nanosecond isomeric states*

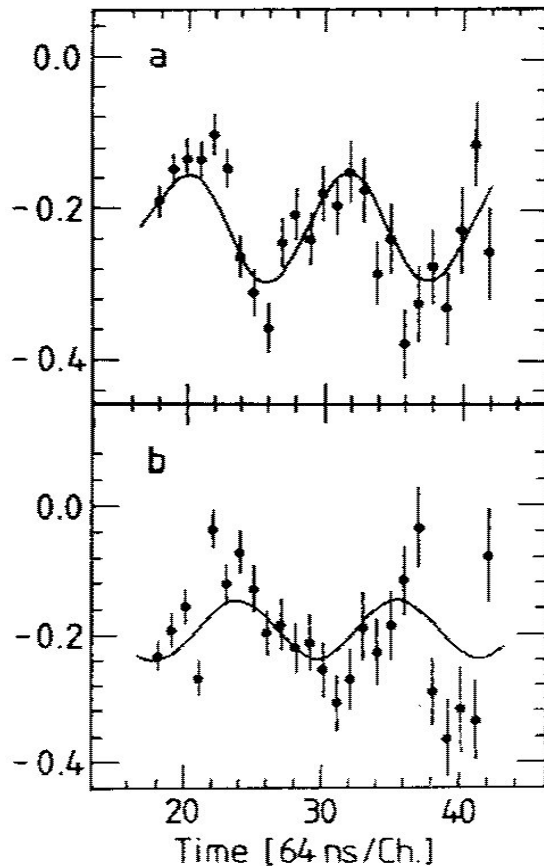
What magnetic fields for what lifetimes?

- Microsecond isomeric states: $t_{1/2} \sim \mathbf{1\ \mu s}$; $g \sim 0.5$
→ magnetic field of $\sim \mathbf{0.2\ T}$ is sufficient
(doable even with permanent magnets)
- Nanosecond lifetimes: $t_{1/2} \sim \mathbf{100\ ns}$; $g \sim 0.5$
→ magnetic field $\sim \mathbf{1.5\ T}$
strong room-temperature or “standard” superconducting magnets
- “Short nanoseconds”: $t_{1/2} \sim \mathbf{1\ ns}$; $g \sim 0.5$
→ magnetic field of $\sim \mathbf{100\ T}$
some ferromagnetic materials

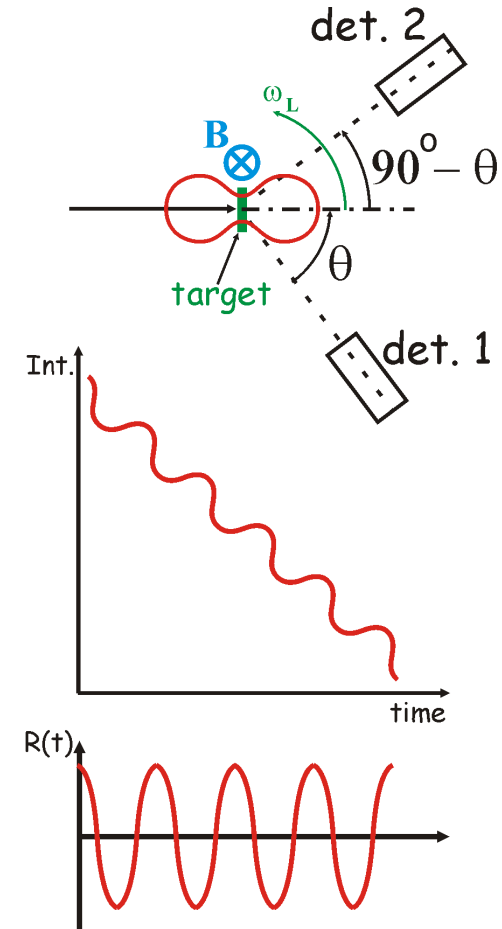
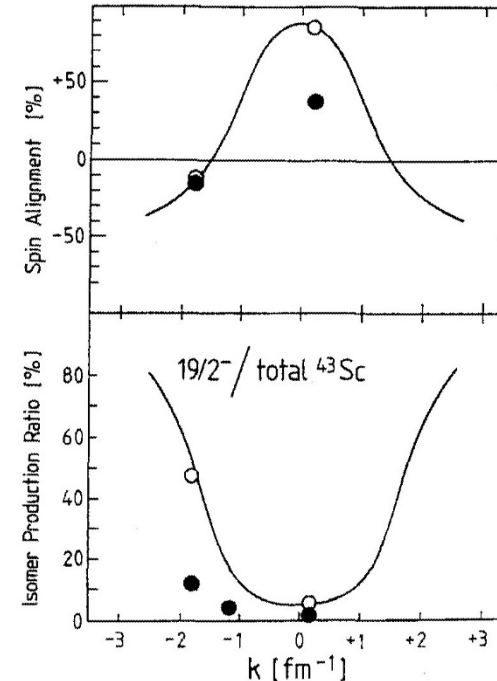
Time Dependent Perturbed Angular Distribution – the spin alignment???

- In *fusion-evaporation reactions* (stable beams) – *trivial* – the spin orientation is obtained readily from the reaction mechanism itself
- In *projectile fragmentation* - spin alignment obtained from the reaction mechanism (*provided specific momentum selection chosen*)
- Proof of principle experiment on ^{43}Sc at GSI:

W.-D. Schmidt-Ott, K. Asahi *et al.*; ZPA 350, 215 (1994)



Nuclear **spin alignment** is **momentum dependent** - observed both at the wing and in the center of the momentum distribution



$$R(t) = \frac{I(\theta, t) - I\left(\theta + \frac{\pi}{2}, t\right)}{I(\theta, t) + I\left(\theta + \frac{\pi}{2}, t\right)} = \frac{3A_2B_2}{4+A_2B_2} \cos\{2(\theta - \omega_L t - \alpha)\}$$

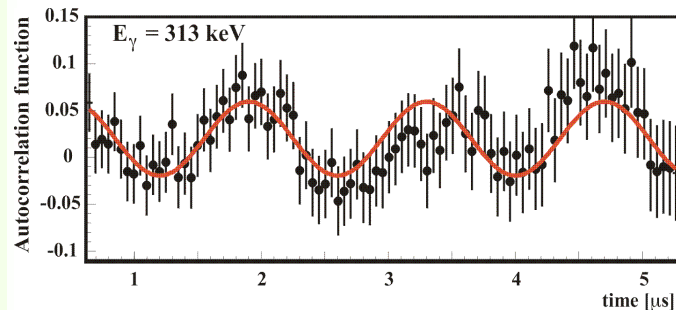
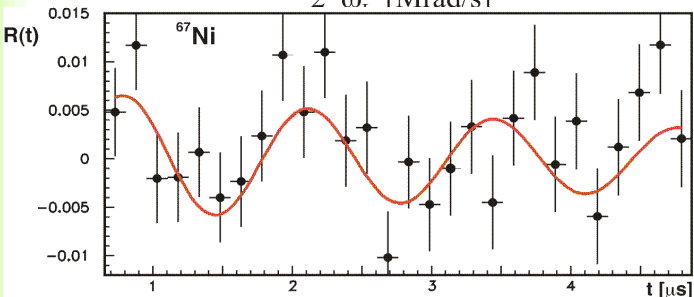
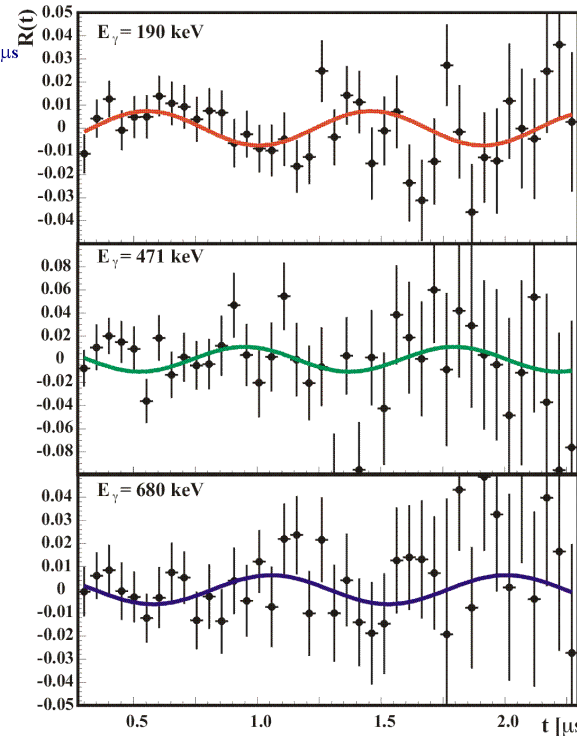
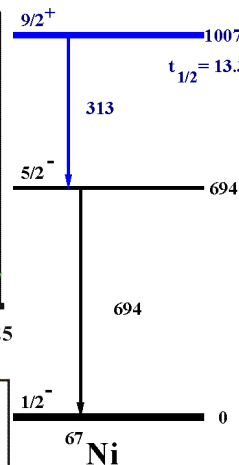
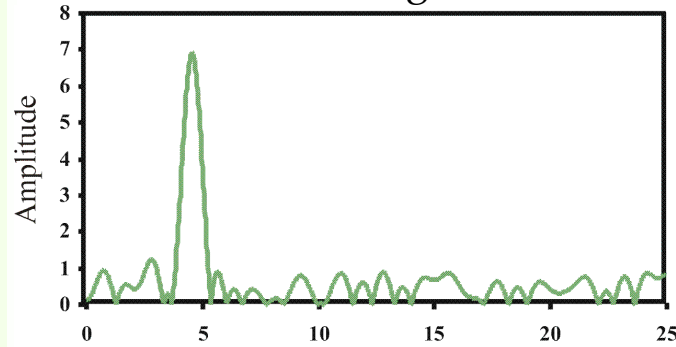
First steps @ GANIL

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1999 – 2002 + ...

First experiments at GANIL (1999 – 200X)

- ^{67}Ni , ^{69}Cu – magnetic moments studies



BaF_2

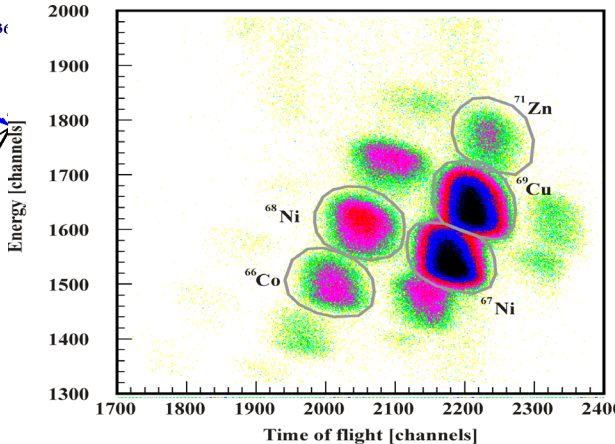
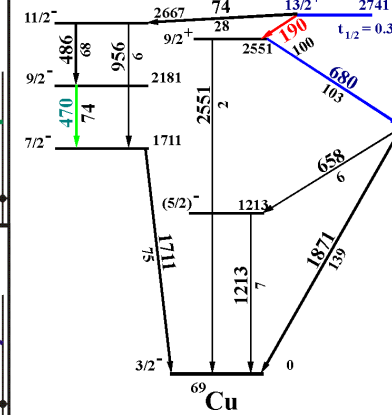
Ge
Clover



secondary
beam

Ge
Clover

BaF_2

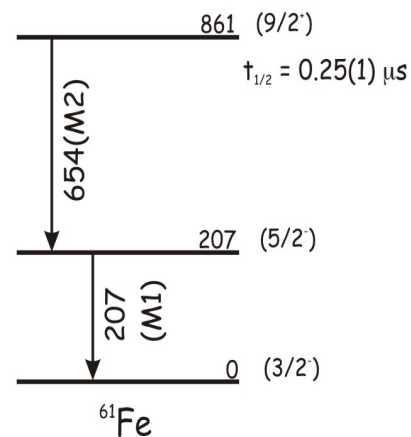
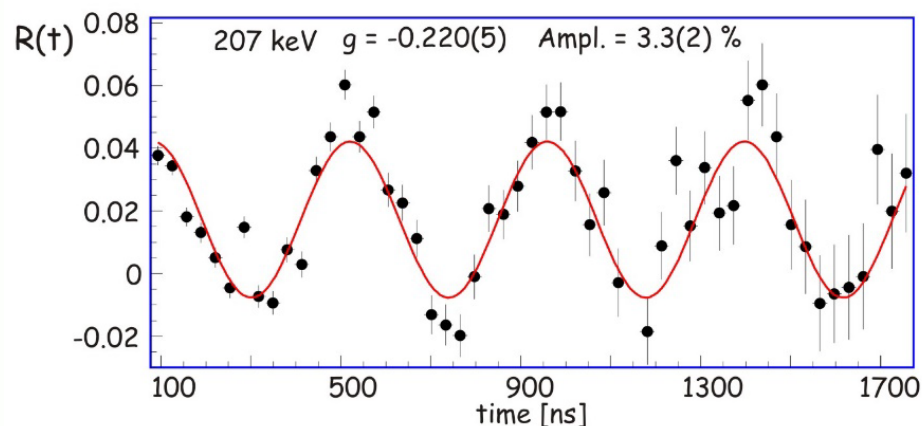
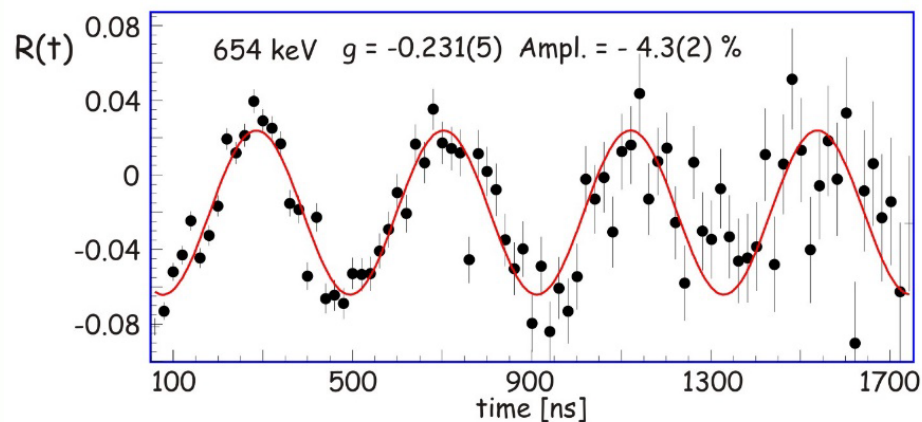


- Different momentum selection for the different isomers/isotopes
- Experimentally observed alignment:
 - $< 2\%$

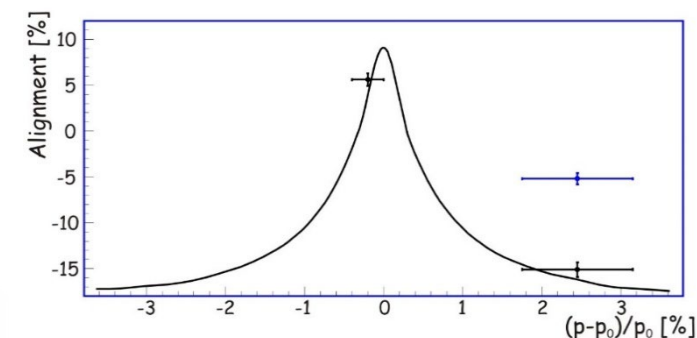
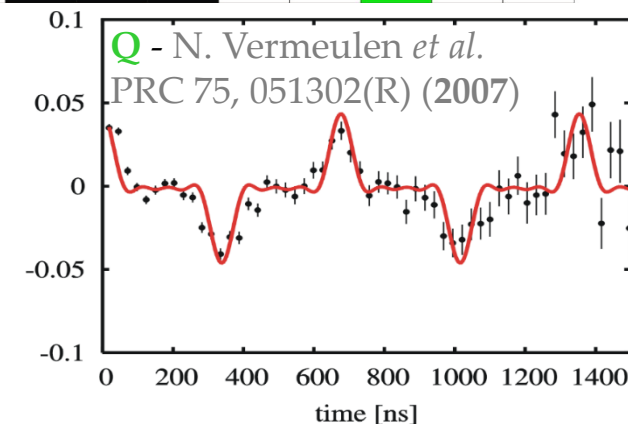
- $g(13/2^+, ^{69}\text{Cu})$ – well reproduced by the theory
- $g(9/2^+, ^{67}\text{Ni})$ – a factor of 2 off the expectations ... $\rightarrow$ **recently corrected**

TDPAD @ GANIL – the first steps with ^{61}Fe

- μ - I. Matea *et al.*; PRL 93, 142503 (2004)



$N = 28$				^{63}Zn	^{64}Zn	^{65}Zn	^{66}Zn	^{67}Zn	^{67}Zn	^{68}Zn	
		^{59}Cu	^{60}Cu	^{61}Cu	^{62}Cu	^{63}Cu	^{64}Cu	^{65}Cu	^{66}Cu	^{67}Cu	
	^{56}Ni	^{57}Ni	^{58}Ni	^{59}Ni	^{60}Ni	^{61}Ni	^{62}Ni	^{63}Ni	^{64}Ni	^{65}Ni	^{66}Ni
	^{55}Co	^{56}Co	^{57}Co	^{58}Co	^{59}Co	^{60}Co	^{61}Co	^{62}Co	^{63}Co	^{64}Co	^{65}Co
	^{54}Fe	^{55}Fe	^{56}Fe	^{57}Fe	^{58}Fe	^{59}Fe	^{60}Fe	^{61}Fe	^{62}Fe	^{63}Fe	



Spin alignment:

- -15.9(8) % - wing
- +6.2(7) % - center

The g-RISING campaign @ GSI

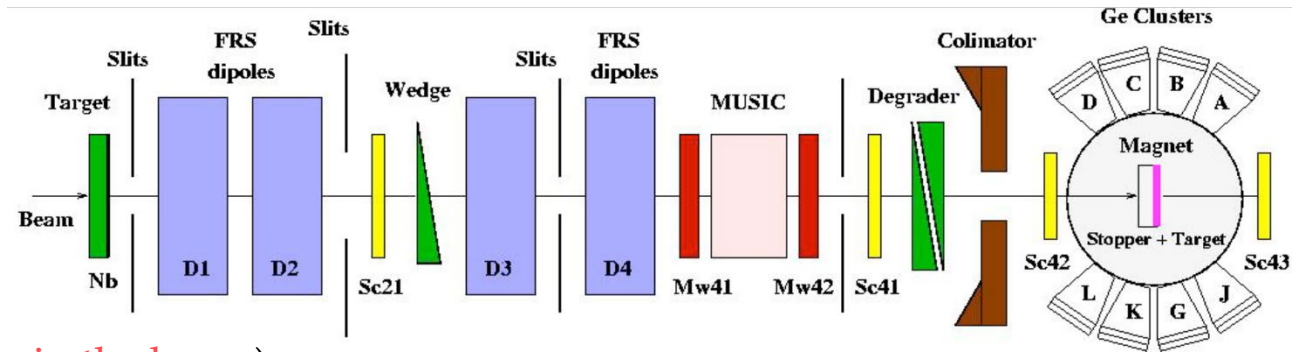
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2005

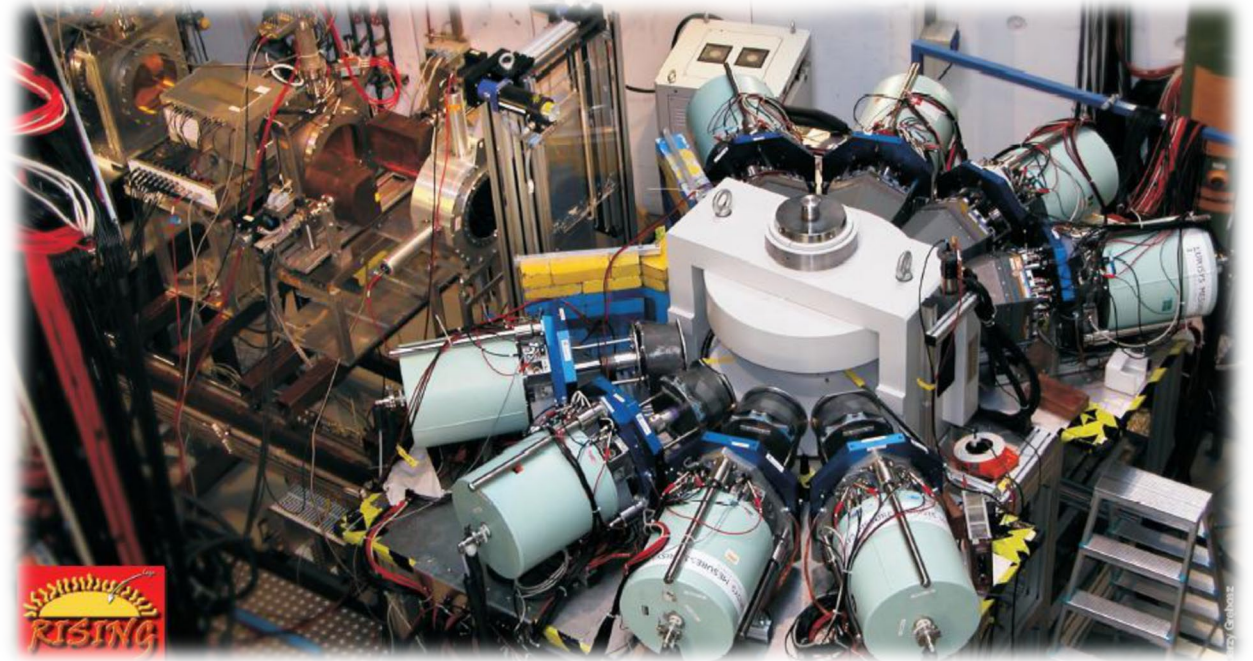
TDPAD @ GSI – the g-RISING campaign (2005)

g-RISING campaign in 2005:

- ^{238}U and ^{136}Xe beams
- 8 HPGe (7 fold) Clusters
- ion separation using FRS
(detectors and materials permanently in the beam)

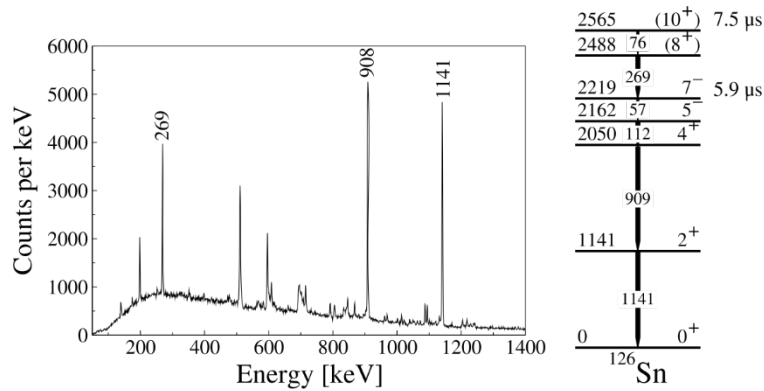


- ^{126}Sn ($10^+/7^-$) - G. Ilie *et al.*, PLB 687 (2010) 305
- ^{192}Pb (12^+)- M. Kmiecik *et al.*, EPJA 45, 153–158 (2010)
- ^{127}Sn ($19/2^+$)- L. Atanasova *et al.*, EPL **91** (2010) 42001

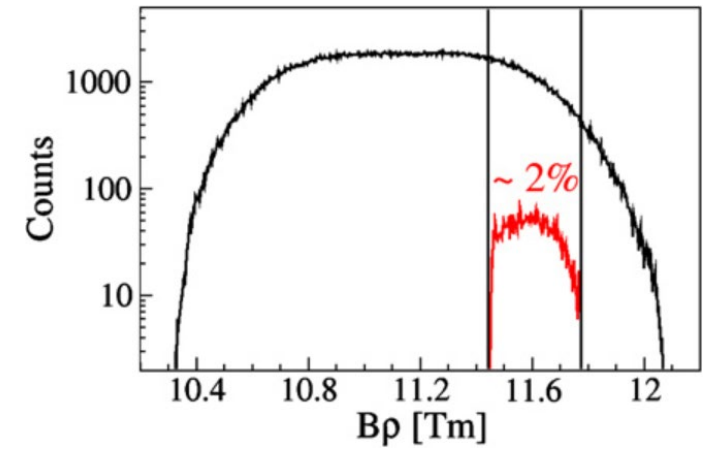


^{126}Sn 10^+ isomer from fission of ^{238}U

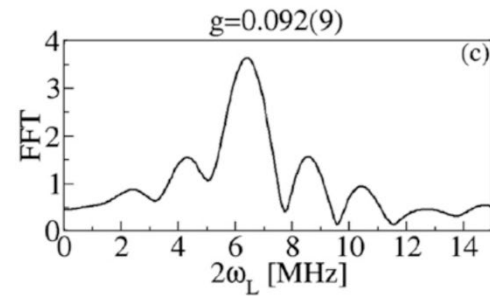
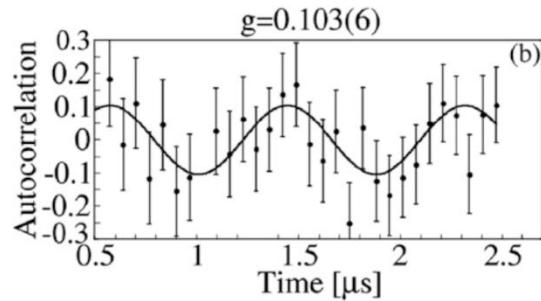
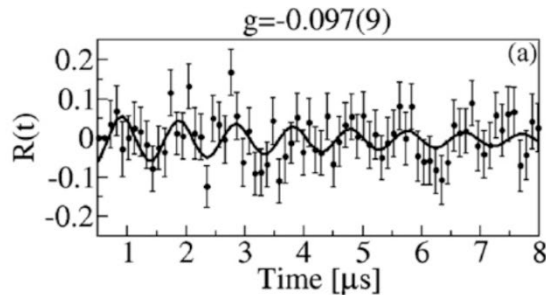
^{126}Sn ($10^+/7^-$) - G. Ilie et al., PLB 687 (2010) 305



Two isomers on top of each other



Momentum selection – non trivial to determine experimentally



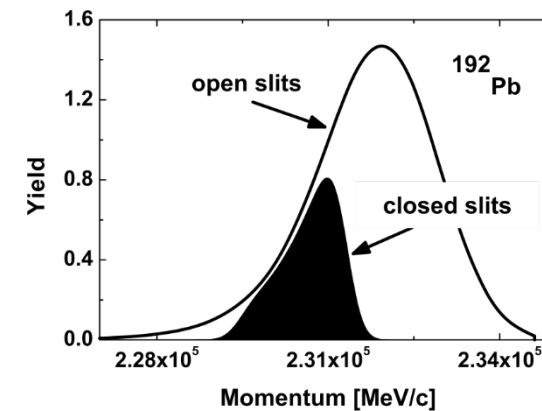
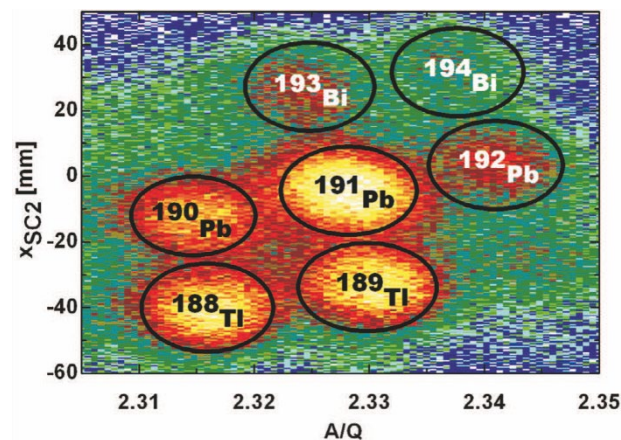
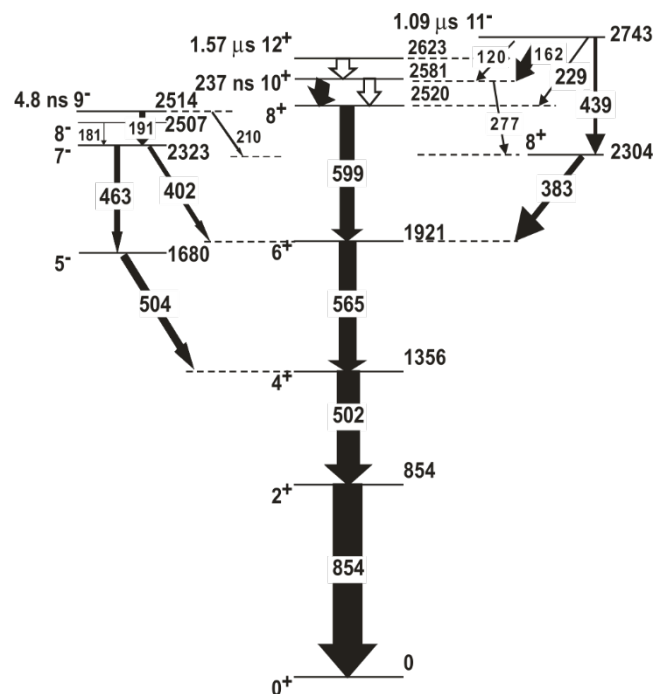
$R(t)$ function over long time scale (8 μs)

- Possible dumping of the amplitude
- Autocorrelation and FFT analysis

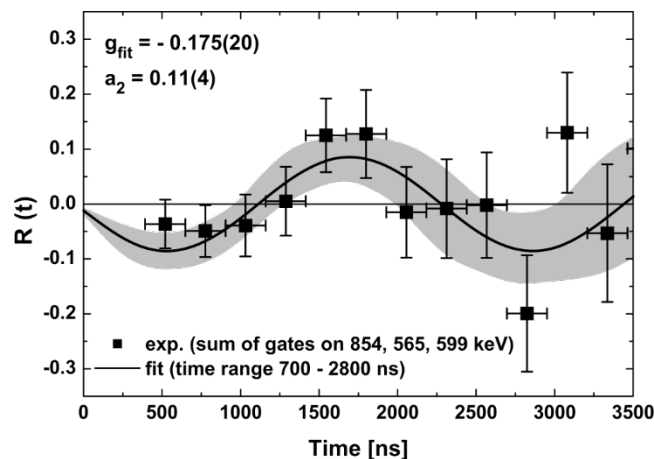
Claimed experimental alignment $\rightarrow 18(8)\%$ in relativistic fission of ^{238}U

^{192}Pb from ^{238}U fission – the difficulties at very high Z

^{192}Pb (12^+)- M. Kmiecik *et al.*, EPJA 45, 153–158 (2010)



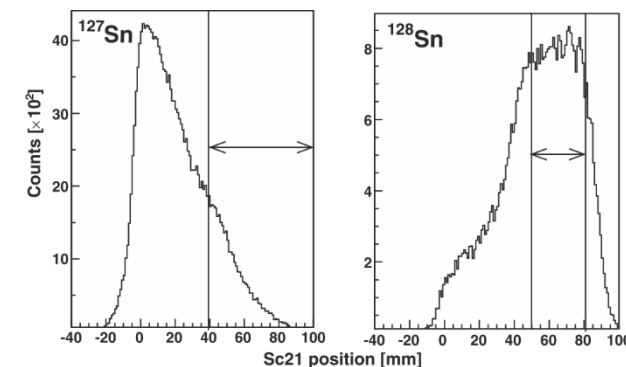
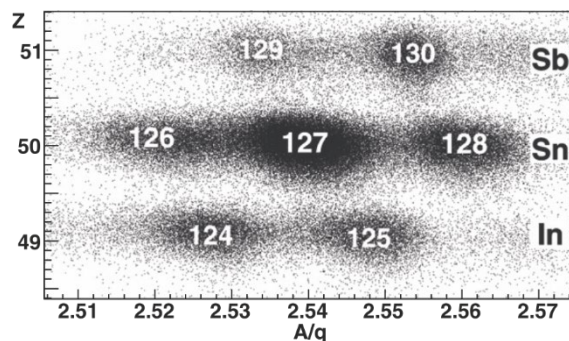
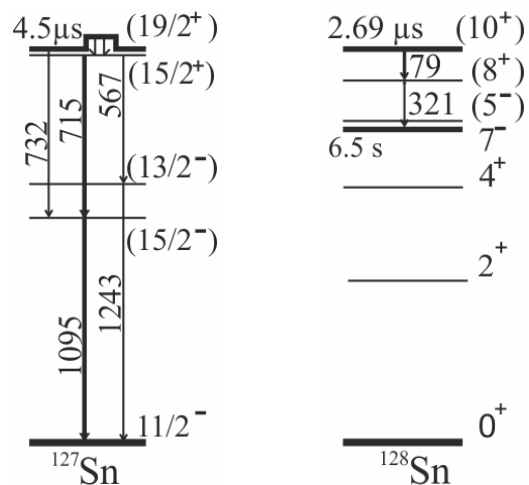
Momentum selection – calculated



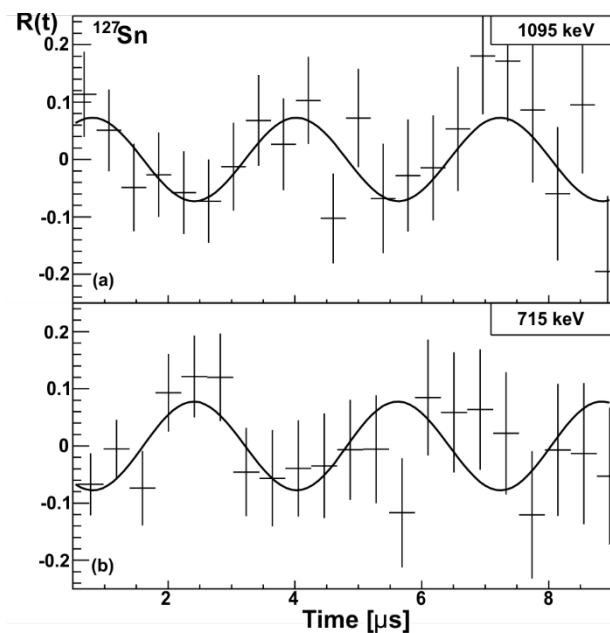
→ Claimed experimental alignment
28(10)% in relativistic fission of ^{238}U

^{127}Sn and ^{128}Sn – fragmentation of ^{136}Xe

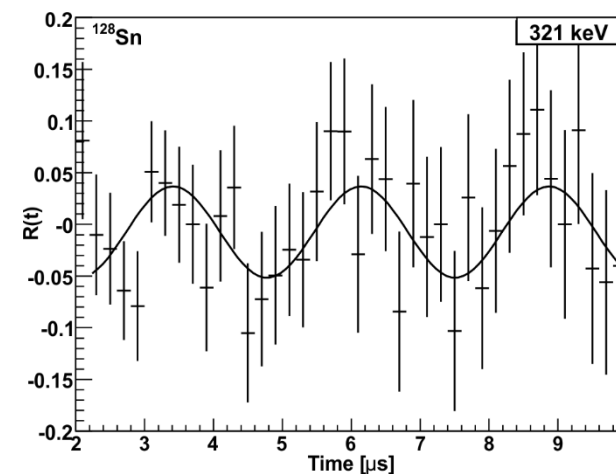
^{127}Sn ($19/2^+$)- L. Atanasova et al., EPL **91** (2010) 42001



Clear momentum selection



Data reanalysed and the results confirmed for the $19/2^+$ isomer in ^{127}Sn



Experimental alignment $\rightarrow -19(5)\%$ at the wing

The ^{68}Ni region revisited @ NSCL

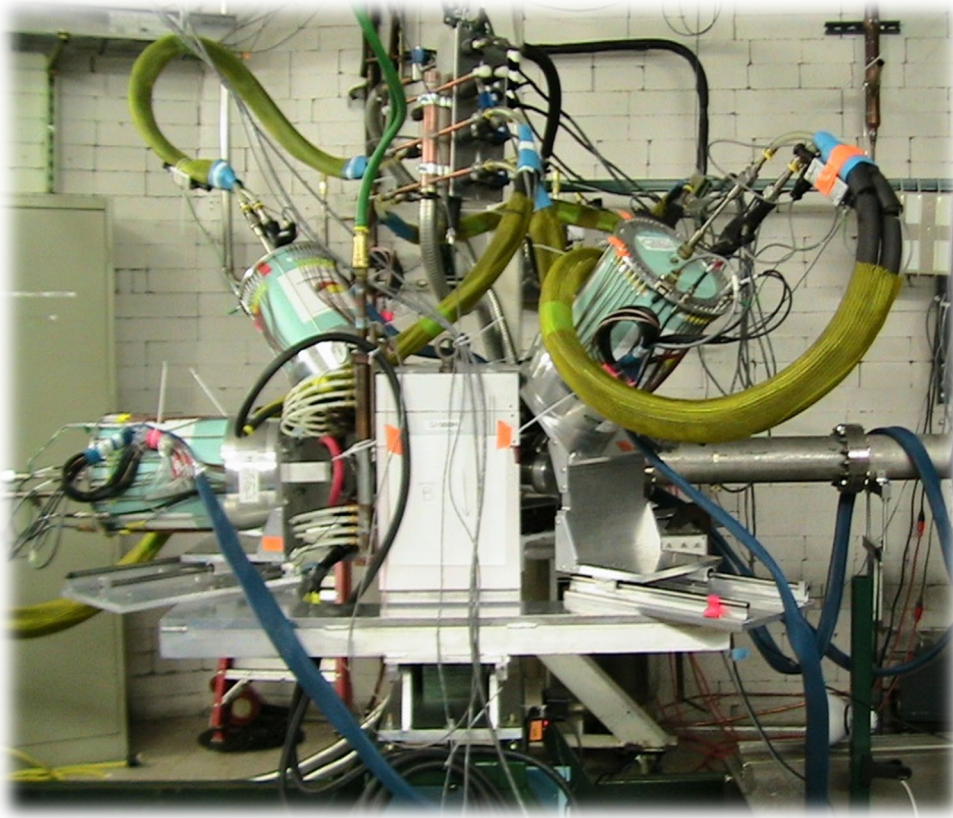
• • •

2005

Neutron-rich N=40 region

- the “doubly magic” ^{68}Ni ?

	^{63}Zn	^{64}Zn	^{65}Zn	^{66}Zn	^{67}Zn	^{68}Zn	^{69}Zn	^{70}Zn	^{71}Zn	^{72}Zn	^{73}Zn	^{74}Zn
^{61}Cu	^{62}Cu	^{63}Cu	^{64}Cu	^{65}Cu	^{66}Cu	^{67}Cu	^{68}Cu	^{69}Cu	^{70}Cu	^{71}Cu	^{72}Cu	^{73}Cu
^{60}Ni	^{61}Ni	^{62}Ni	^{63}Ni	^{64}Ni	^{65}Ni	^{66}Ni	^{67}Ni	^{68}Ni	^{69}Ni	^{70}Ni	^{71}Ni	^{72}Ni
^{59}Co	^{60}Co	^{61}Co	^{62}Co	^{63}Co	^{64}Co	^{65}Co	^{66}Co	^{67}Co	^{68}Co	^{69}Co	^{70}Co	
^{58}Fe	^{59}Fe	^{60}Fe	^{61}Fe	^{62}Fe	^{63}Fe	^{64}Fe	^{65}Fe	^{66}Fe	^{67}Fe	^{68}Fe		

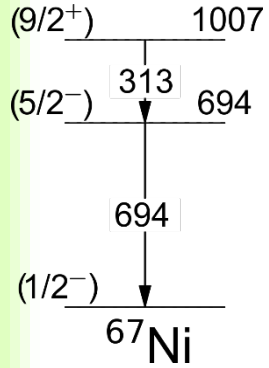


- ^{76}Ge beam @ 130 MeV/u
- 2mm ^9Be target
- 6+ nucleon removal reaction**
- 4 SeGA detectors
- thin plastic scintillator for $t=0$
- A1900 fragment separator ~90% beam purity

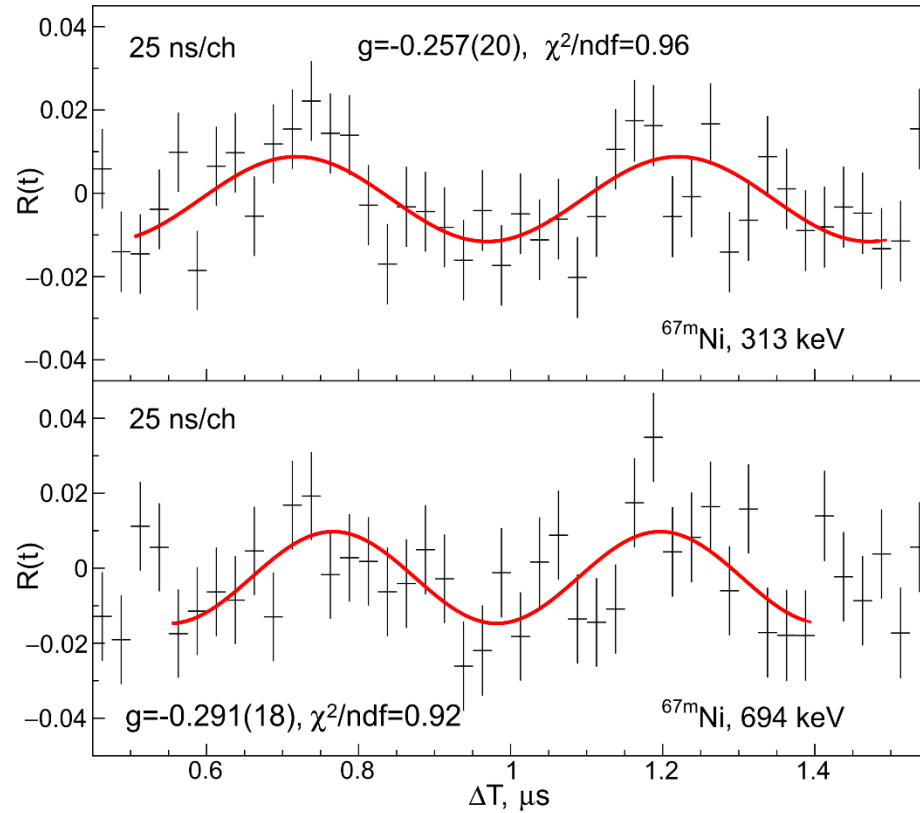
$N=40$			^{75}Ge	^{76}Ge	
		^{73}Ga	^{74}Ga	^{75}Ga	
	^{70}Zn	^{71}Zn	^{72}Zn	^{73}Zn	^{74}Zn
	^{69}Cu	^{70}Cu	^{71}Cu	^{72}Cu	^{73}Cu
	^{68}Ni	^{69}Ni	^{70}Ni	^{71}Ni	$Z=28$

Odd-mass cases – ^{67}Ni and ^{69}Ni

K. Stoychev *et al.*, submitted to PRC

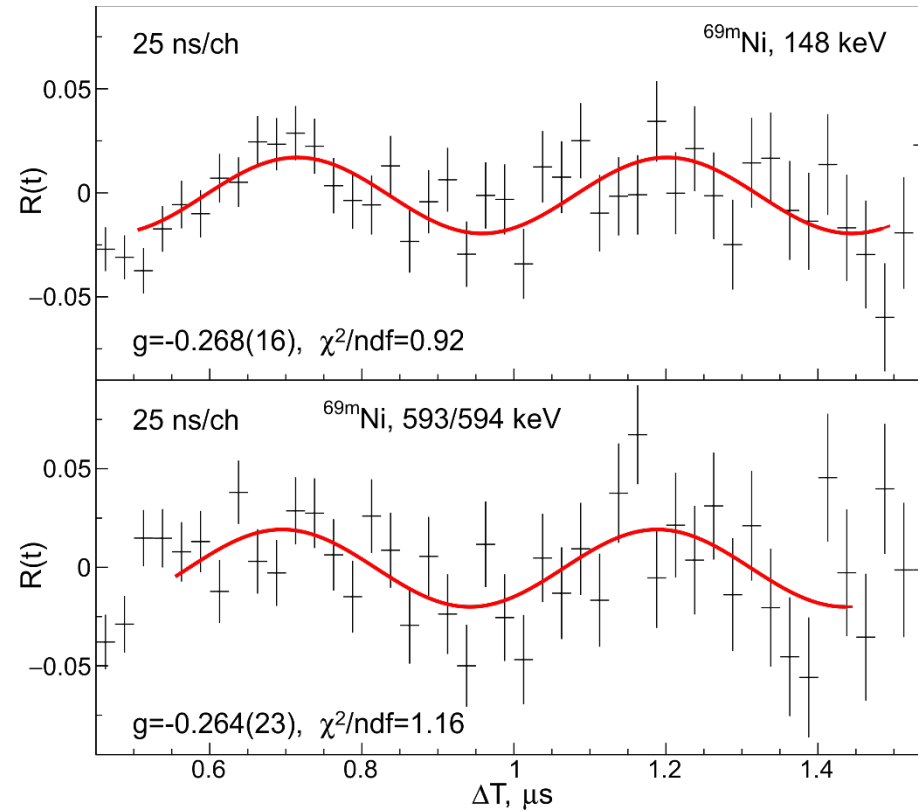


^{67}Ni , 9/2⁺, 13 μs

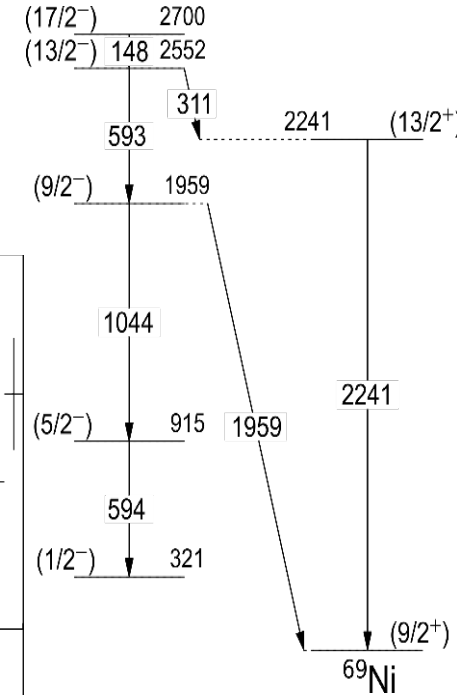


$$g(9/2^+, ^{67}\text{Ni}) = -0.276(13)$$

^{69}Ni , 17/2⁻, 439 ns

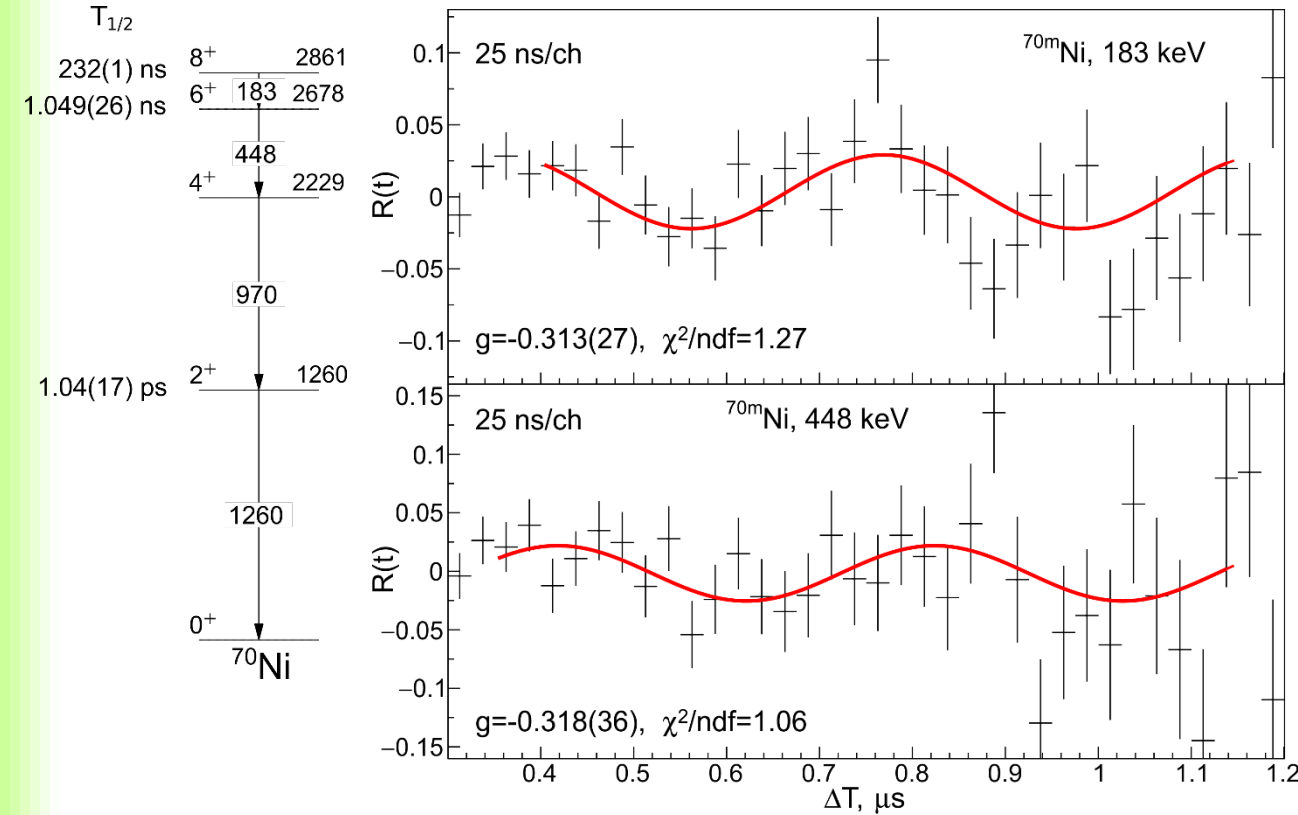


$$g(17/2^-, ^{69}\text{Ni}) = -0.267(13)$$



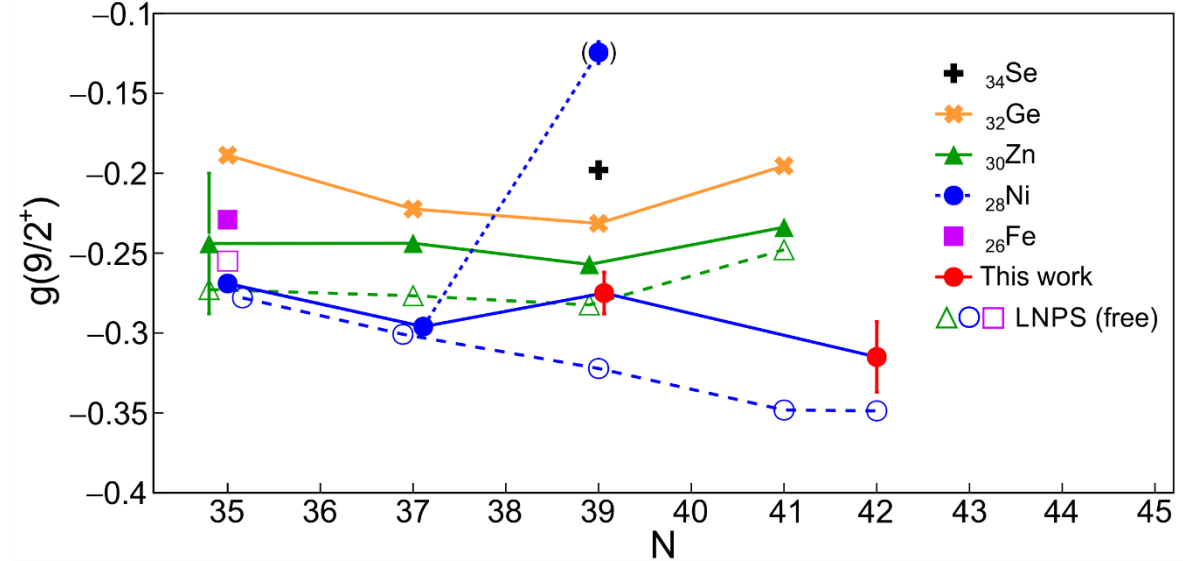
^{70}Ni and the theoretical comparison

K. Stoychev *et al.*, submitted to PRC



$$g(8^+, ^{70}\text{Ni}) = -0.313(27)$$

- Spin alignment:
 - ^{67}Ni : -3.2(7)% - wing
 - ^{69}Ni : -7.5(5)% - wing
 - ^{70}Ni : +5.6(1.8)% - center



- g factors of the Ni isotopes are well reproduced using **free-nucleon g factors** within the **LNPS interaction**
- a quenching factor of **0.9** is more appropriate in this case, compared to the “standardly used” **0.7**

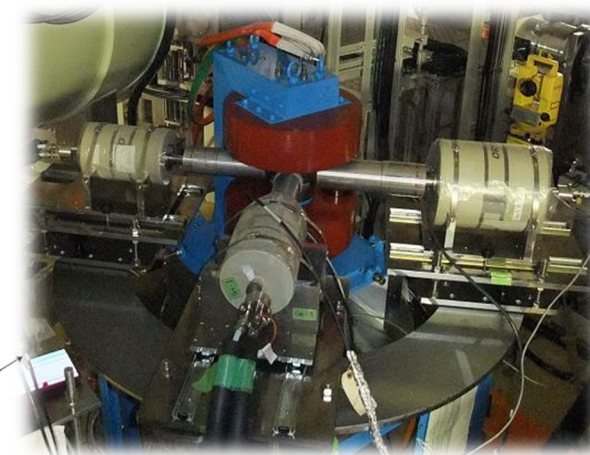
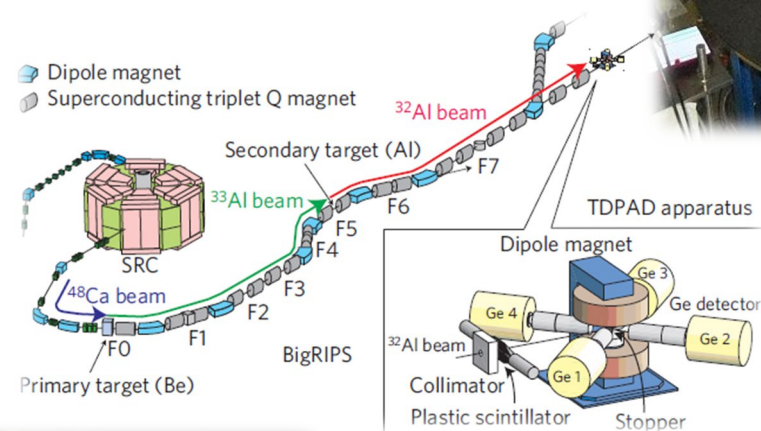
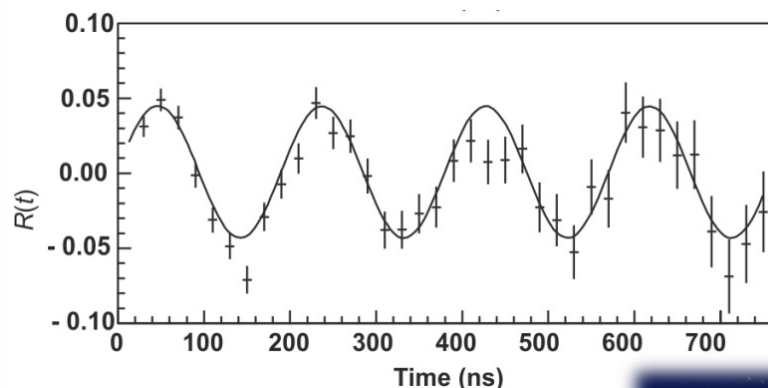
The ^{132}Sn region @ RIKEN

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2018 - 2024

Two-step reactions - the RIKEN approach

- Spin alignment in two-step projectile fragmentation
 - Starting with **1 (or 2?) nucleons away of the isotope of interest**
 - Using a **thick production target** and applying the **dispersion matching technique**
→ One needs to obtain a **higher (and well controllable) level of spin orientation**
- Proof of principle – ^{32}Al



Spin alignment:

- **8(1)% - center**



ARTICLES

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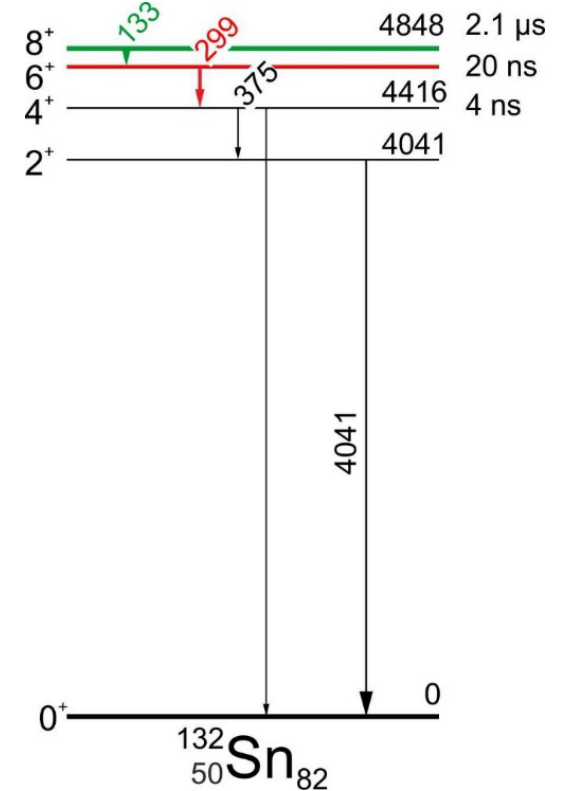
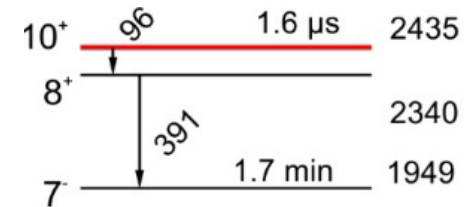
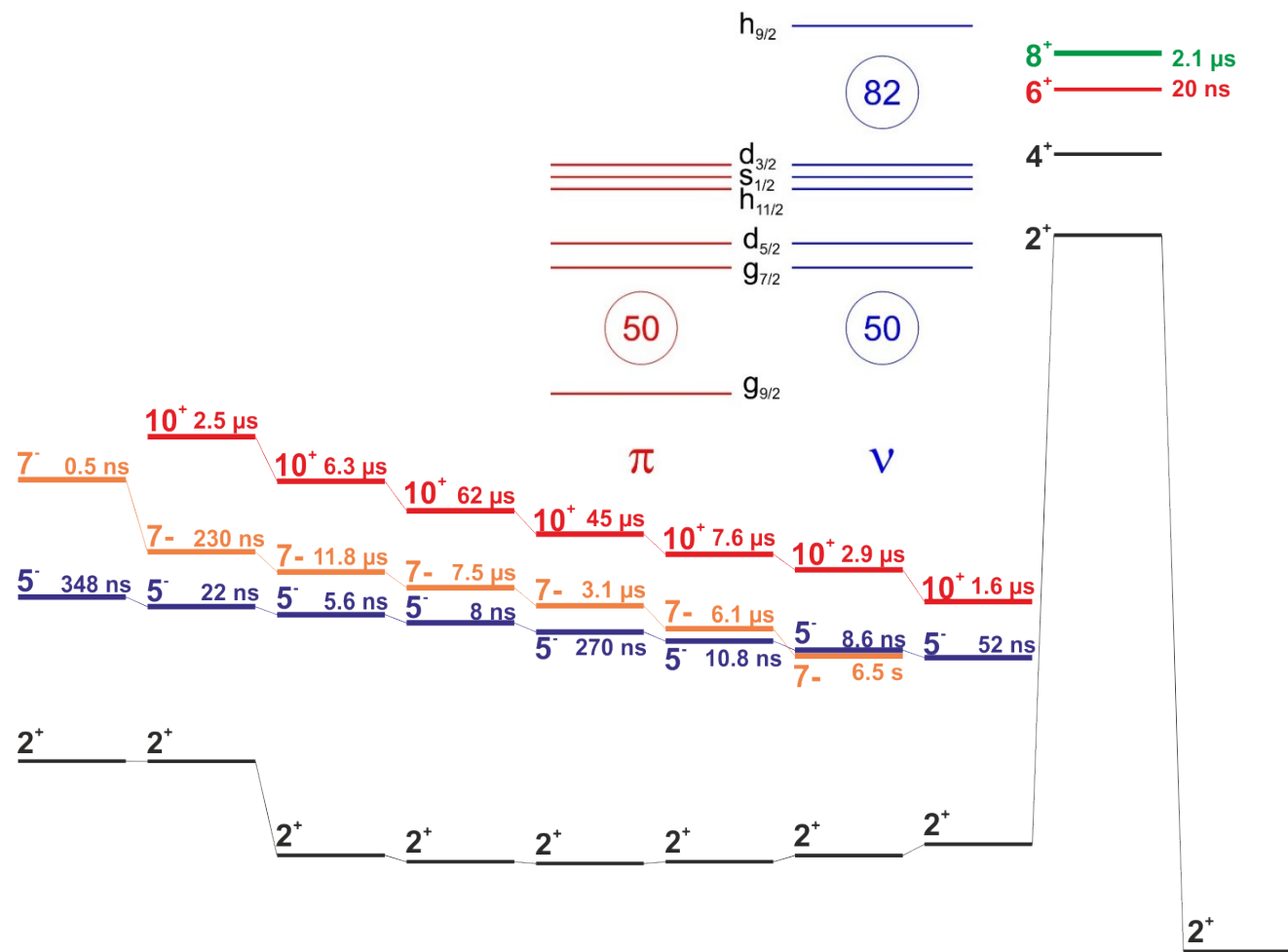
nature
physics

Production of spin-controlled rare isotope beams

Yuichi Ichikawa^{1*}, Hideki Ueno¹, Yuji Ishii², Takeshi Furukawa³, Akihiro Yoshimi⁴, Daisuke Kameda¹, Hiroshi Watanabe¹, Nori Aoi¹, Koichiro Asahi², Dimiter L. Balabanski⁵, Raphaël Chevrier⁶, Jean-Michel Daugas⁶, Naoki Fukuda¹, Georgi Georgiev⁷, Hironori Hayashi², Hiroaki Iijima²,

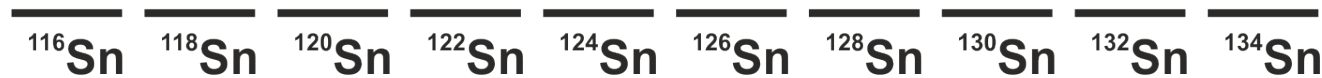
Y. Ichikawa *et al.*; Nature Physics 8, 918 (2012)

Nuclear structure around ^{132}Sn



$^{130}\text{Sn } 10^+: \text{vh}_{11/2}^2$

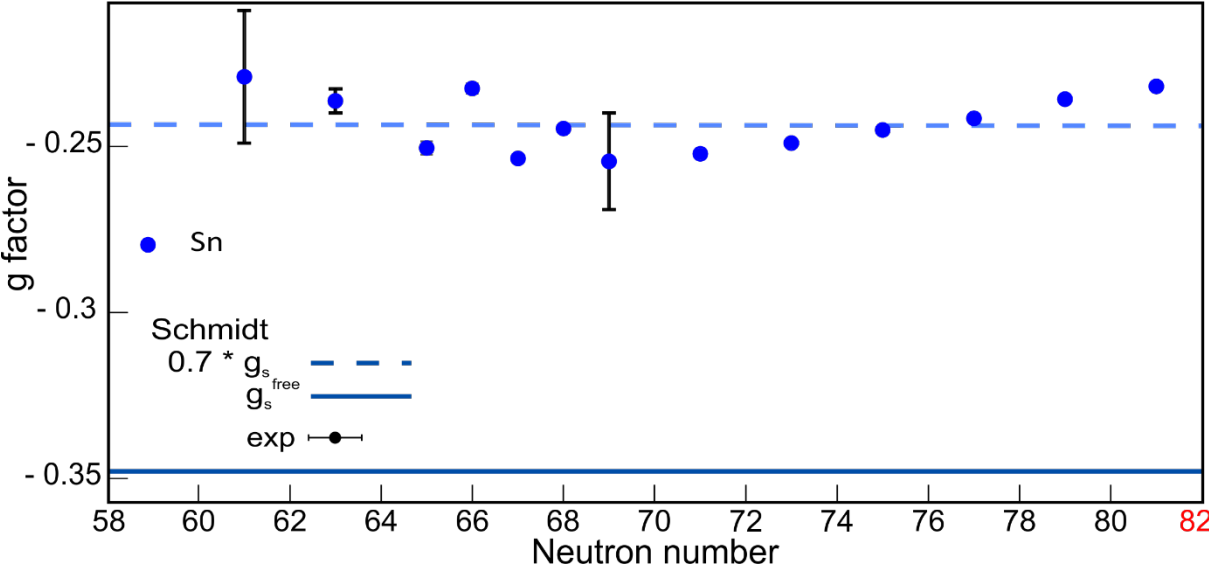
$$^{132}\text{Sn } 8^+: \text{vh}_{11/2}^{-1} \otimes \text{v}_{f7/2}$$



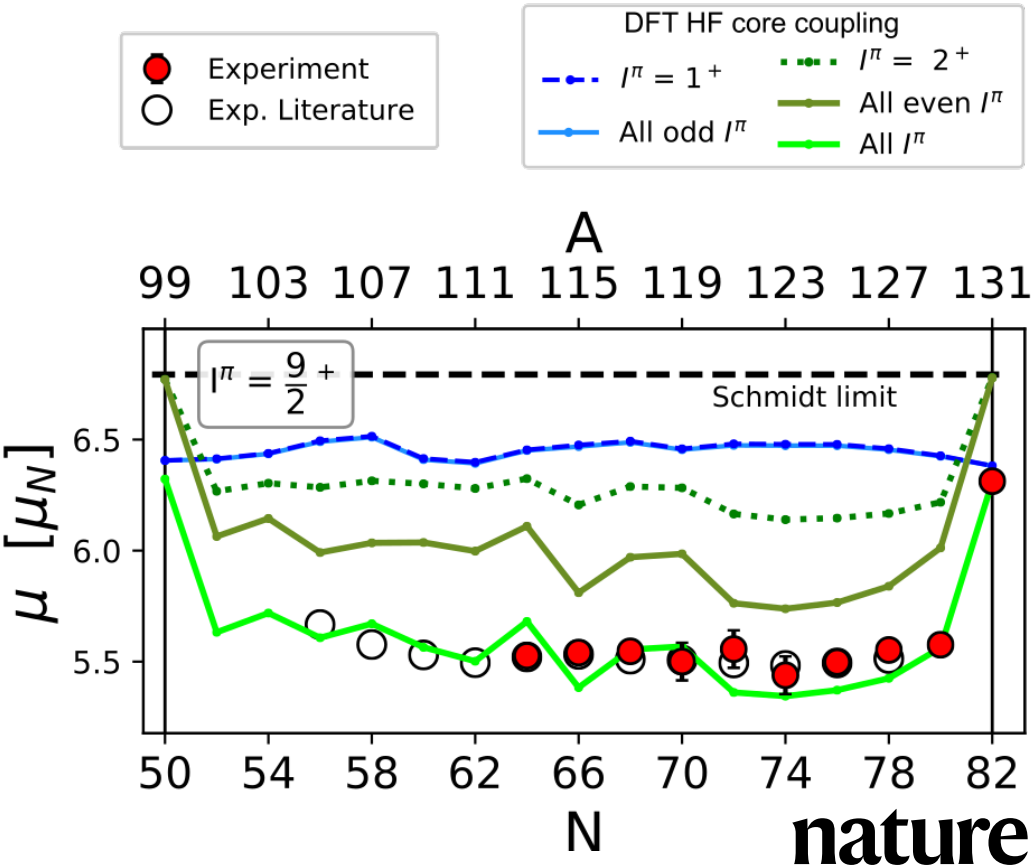
Sn126 1E+5 y 0+	Sn127 2.10 h (11/2-)*	Sn128 59.07 m 0+*	Sn129 2.23 m (3/2+)*	Sn130 3.72 m 0+*	Sn131 56.0 s (3/2-)*	Sn132 39.7 s 0+*	Sn133 1.44 s (7/2-)*	Sn134 1.04 s 0+*
β-	β-	β-	β-	β-	β-	β	β _n	β _n
In125 2.36 s 9/2(+)*	In126 1.60 s 8-*	In127 1.09 s (9/2+)*	In128 0.72 s 8-*	In129 0.61 s (9/2+)*	In130 0.54 s+0.55 s 5+8-*	In131 0.282 s (9/2+)*	In132 0.201 s 7-*	In133 180 ms
β-	β-	β-	β-	β-	β-	β	β	β

How “single-particle” is the structure around ^{132}Sn 's?

^{112}Sn 3.85 d 7/2+	^{114}Sn 9.01 h 8-	^{116}Sn 4.40 h 7/2+	^{118}Sn 39.5 m (8-)	^{120}Sn 23.03 m (7/2+)	^{122}Sn 2.79 m (4+)	^{124}Sn 2.5 m (7/2+)	^{126}Sn 0.85 s (0-)	^{128}Sn 1.71 s (7/2+)
β^-	β^-	β^-	β^-	β^-	β^-	β^-	β^-	β^-
^{126}In 1E+5 y 0+	^{127}Sn 2.10 h (11/2-)	^{128}Sn 59.07 m 0+	^{129}Sn 2.23 m (3/2+)	^{130}Sn 3.72 m 0+	^{131}Sn 56.0 s (3/2+)	^{132}Sn 39.7 s 0+	^{133}Sn 1.44 s (7/2-)	^{134}Sn 1.04 s 0+
β^-	β^-	β^-	β^-	β^-	β^-	β^-	β^-	β^-
^{125}In 2.36 s 9/2(+)	^{126}In 1.60 s 8-	^{127}In 1.09 s (9/2+)	^{128}In 0.72 s 8-	^{129}In 0.61 s (9/2+)	^{130}In 0.54 s/0.55 s 5+/8-	^{131}In 0.282 s (9/2+)	^{132}In 0.201 s 7-	^{133}In 180 ms
β^-	β^-	β^-	β^-	β^-	β^-	β^-	β^-	β^-



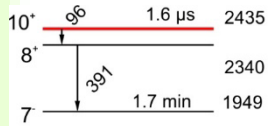
- Very constant g factors of *all 11/2- states in the Sn's*
 - How *pure are the nuclear wave functions* right at ^{132}Sn
- and could the *higher-spin states* bring a new insight?



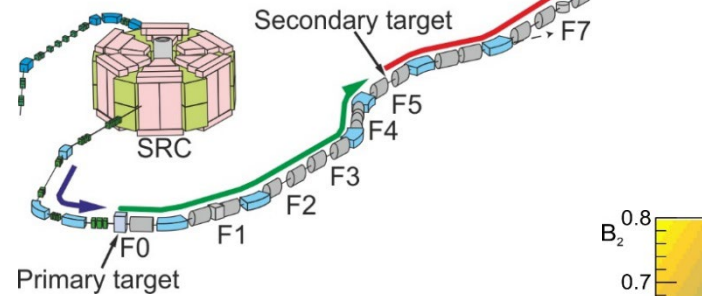
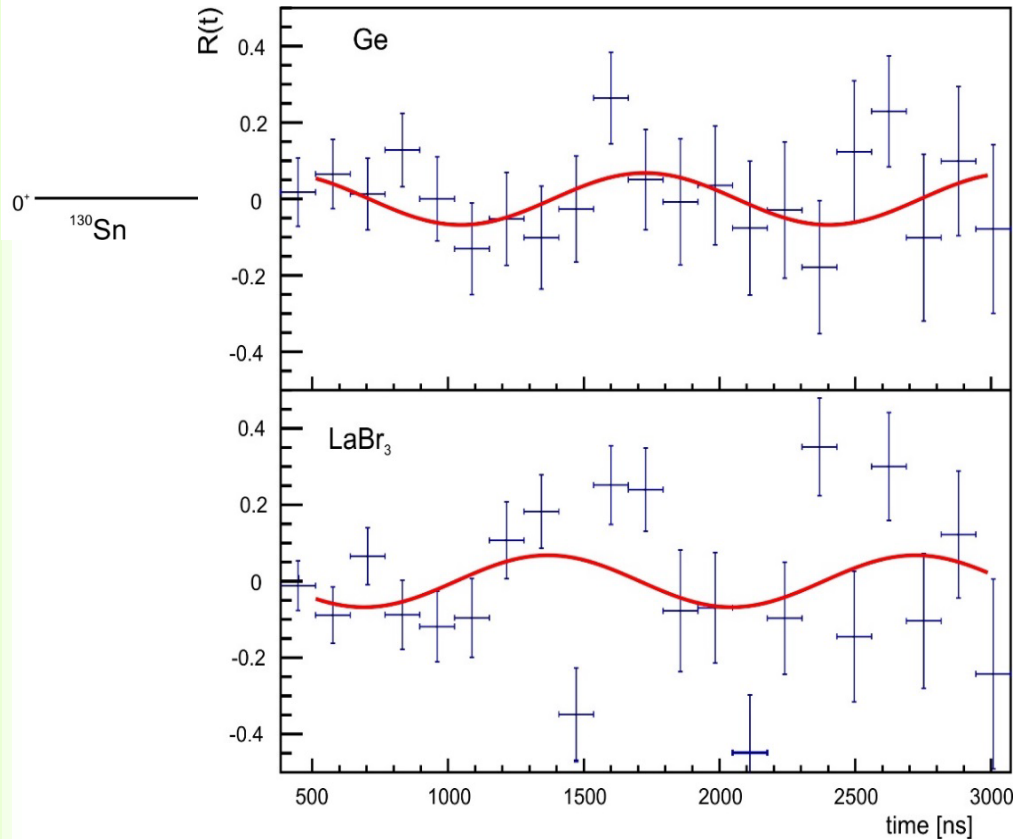
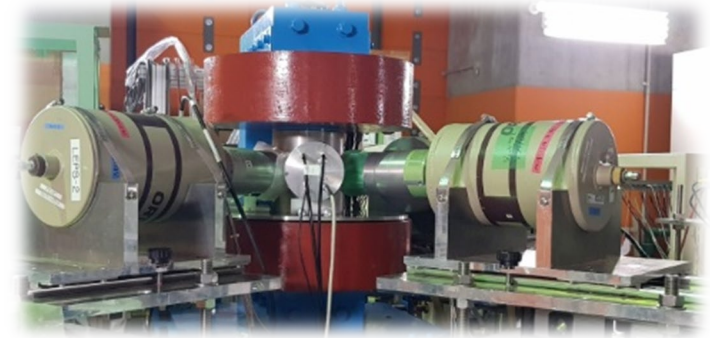
A.R. Vernon et al., Nature 607, 260 (2022)

Reproduced by the theory using *free-nucleon g factors*

^{130}Sn (10^+) – the first attempt (2018)

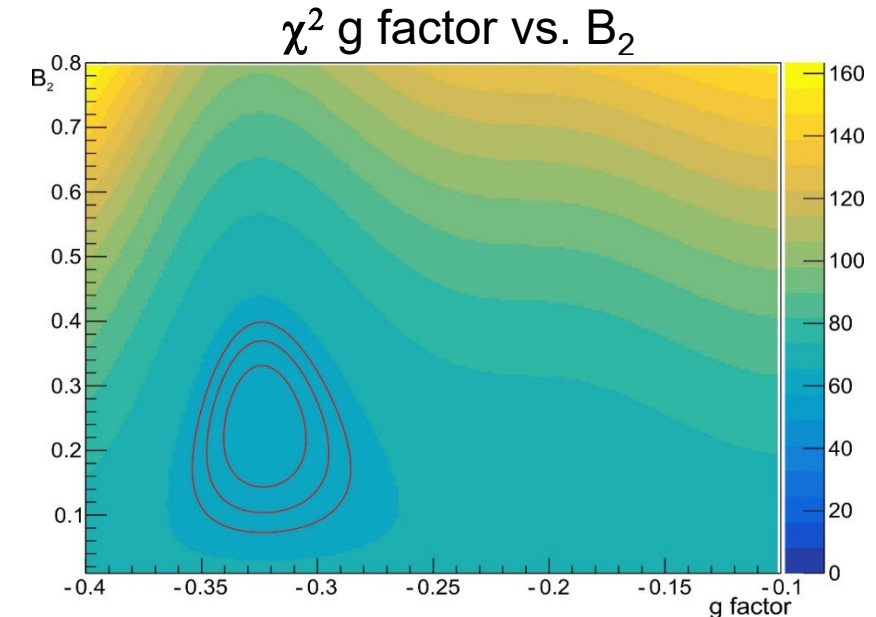


Primary beam - ^{238}U @ 345 MeV/u, 40 pA
 Secondary beam - ^{132}Sn , 223 MeV/u
 Tertiary beam - ^{130}Sn , 170 MeV/u



TDPAD setup:

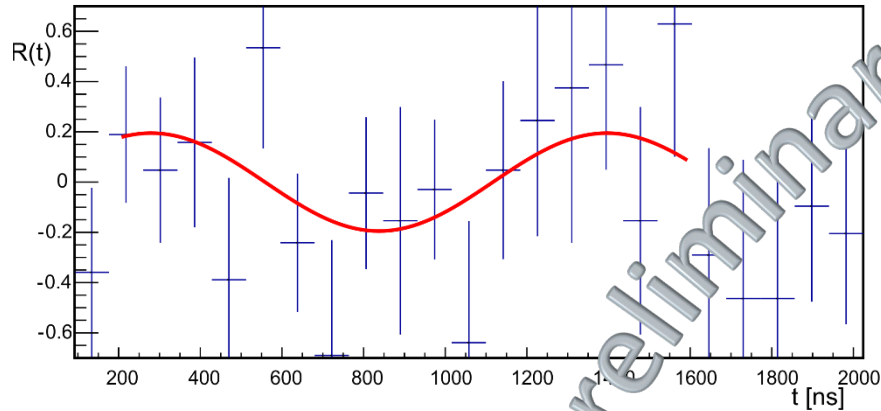
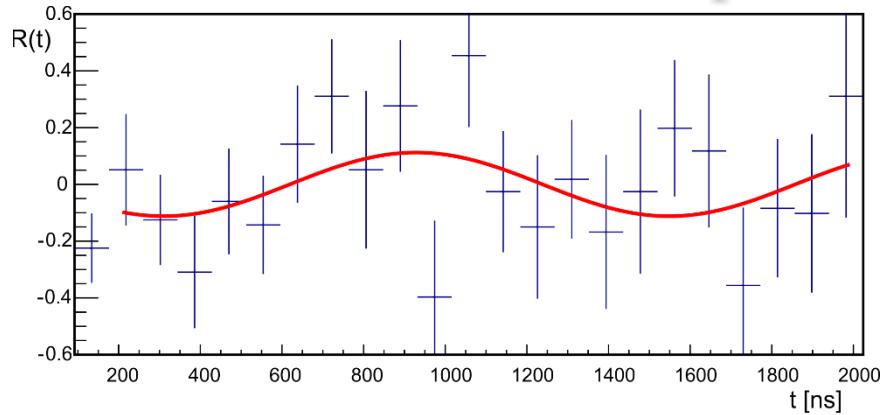
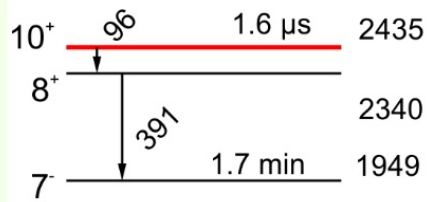
- plastic scintillator ($t=0$)
- 4 Ge (LE) + 2 LaBr_3 detectors
- magnetic field $B=150$ mT



$g = -0.32(2); B_2 = 0.24(9) (\leq 3\sigma)$

T.J. Gray, PhD Thesis, ANU 2021

NP1912-RIBF143R2 – second attempt in 2024



$$|g| = 0.35(5)$$

- Ion rate < 200 pps
- Beam purity ~85%
- Isomeric ratio (2n removal) ~ 2 %

data under analysis by **F. Graf von Spee**

- Consistency (opposite sign) between the 96 keV and the 391 keV transitions



TDPAD in projectile fragmentation or ... ?

- Control over the spin orientation (two-step reactions)
- Access to the “entire” nuclear chart

BUT ...

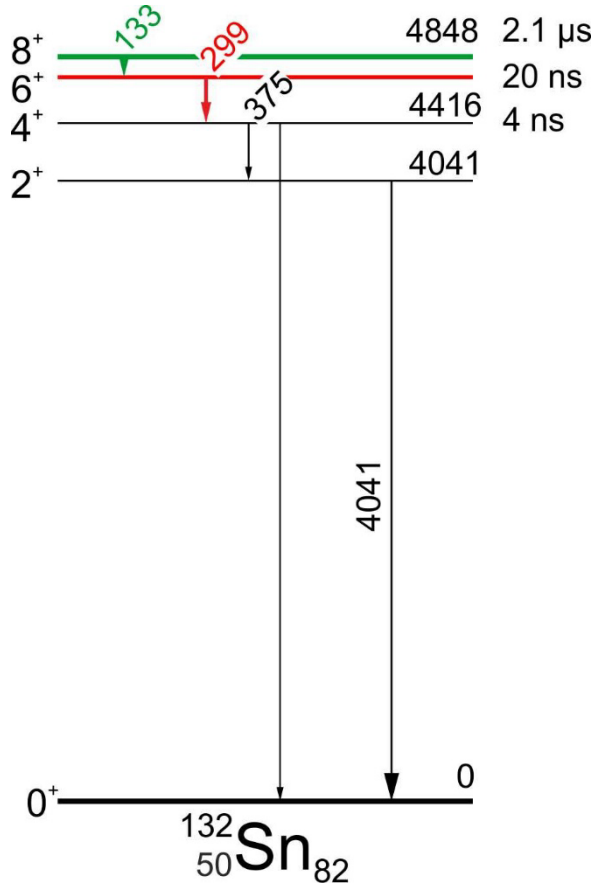
- Limited to relatively **long lifetimes (200+ ns)**
- We are pushing the limits of the statistics. How far could we go and still be confident in our results?

What about **TDPA**C?

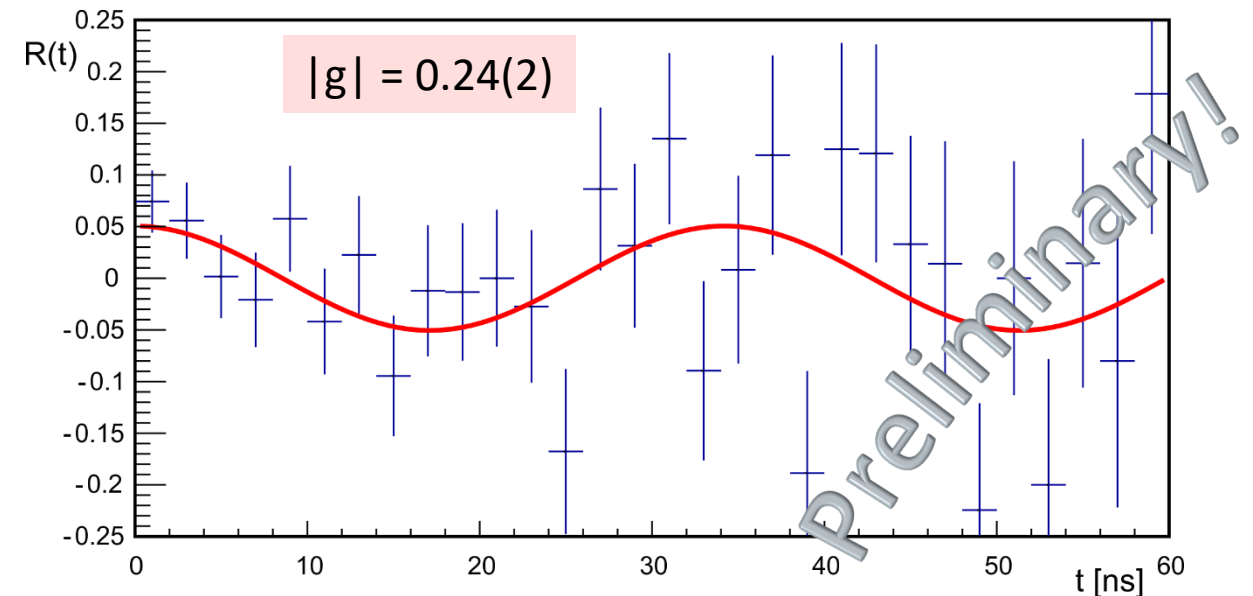
- Isomeric states populated after **isomeric** or **β -decay**
- No life-time limits (down to a ns)
- **NO spin orientation needed** – **γ – γ coincidences**
- Could be done both in fragmentation and by ISOL techniques

^{132}Sn 6^+ moment from 8^+ isomeric decay @ RIKEN

data under analysis by **F. Graf von Spee**



- ^{132}Sn secondary beam – 90 000+ pps (over 48 hours)
- 2 Ge LEPS + 2 LaBr₃ detectors
- Implantation in Fe host ($B_{\text{hf}}(\text{SnFe}) \sim -8\text{T}$)
- Beam energy - from 166 MeV/u down to ~ 130 MeV/u (to reduce the prompt flash)
- Limited by gamma-ray count rates (~ 5 kpps/Ge; ~ 20 kpps/LaBr₃)



Other possibilities in β -decay?
...

Moment measurements using TDPAC @ ISOL facilities

In collaboration with the ISOLDE SSP group – H. Haas (off-line studies):

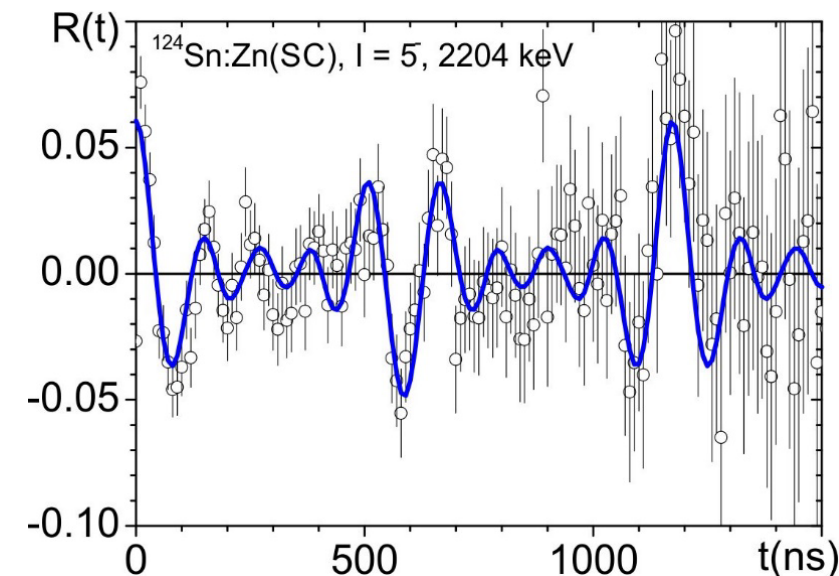
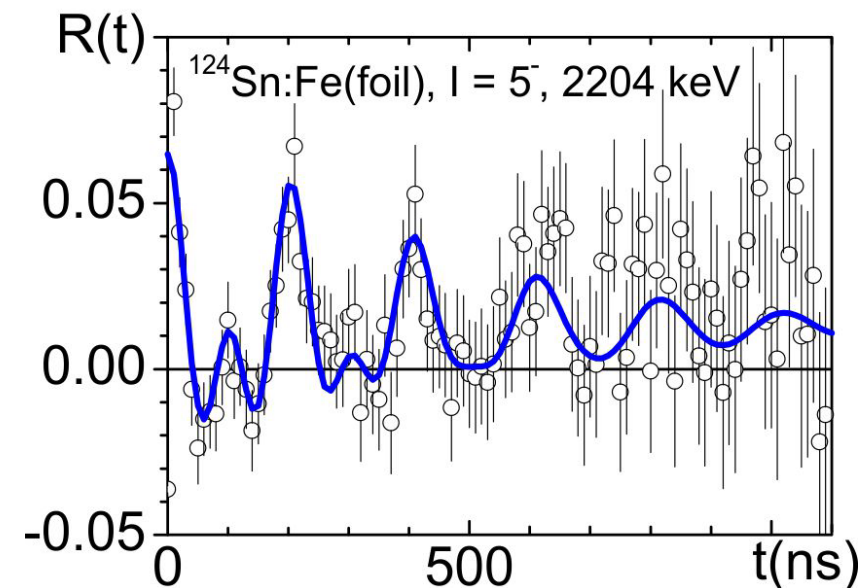
Run in June 2023 using the SSP setup (4 LaBr₃ detectors)

Data collected on:

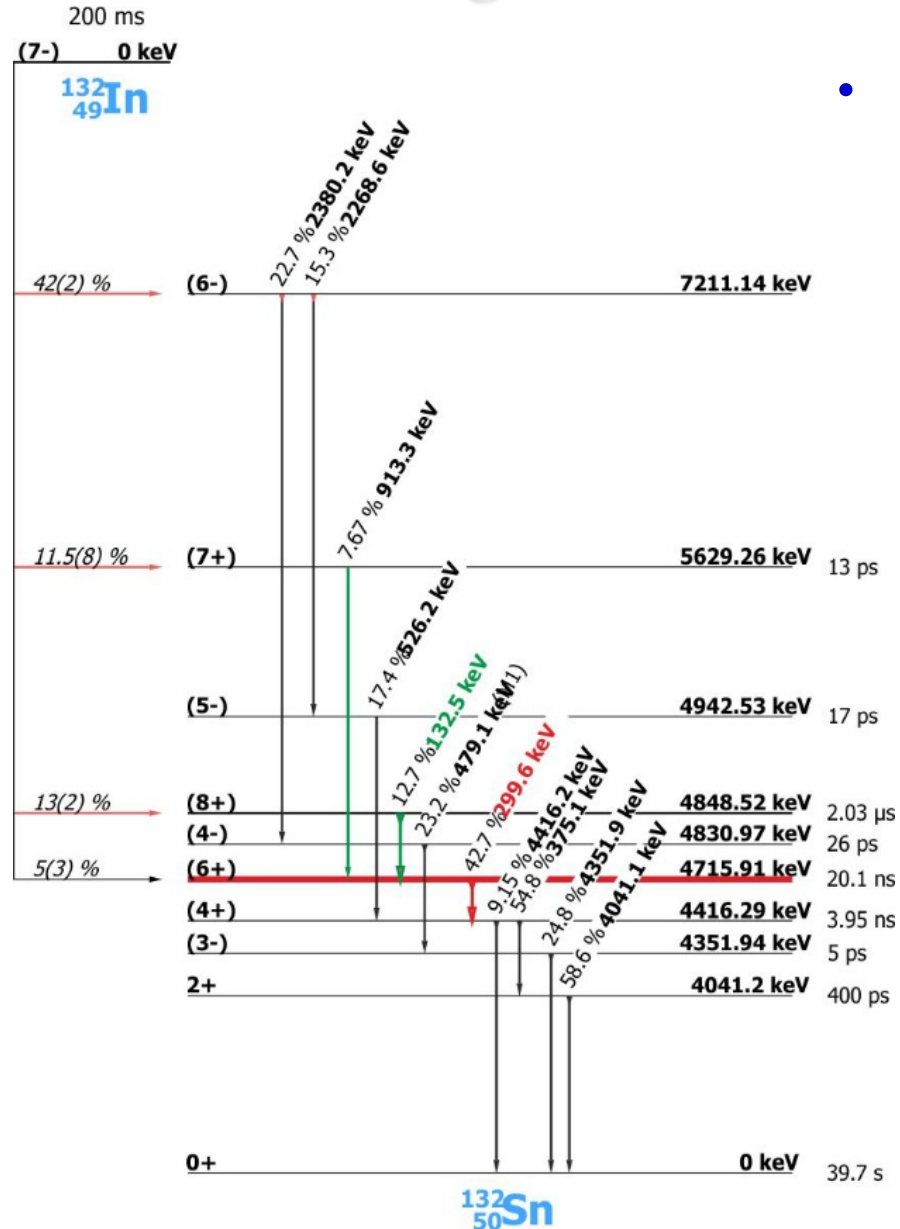
- ¹¹⁶Sn (5⁻) in Fe and Zn (s.c.)
- ¹¹⁸Sn (5⁻) in Fe and Zn (s.c.)
- ¹²⁰Sn (5⁻) graphite
- ¹²²Sn (5⁻) in Fe
- ¹²⁴Sn (5⁻) in Fe, Zn (s.c.) and Cd (s.c.)

Obtained high-precision frequencies for a number of cases in Fe, Zn and Cd

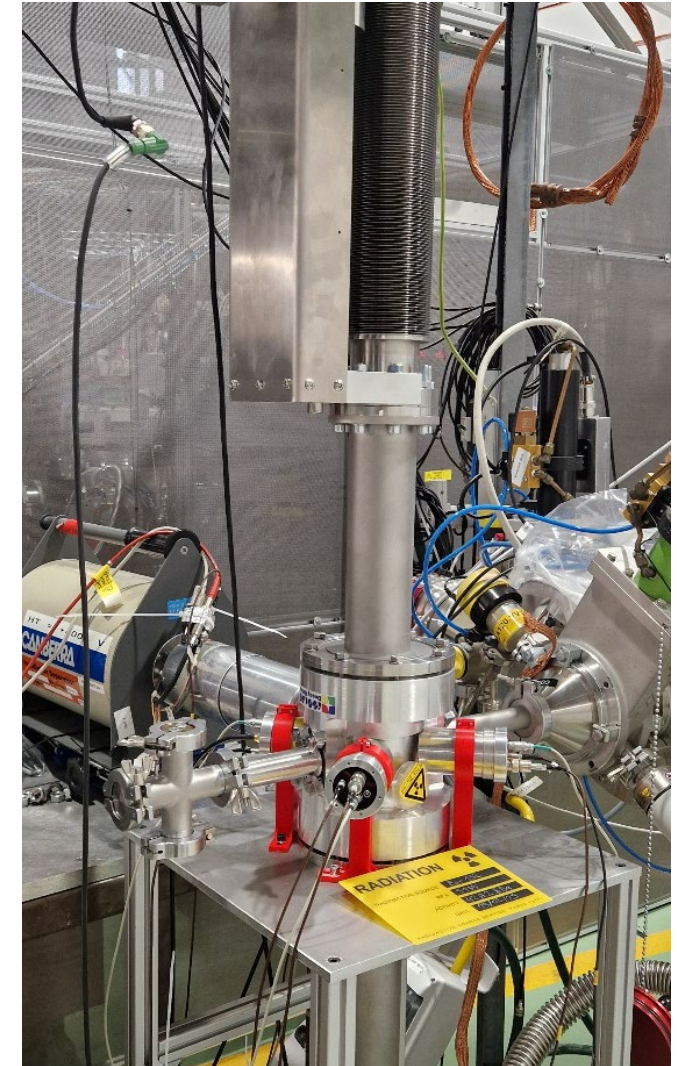
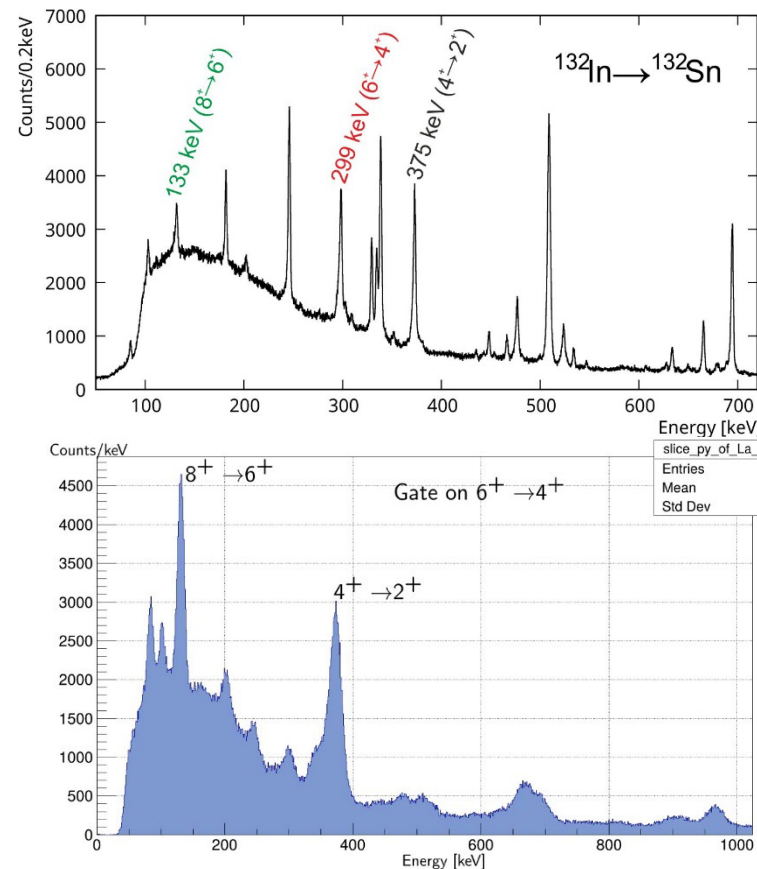
→ accurate values for the magnetic and quadrupole moments (unknown) and the EFG ratio of Sn in Zn and Cd



Commissioning of the on-line TDPAC setup @ ISOLDE (Apr. 2025)



- $^{132}\text{In} \rightarrow ^{132}\text{Sn}$ – the 6^+ ($t_{1/2} = 20$ ns) implanted in Fe ($B_{\text{hf}}(\text{SnFe}) \sim -8\text{T}$)
 - Implantation rate $\sim 10^7$ pps
 - **A total of $\sim 10^5$ γ - γ detected but ...**
 - **Some technical difficulties**



TDPAC @ IFIN-HH

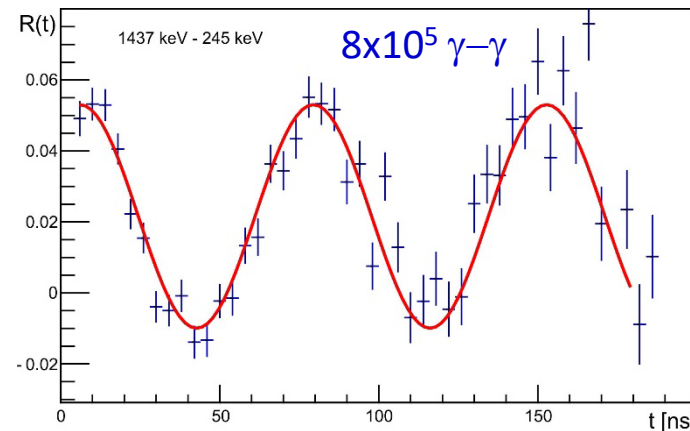
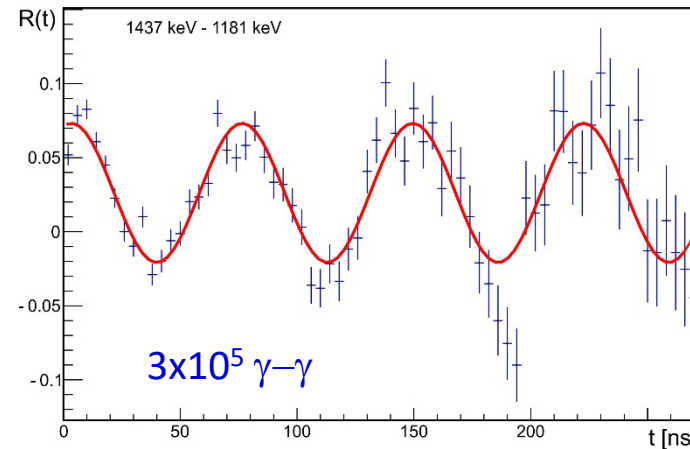
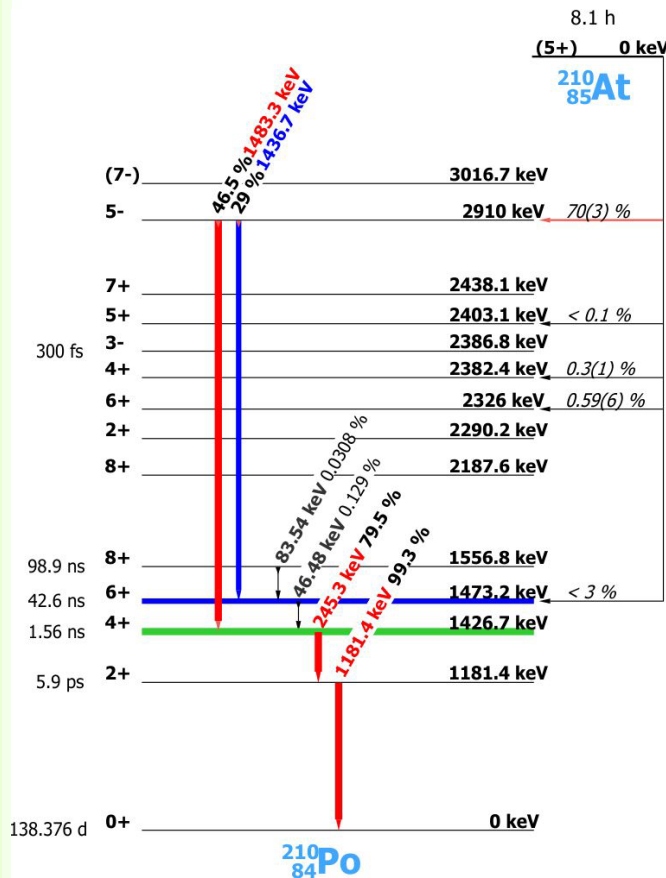
• • •

off-line measurement

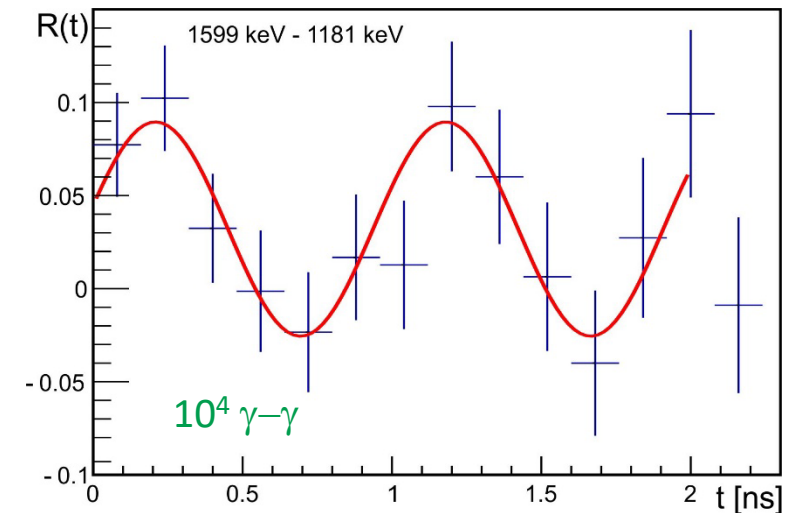
Magnetic moments in ^{210}Po @ IFIN-HH (Feb. 2025)

Spokespersons: **K. Gladnishki** and **K. Stoychev**

- Study of the ^{210}Po isomers, populated in β -decay of ^{210}At
- Off-line measurement following $^{206}\text{Pb}(^7\text{Li},3n)^{210}\text{At}$ reaction
- 6^+ isomer (known) with external magnetic field (0.98 T) – thick target
- 4^+ isomer ($t_{1/2} = 1.56$ ns) – recoil implanted in Ni ($B_{\text{hf}}(\text{PoNi}) = \mathbf{66\ T}$) – (very) thin target



^{209}At 5.41 h 9/2- EC, α	^{210}At 8.1 h (5)+ EC, α	^{211}At 7.214 h 9/2- EC, α	^{212}At 0.314 s (1)- EC, α	^{213}At 125 ns 9/2- α	^{214}At 558 ns 1- α
^{208}Po 2.898 y 0+ EC, α	^{209}Po 102 y 1/2- EC, α	^{210}Po 138.376 d 0+ α	^{211}Po 0.516 s 9/2+ α	^{212}Po 0.299 μ s 0+ α	^{213}Po 4.2 μ s 9/2+ α
^{207}Bi 31.55 y 9/2- EC	^{208}Bi 3.68E+5 y (5)+ EC	^{209}Bi 9/2- 100	^{210}Bi 5.013 d 1- β^- , α	^{211}Bi 2.14 m 9/2- β^- , α	^{212}Bi 60.55 m 1(-) α , β^- , α
^{206}Pb 0+ 24.1	^{207}Pb 1/2- 22.1	^{208}Pb 0+ 52.4	^{209}Pb 3.253 h 9/2+ β^-	^{210}Pb 22.3 y 0+ β^- , α	^{211}Pb 36.1 m 9/2+ β^-



- Lifetimes down to **1 ns** reachable in β -decay TDPAC
- Can we “go shorter”? How much?

$^{54}\text{Fe}, 10^+$ - the highest precision TDPAD measurement

PHYSICAL REVIEW C

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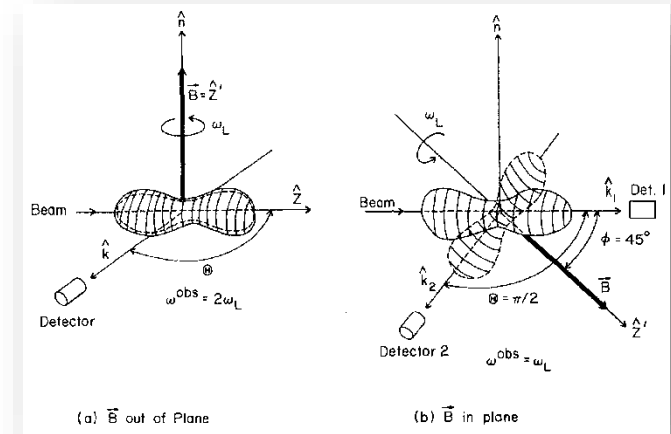
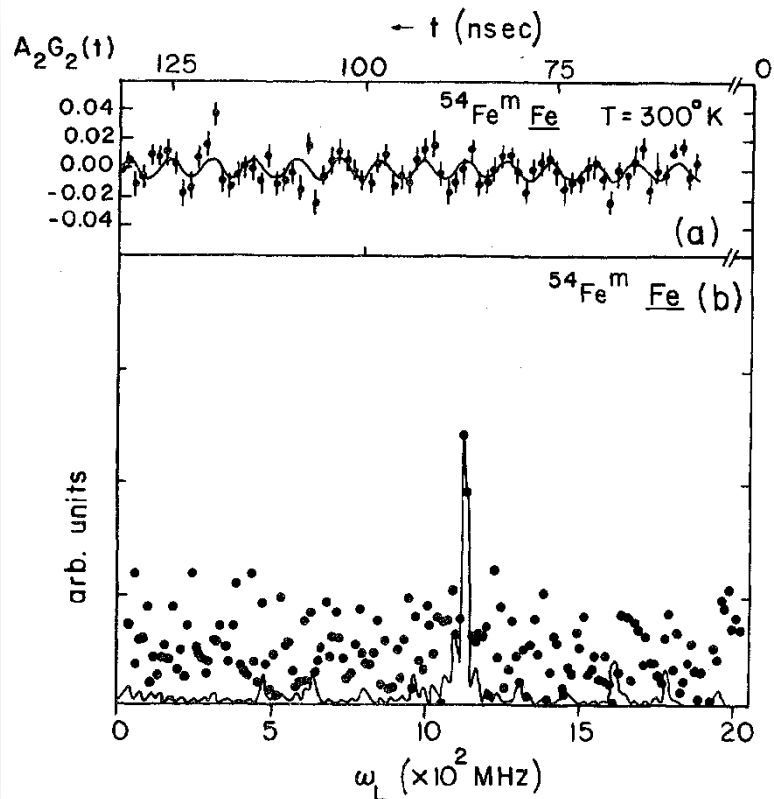
Magnetic moment of the $^{54}\text{Fe}(10^+)$ level

M. H. Rafailovich, E. Dafni,* J. M. Brennan, and G. D. Sprouse

Department of Physics, State University of New York,

Stony Brook, New York 11794

(Received 20 April 1982)



- 60+ periods observed over $T_{1/2}$
- $g(10^+, ^{54}\text{Fe}) = 0.7281(10) \rightarrow 0.13\% \text{ accuracy!!!}$

Take-home messages

- TDPAD measurements in **projectile-fragmentation**: single-step and two-step reactions done in a few of the presently existing fragmentation facilities. After 20+ years we are still learning and every experiment is unique case.
- TDPAC – might be the way to go towards shorter-lived isomers down to (sub) **nanosecond lifetimes**. Could appear accessible both in fragmentation and at ISOL facilities.
- Pushing the limits of statistics – is the **χ^2 fitting** the best way to go? Can the **Bayesian approach** give us more confidence in the results obtained?
- **Experimental uncertainties** – rarely below the 1% level. When do we need to start worrying about the correction factors?

Thank you for your attention!

Nuclear electromagnetic moments in the new millennium.
The sunset of high-spin physics and the sunrise of exotic nuclear studies

G. G., Dimiter L. Balabanski, Andrew E. Stuchbery and Hideki Ueno
Submitted to EPJA