Nuclear moments of isomeric states – from projectile fragmentation to low-energy RIB's and back

Georgi Georgiev, IJCLab, Orsay, France

ISNS 24

Overview

- Nuclear moments and why are they interesting – a few general remarks
- Chronicle of the TDPAD measurements over the last 25 years – a personal view
    - Proof of principle @ GSI
    - First steps at GANIL
    - Another jump to NSCL?
    - Experiments at RIKEN – are we reaching the maturity?
- Is there something that we can do differently? Plans and ideas.
- Summary

Nuclear structure and magnetic moments

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

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

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

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

free-nucleon *effective*

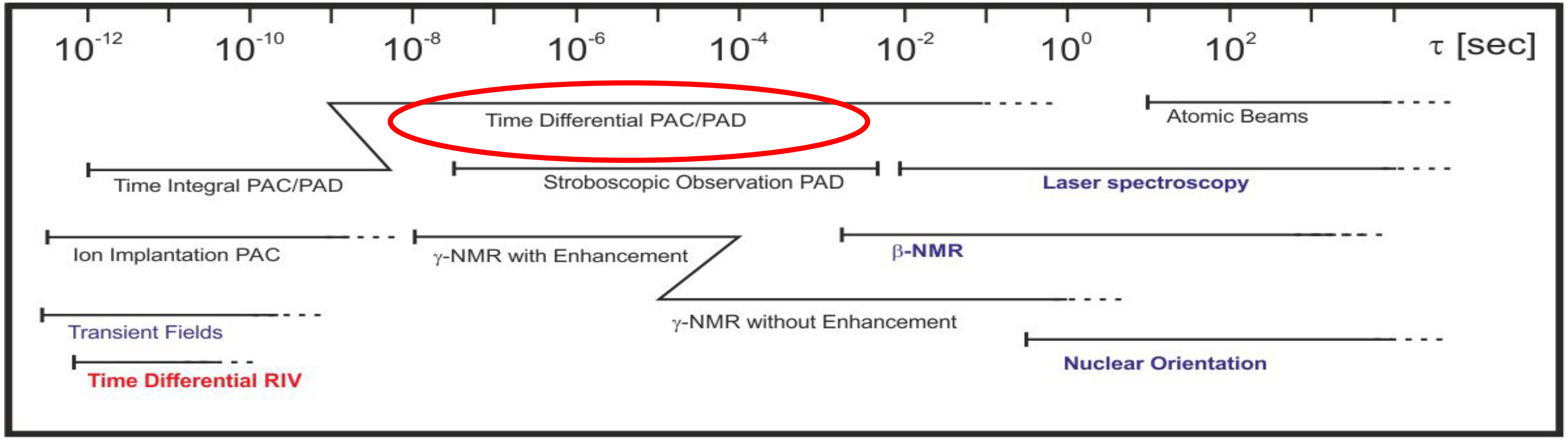
$$\begin{aligned} g_s^\pi &= 5.58 & g_\ell^\pi &= 1 & g_s^\pi &= 0.7 * g_s^\pi & g_\ell^\pi &= 1 + \Delta g^\pi \\ g_s^\nu &= -3.28 & g_\ell^\nu &= 0 & g_s^\nu &= 0.7 * g_s^\nu & g_\ell^\nu &= \Delta g^\nu \end{aligned}$$

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

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

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

Methods according to the lifetimes



E. Recknagel in Pure and Applied Physics, 40C

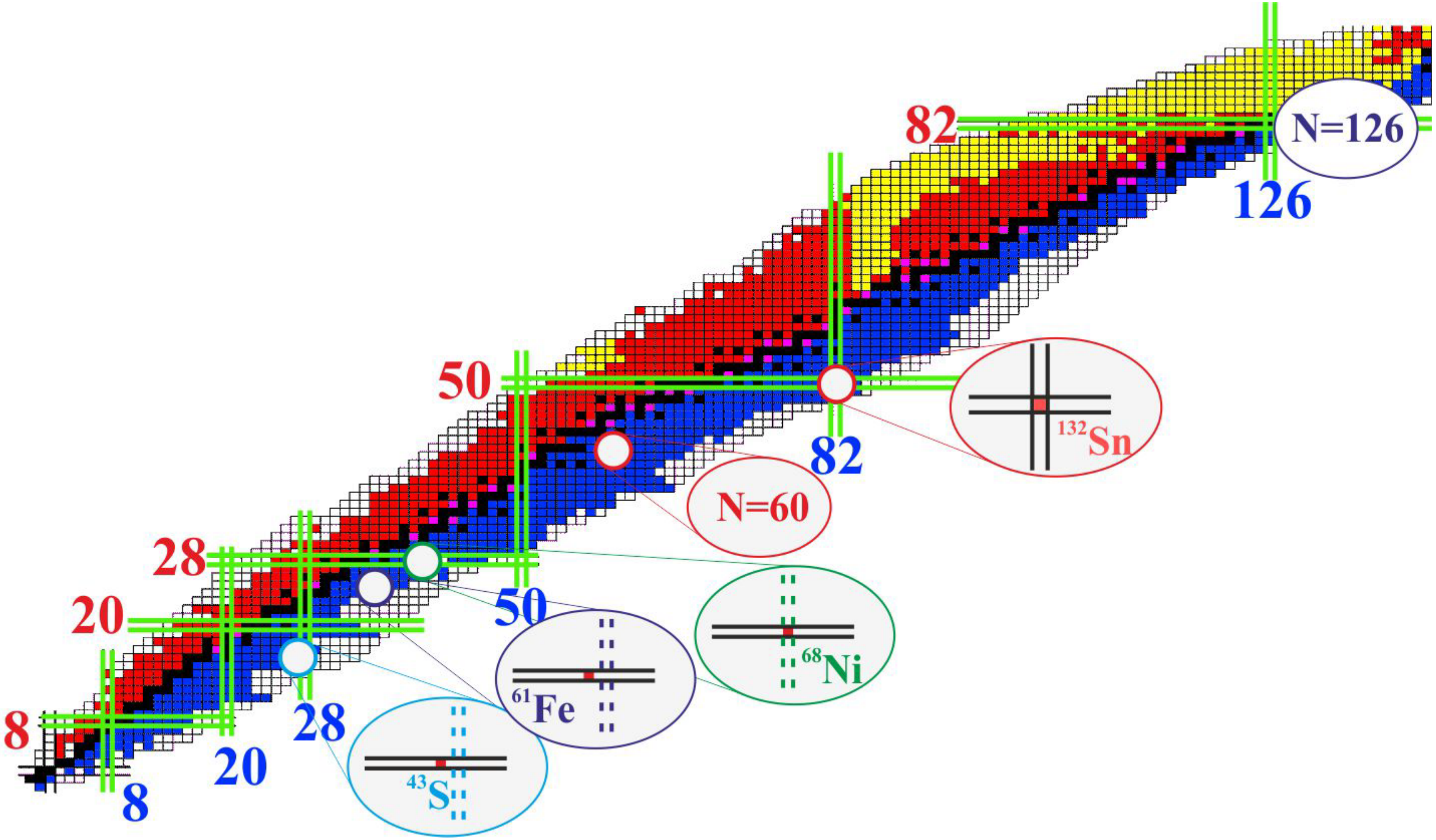
Methods are strongly dependent on the *nuclear lifetimes* (>12 orders of magnitude) and they provide different level of *precision and accuracy*

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

- Time Dependent Recoil In Vacuum (TDRIV)
  → for moments of picosecond excited states;
- 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

A few regions of interest on the Segre chart

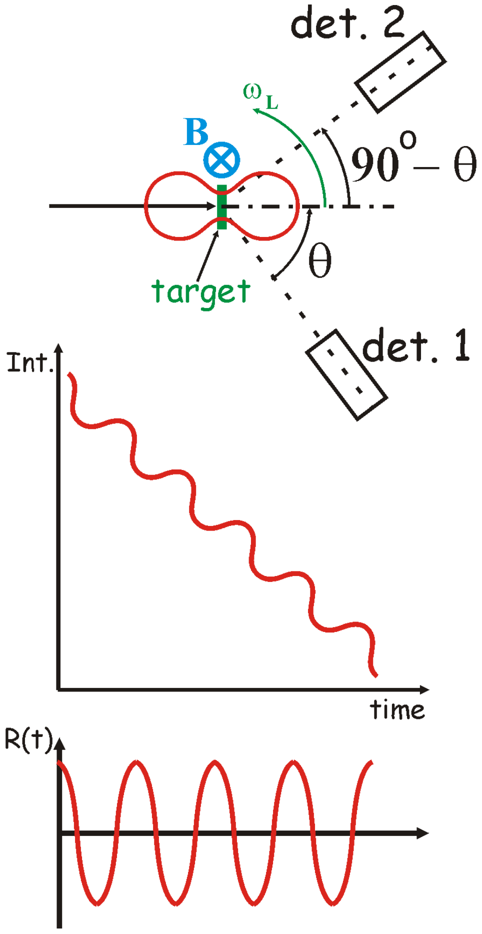
In the vicinity of shell closures or in regions of onset of deformation?

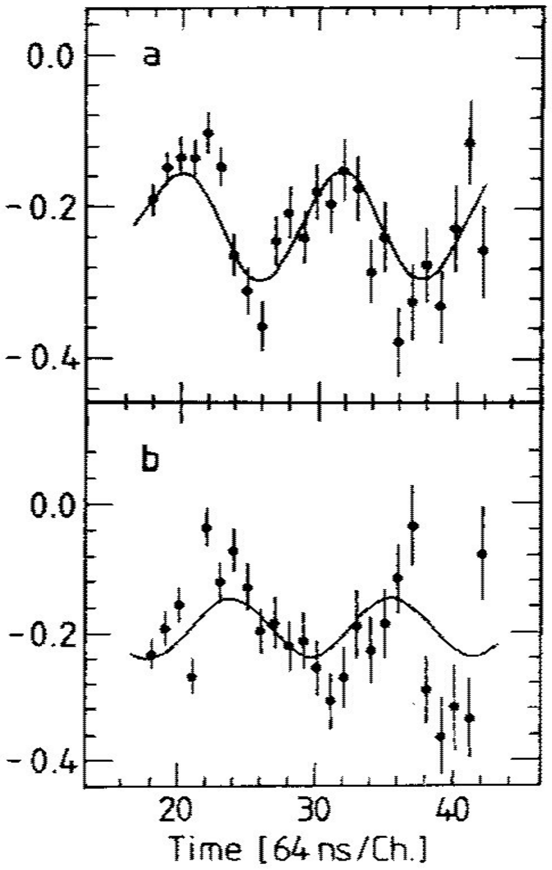


Time Dependent Perturbed Angular Distribution – a chronicle

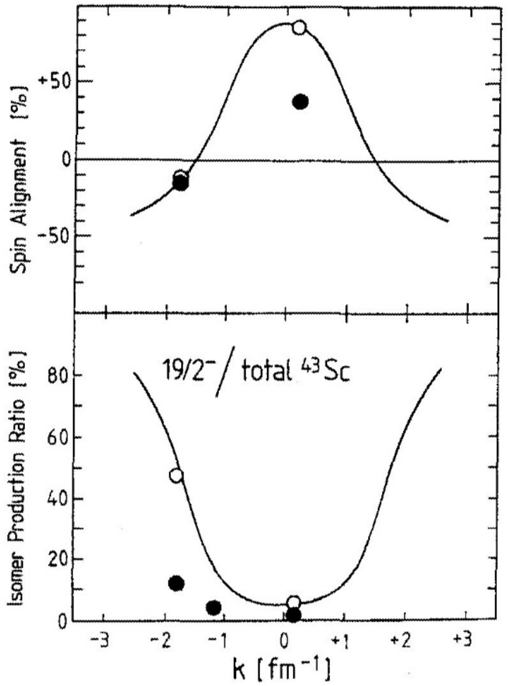
- In *fusion-evaporation reactions* (stable beams) – *trivial* – the spin orientation is obtained readily from the reaction mechanism itself
- In ***projectile fragmentation*** - spin alignment obtained from the reaction mechanism (*provided specific momentum selection chosen*)
- **Proof of principle 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

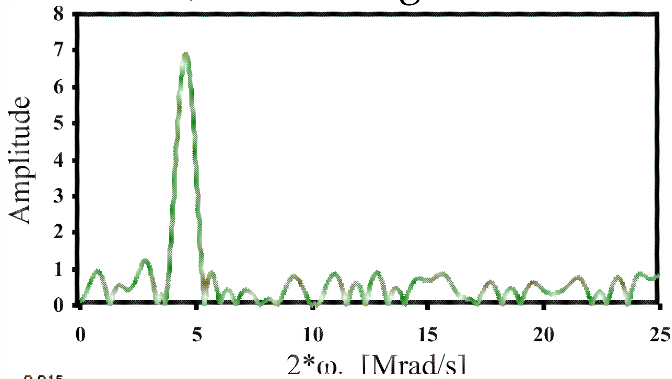


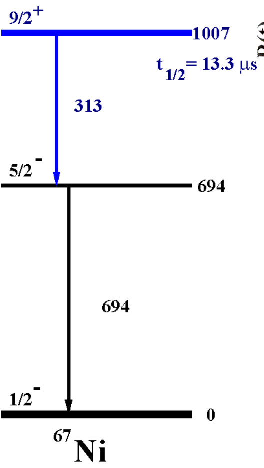
$$R(t) = \frac{I(\theta,t) - I\left(\theta + \frac{\pi}{2}, t\right)}{I(\theta,t) - I\left(\theta + \frac{\pi}{2}, t\right)} = $$

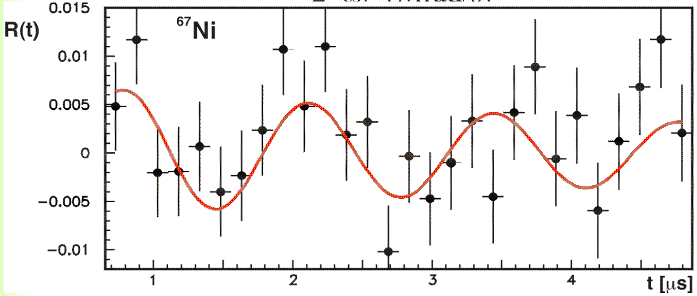
$$= \frac{3A_2B_2}{4+A_2B_2}\cos\{2(\theta - \omega_L t - \alpha)\}$$

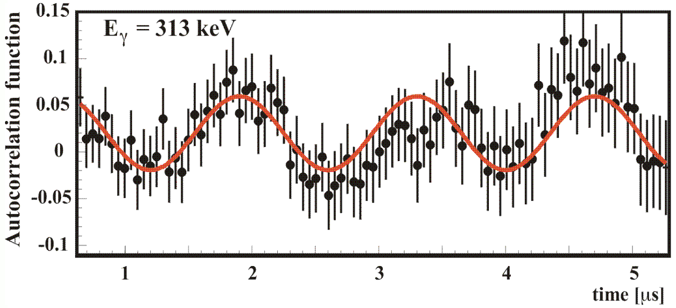
First experiments at GANIL (1999 – 200X)

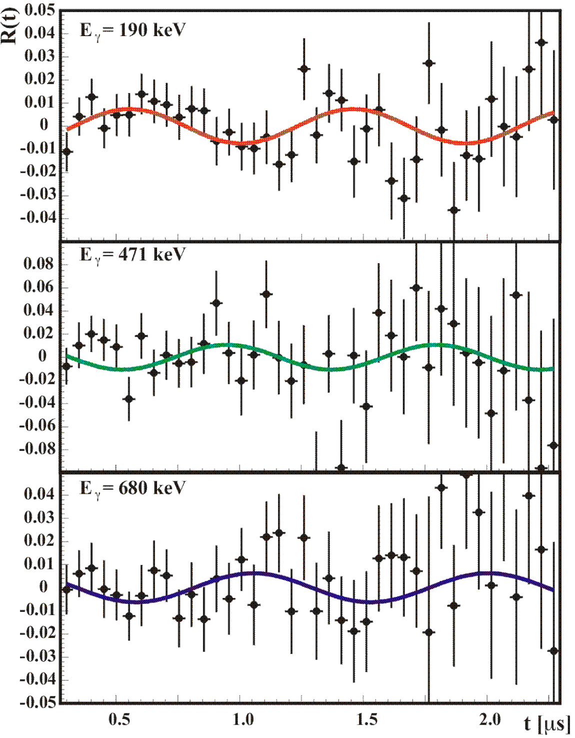
- ^{67}**Ni**, ^{69}**Cu** – magnetic moments studies

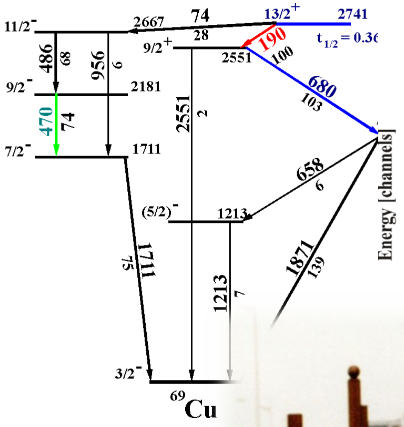


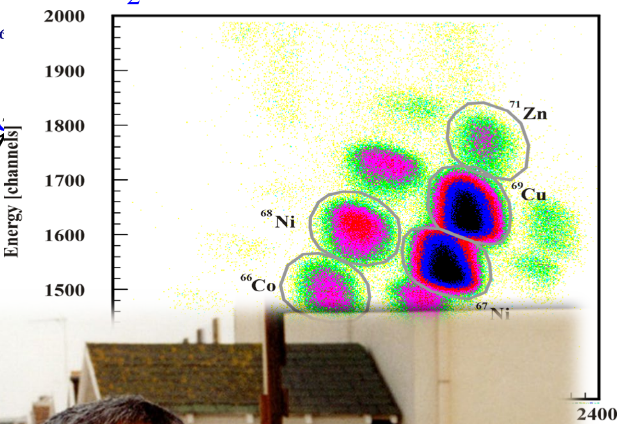












- A message to take home?
  - ✓ *there are things to be improved*

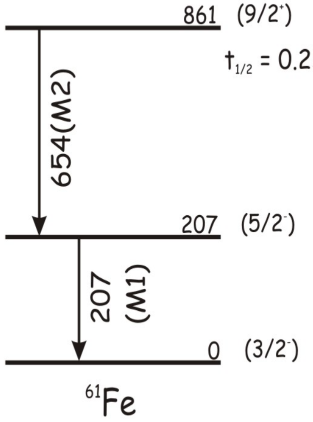
- *g(13/2+, ^{69}Cu)* – well reproduced by the theory
- *g(9/2+, ^{67}Ni) – a factor of 2 off the expectations …* → ***see talk of K. Stoychev***

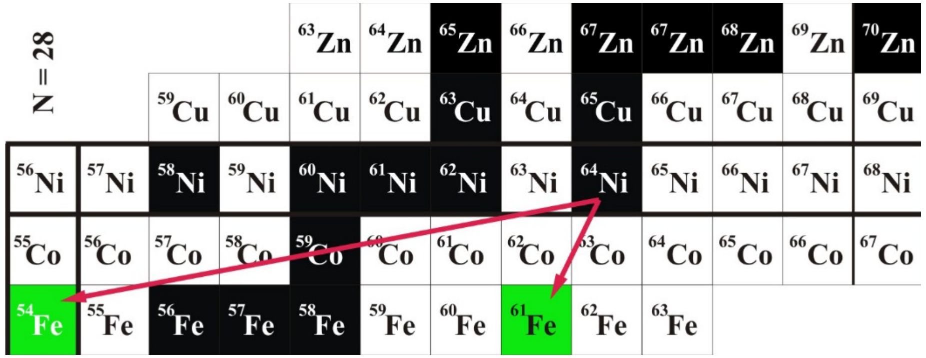
G. Georgiev *et al.*; JPG 28, 2993 (**2002**)

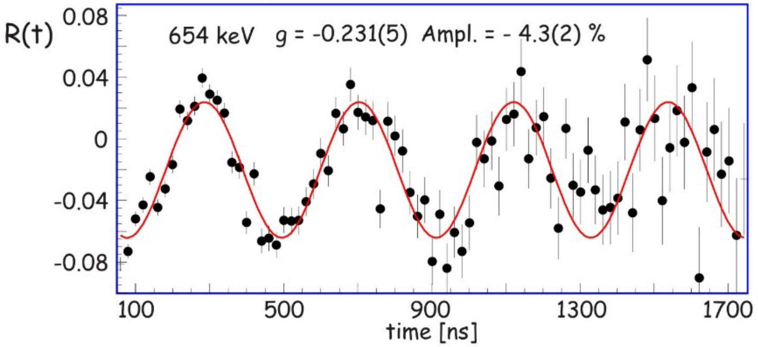
^{62}Fe case

- μ - I. Matea *et al.*; PRL 93, 142503 (**2004**), ***Ampl. (R(t)) ~4%)***
- Q - N. Vermeulen *et al.*; PRC 75, 051302(R) (**2007**)

A number of ***improvements of the setup*** bring much clearer results

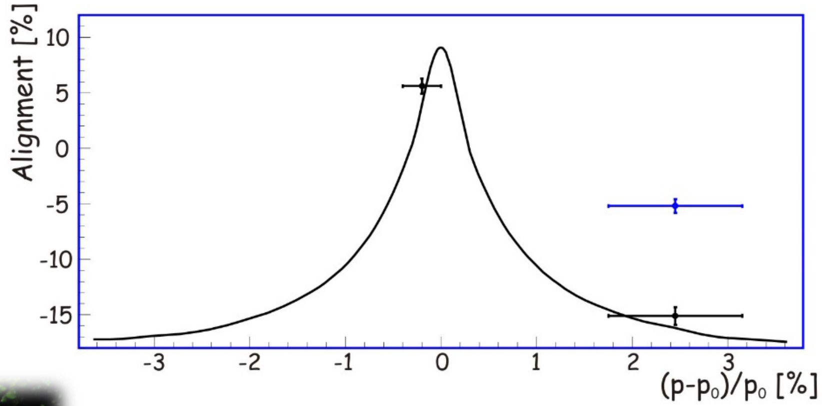


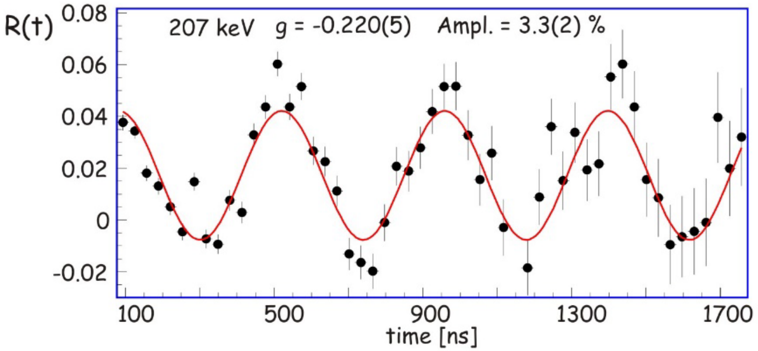


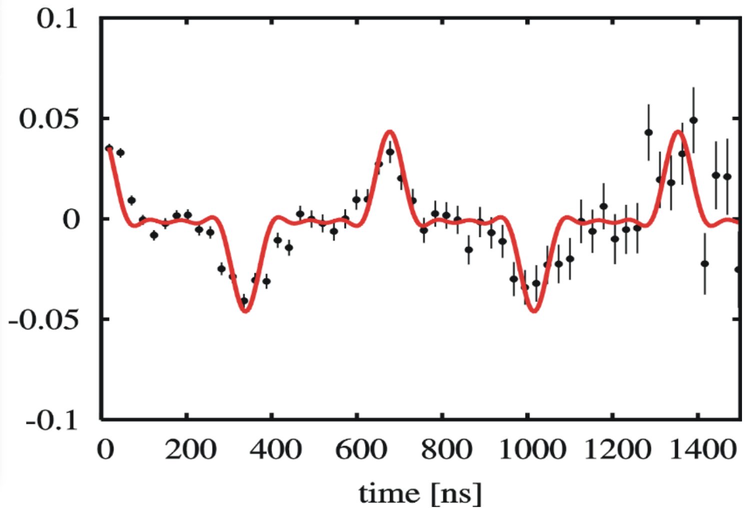


The nuclear ***spin alignment*** at the **center** and at the **wing** of the *momentum distribution* is well reproduced by the model!

3-nucleon removal reaction

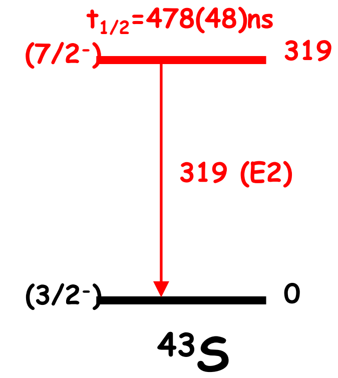


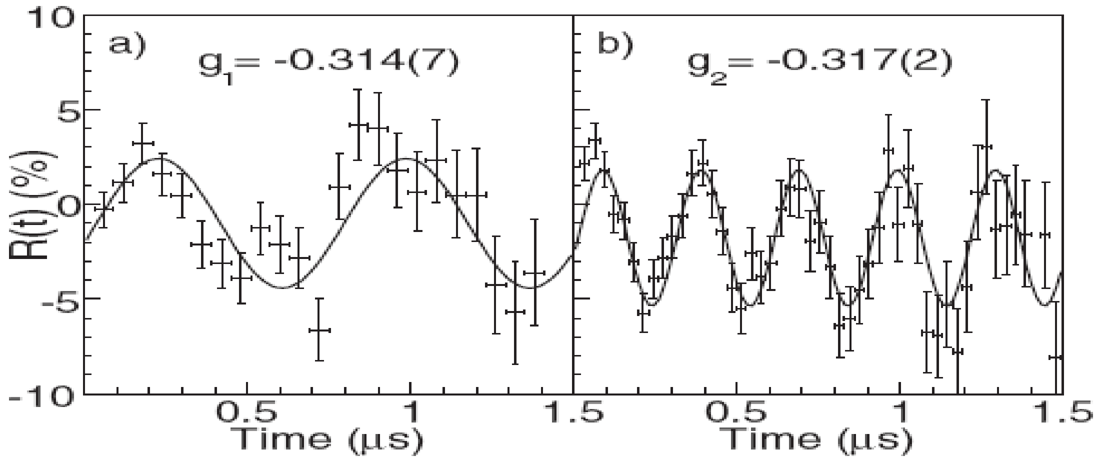


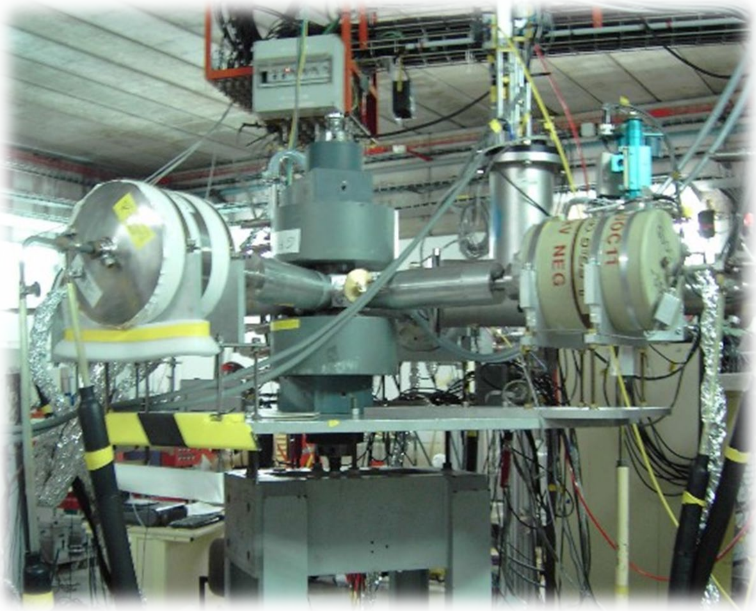


^{43}S case

- L. Gaudefroy *et al.*; PRL 102 092501 (**2009**), *Ampl. (R(t)) ~4%*





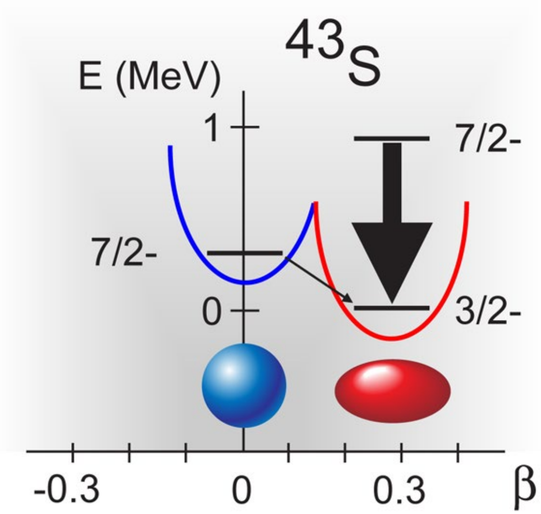


^{43}S from projectile fragmentation of ^{48}Ca

- ***5 nucleon removal** reaction → still significant level of spin orientation is observed*

The questions:

1. How many nucleons could one remove in projectile fragmentation and still observe spin orientation?
2. What is the level of spin orientation in fission reactions?

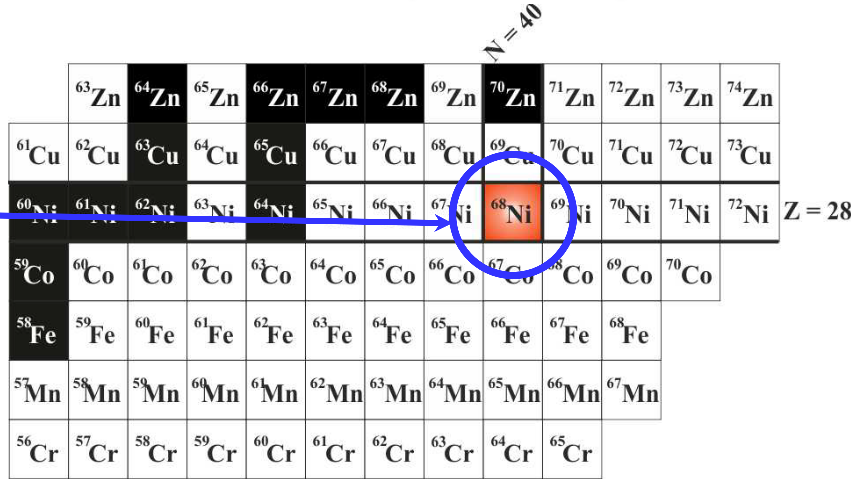


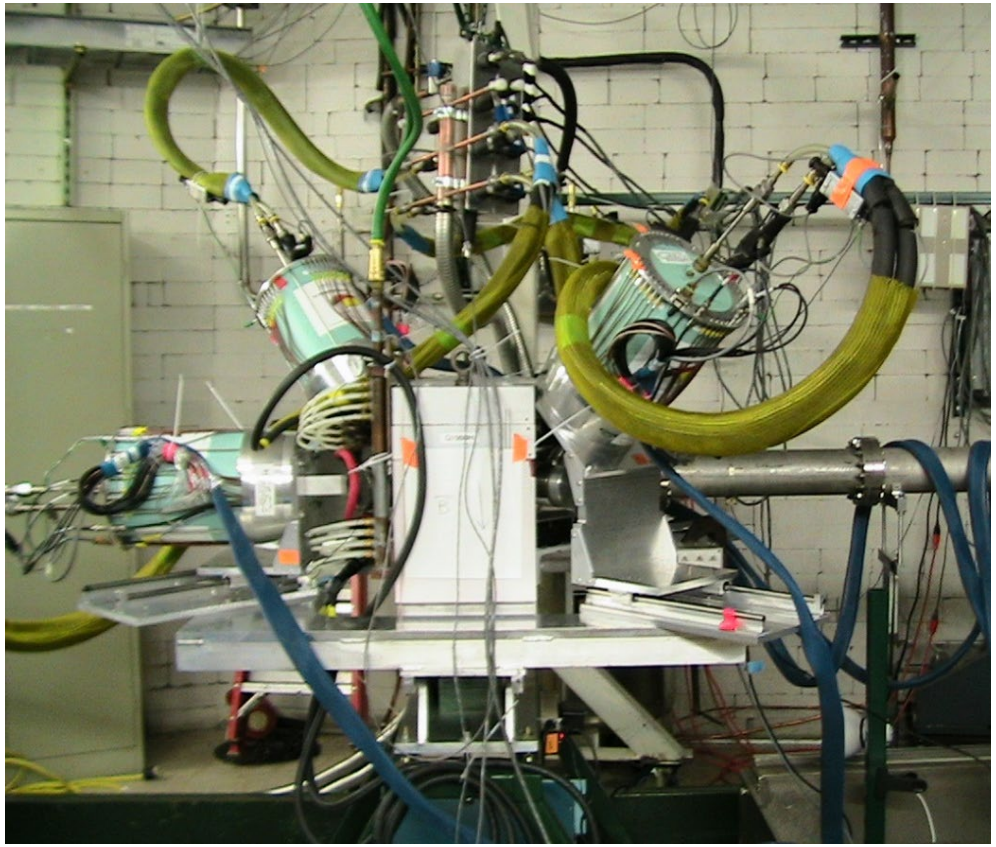
Shell Erosion and Shape Coexistence in ^{43}S
PRL 102, 092501 (2009),
Selected for a Viewpoint in *Physics*

NSCL - magnetic moments studies around N=40 – *see the talk of K.Stoychev*

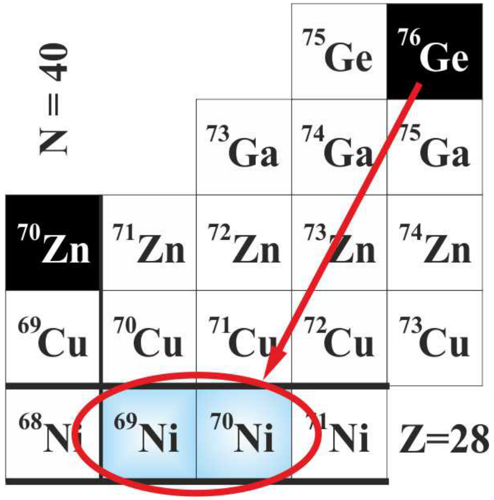
Neutron-rich N=40 region

- “doubly magic” ^{68}Ni?

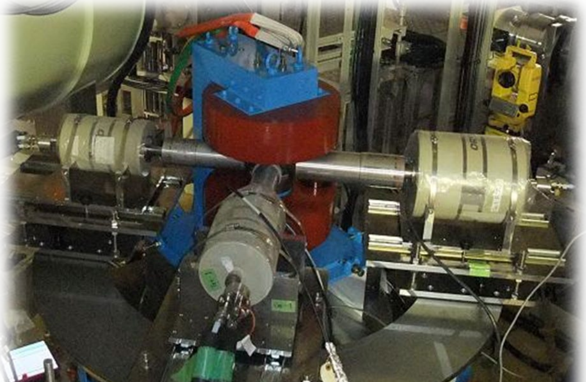




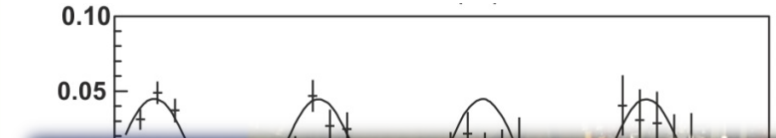
- ^{76}Ge beam @ 130 MeV/u
- ^{9}Be target
- **6+ nucleon removal reaction**
- 4 SeGA detectors
- thin plastic scintillator for t=0
- A1900 fragment separator ~90% beam purity



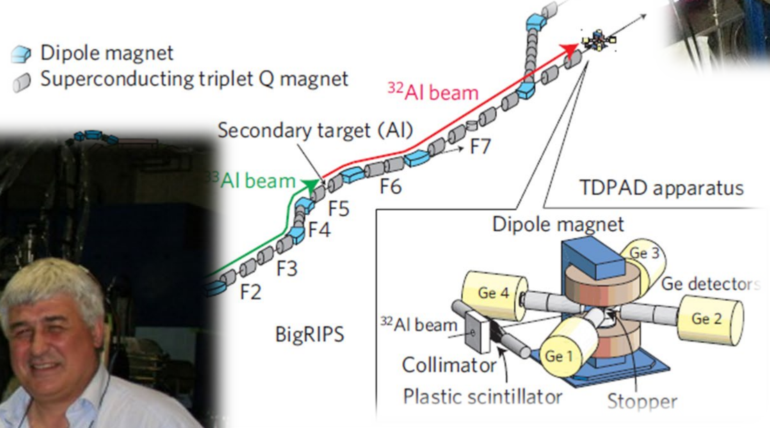
The RIKEN approach



- 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



Ampl. (R(t)) ~5%



ARTICLES

nature physics

PUBLISHED ONLINE: 21 OCTOBER 2012 | DOI: 10.1038/NPHYS2457

roduction of spin-controlled rare isotope beams

uichi Ichikawa[1*†], Hideki Ueno[1], Yuji Ishii[2], Takeshi Furukawa[3], Akihiro Yoshimi[4], Daisuke Kameda[1], iroshi Watanabe[1], Nori Aoi[1], Koichiro Asahi[2], Dimiter L. Balabanski[5], Raphaël Chevrier[6], ean-Michel Daugas[6], Naoki Fukuda[1], Georgi Georgiev[7], Hironori Hayashi[2], Hiroaki Iijima[2],

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

Further results from RIKEN

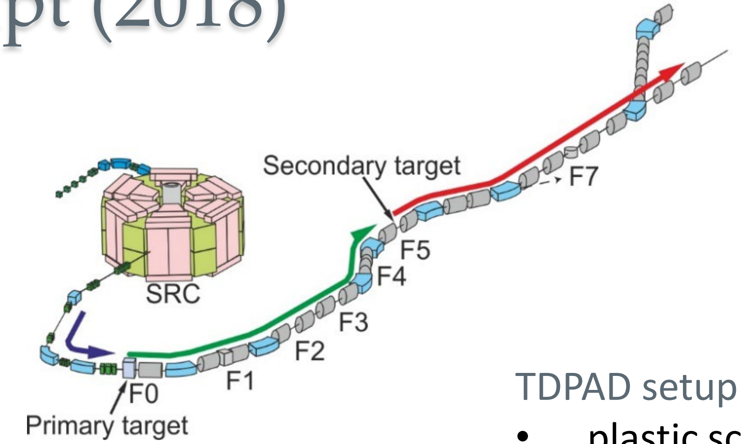
- ^{75}Cu – shell evolution towards ^{78}Ni
  Y. Ichikawa *et al.*; Nature Physics 15, 321 (2019), *Ampl. R(t) ~10%*

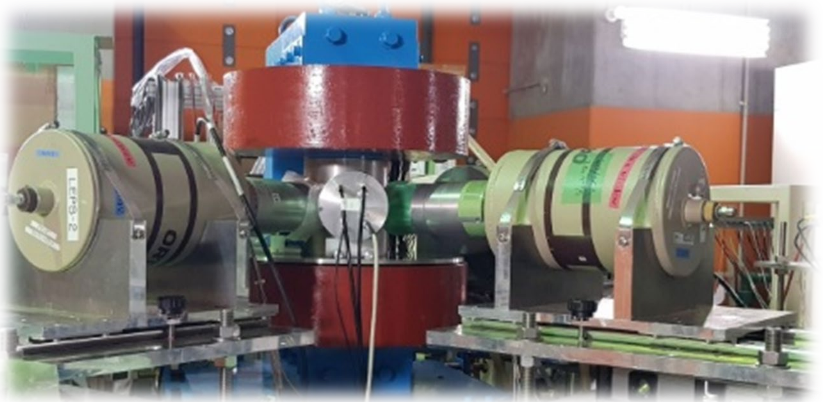
- **^{99}Zr** – onset of deformation and phase transition at N=60

→ ***see the talk of Yuichi Ichikawa***

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

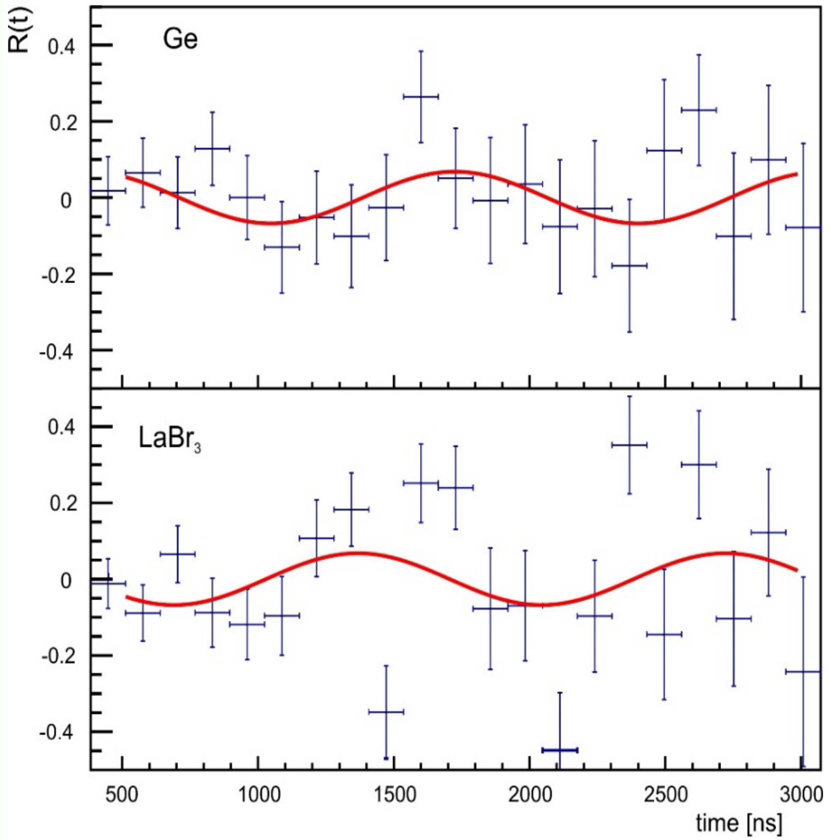
Primary beam -	**^{238}U**@345 MeV/u, 40 pnA
Secondary beam –	**^{132}Sn,** 223 MeV/u
Tertiary beam -	**^{130}Sn,** 170 MeV/u



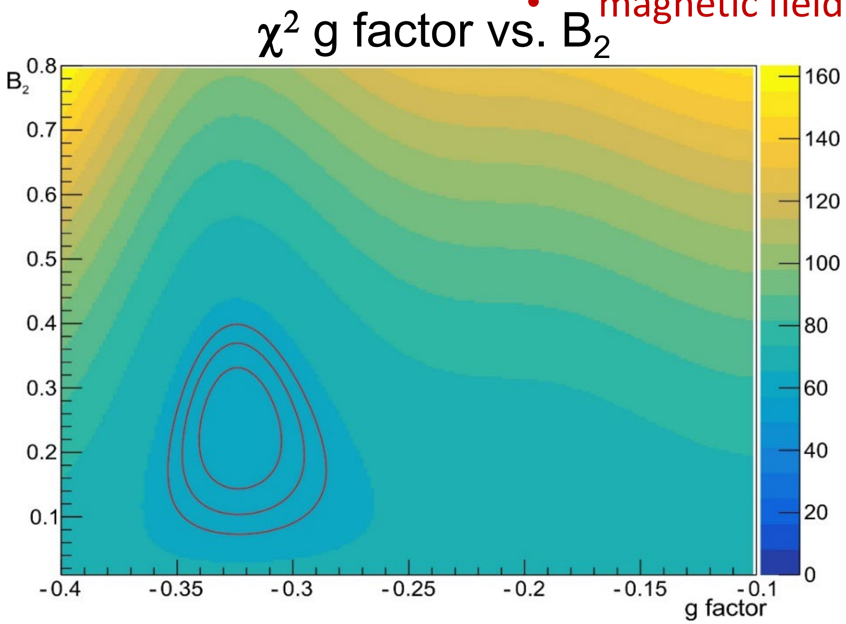


TDPAD setup:

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



Oscillations observed for the 96 keV line simultaneous fit for Ge and $LaBr_3$ detectors



g = -0.32(2); B2 = 0.24(9) ($\leq 3^*\sigma$)

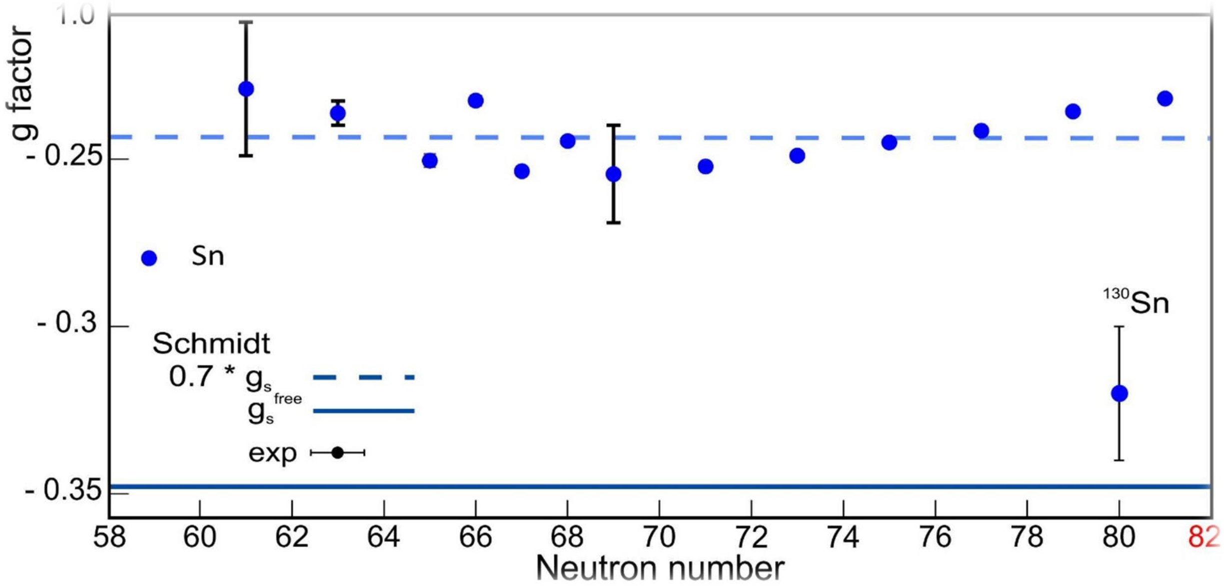
T.J. Gray, PhD Thesis, ANU 2021

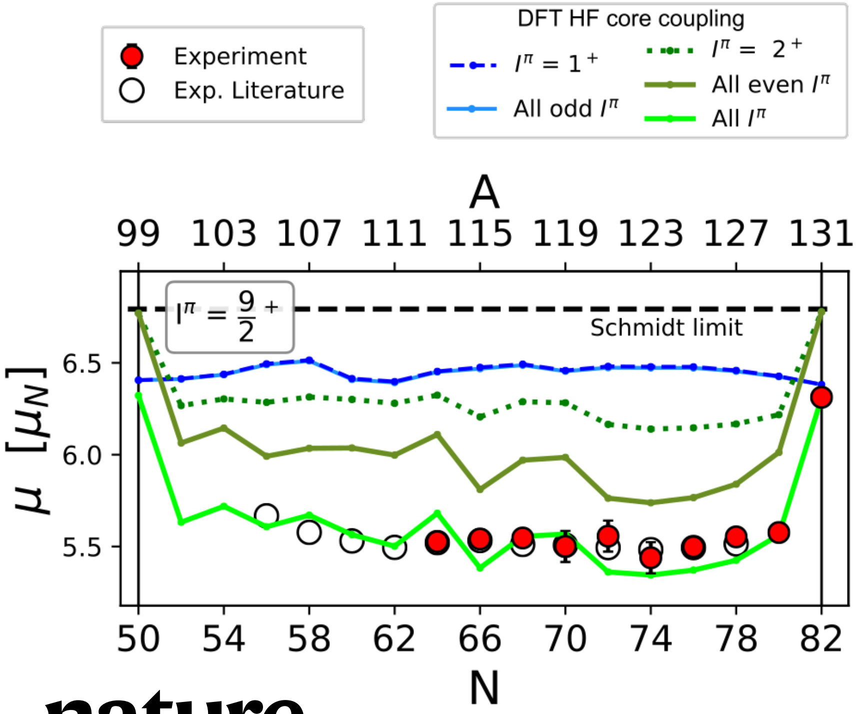
Is this real or …

just fake news?

- Some suggested improvements
- Experiment re-proposed to the RIKEN NP PAC (2019)

How “single-particle” are the g factors in the Sn’s? And the In’s?





nature

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

- Similar behavior in the **Sn and the In isotopes, at N=82**
- Is there something special for the “high-spin” states?

NP1912-RIBF-143R2 →

scheduled in November 2024

TDPAC in projectile fragmentation

- The method looks already quite mature:
    - Control over the spin orientation (two-step reactions)
    - Access to the “entire” nuclear chart

BUT …

- Limited to relatively long lifetimes (200+ ns)

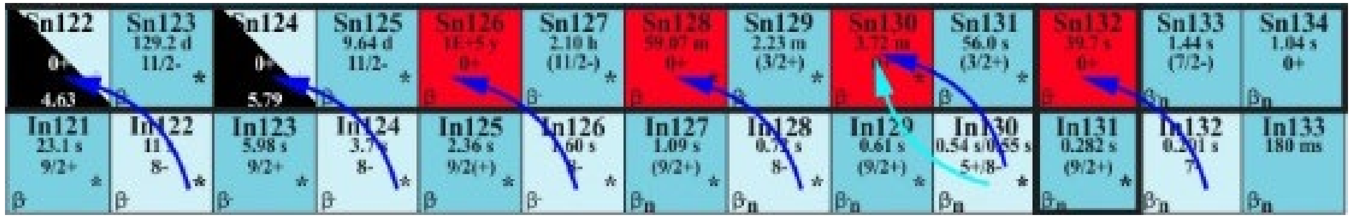
What about **TDPAC**?

- Isomeric states populated after β-decay
- No life-time limits (down to a ns)
- NO spin orientation needed – γ–γ coincidences

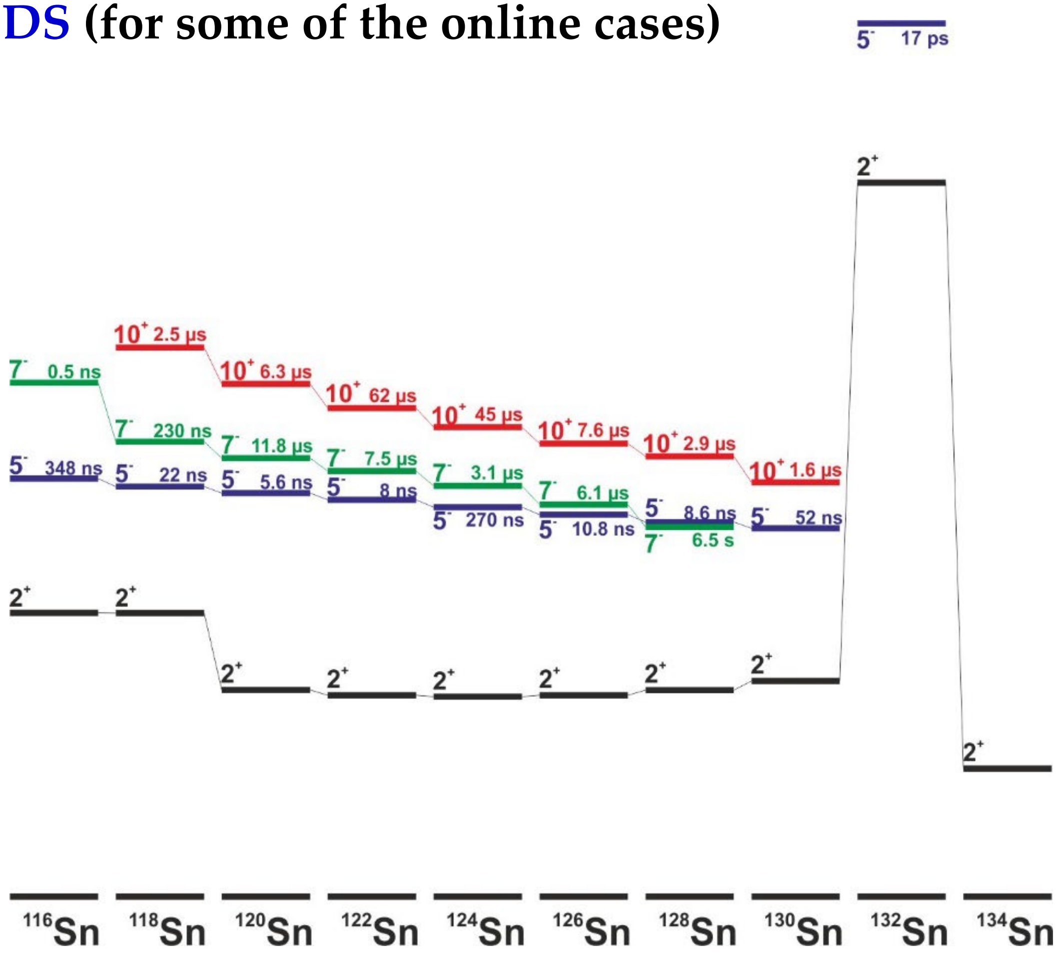
Nuclear moments of neutron rich Sn isomers by on-line PAC

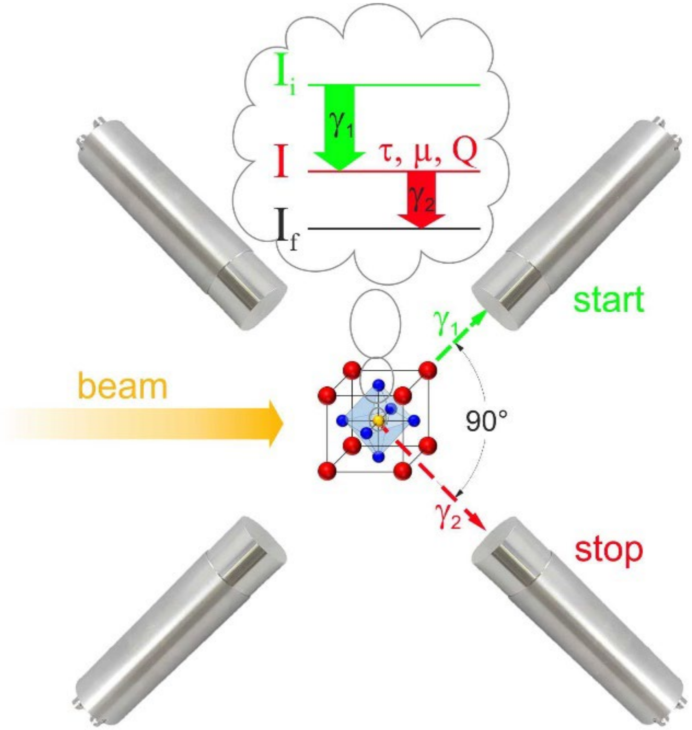
IS 673 – H. Haas and G. Georgiev

- Structure of the short-lived states in the semi-magic Sn nuclei
- **In collaboration with the SSP group @ ISOLDE (for the off-line cases) and with the IDS (for some of the online cases)**



Sn122 0+ 4.63	Sn123 129.2 d 11/2-	Sn124 0+ 5.79	Sn125 9.64 d 11/2-	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	Sn131 56.0 s (3/2+)	Sn132 39.7 s 0+	Sn133 1.44 s (7/2-)	Sn134 1.04 s 0+
In121 23.1 s 9/2+	In122 11 8-	In123 5.98 s 9/2+	In124 3.7 8-	In125 2.36 s 9/2(+)	In126 1.60 s	In127 1.09 s (9/2+)	In128 0.7 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





4 LaBr$_3$ detectors for the short-lived cases

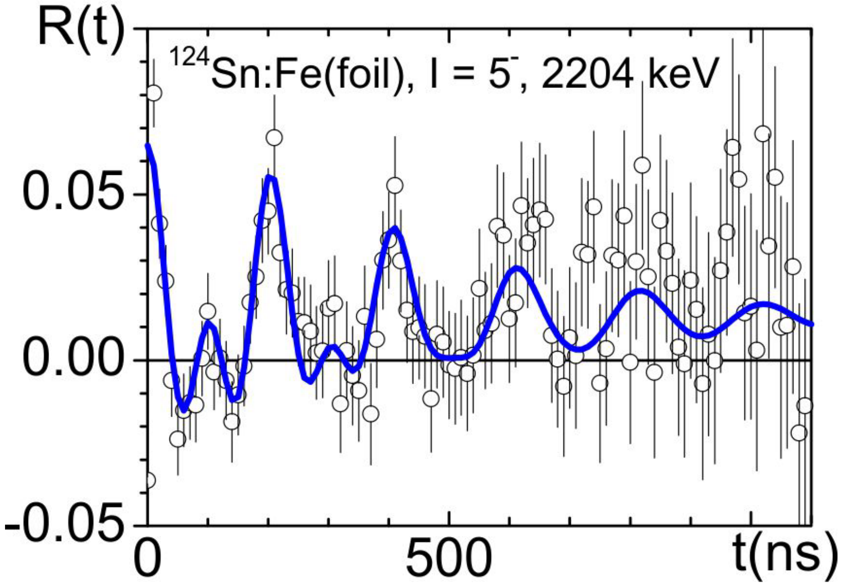
or

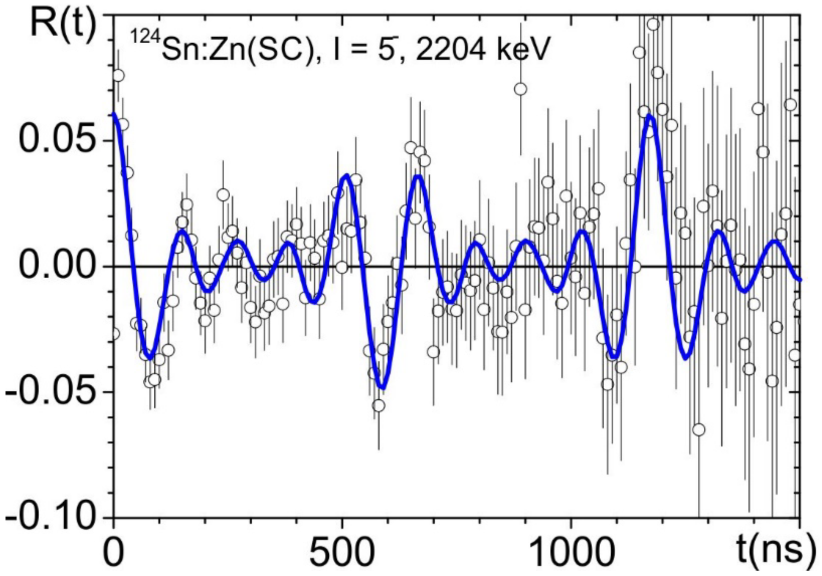
Ge detectors for the longer lifetimes

Some of the results so far for the $I^{\pi} = 5^{-}$ isomers

Run in June 2023 using the SSP setup (4 $LaBr_3$ detectors)
Data collected on:

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



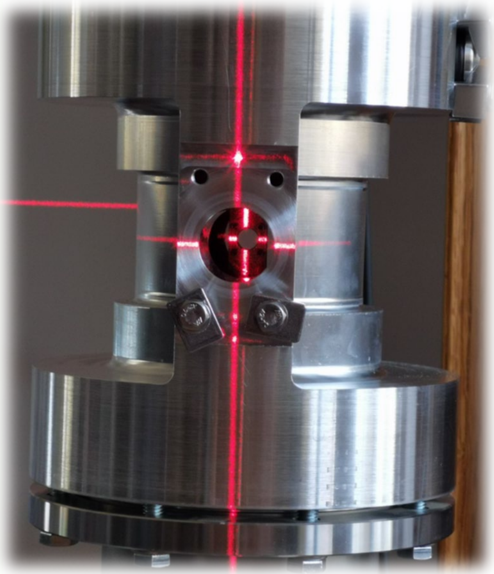


Obtained high-precision frequencies for a number of cases in Fe, Zn and Cd

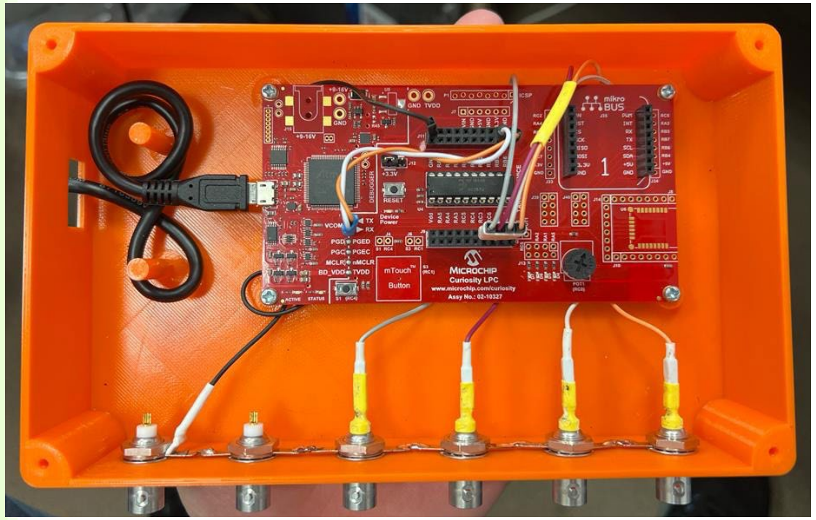
→ accurate values for the magnetic and quadrupole moments (unknown) and the EFG ratio of Sn in Zn and Cd

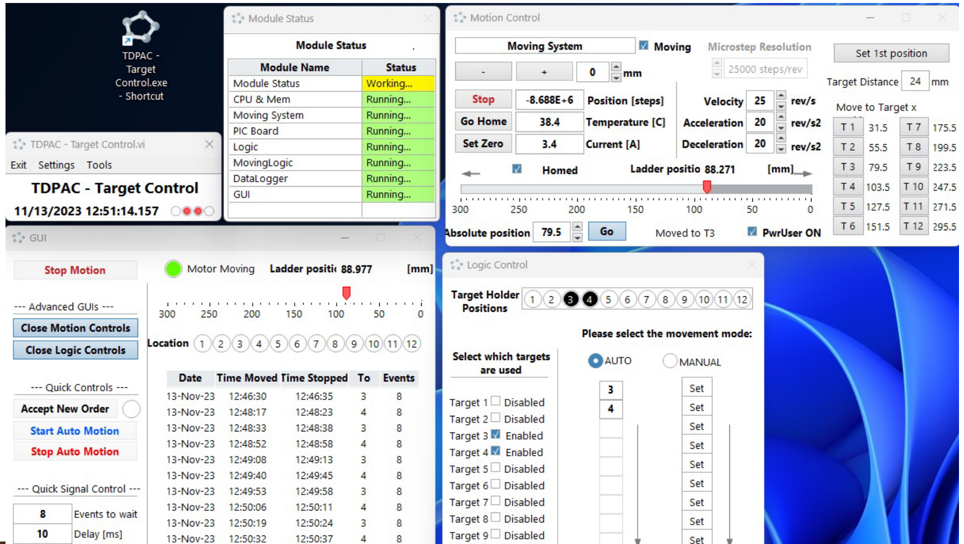
What next?

- Development of a dedicated setup in collaboration with IFIN-HH, Bucharest (designed at IJCLab; manufactured by IFIN-HH) – to be installed at the IDS
  - Development of a set of high-homogeneity permanent magnets in collaboration with KU Leuven (D. Sakelariou) – important for the measurements of the longer-lived cases
  - Development of a step-motor mechanism for on-line exchange of the implantation hosts (collaboration with IFIN-HH) – for removing the daughter activities



Stepper-motor control – developed and tested at IFIN-HH





TDPAC - Target Control

11/13/2023 12:51:14.157

Module Status

Module Name	Status
Module Status	Working...
CPU & Mem	Running...
Moving System	Running...
PIC Board	Running...
Logic	Running...
MovingLogic	Running...
DataLogger	Running...
GUI	Running...

● Motor Moving

Ladder positi 88.977 [mm]

8 Events to wait

10 Delay [ms]

100 Width [ms]

0 Events

Date	Time Moved	Time Stopped	To	Events
13-Nov-23	12:46:30	12:46:35	3	8
13-Nov-23	12:48:17	12:48:23	4	8
13-Nov-23	12:48:33	12:48:38	3	8
13-Nov-23	12:48:52	12:48:58	4	8
13-Nov-23	12:49:08	12:49:13	3	8
13-Nov-23	12:49:40	12:49:45	4	8
13-Nov-23	12:49:53	12:49:58	3	8
13-Nov-23	12:50:06	12:50:11	4	8
13-Nov-23	12:50:19	12:50:24	3	8
13-Nov-23	12:50:32	12:50:37	4	8
13-Nov-23	12:50:45	12:50:50	3	8

☑ Moving

0 mm

Microstep Resolution 25000 steps/rev

-8.688E+6 Position [steps]

38.4 Temperature [C]

3.4 Current [A]

Velocity 25 rev/s

Acceleration 20 rev/s2

Deceleration 20 rev/s2

☑ Homed

Ladder positio 88.271 [mm]

Absolute position 79.5

Moved to T3

☑ PwrUser ON

Target Distance 24 mm

Move to Target x

T 1	31.5	T 7	175.5
T 2	55.5	T 8	199.5
T 3	79.5	T 9	223.5
T 4	103.5	T 10	247.5
T 5	127.5	T 11	271.5
T 6	151.5	T 12	295.5

Target Holder Positions: 1 2 ● 3 ● 4 5 6 7 8 9 10 11 12

Select which targets are used

Target 1 ☐ Disabled

Target 2 ☐ Disabled

Target 3 ☑ Enabled

Target 4 ☑ Enabled

Target 5 ☐ Disabled

Target 6 ☐ Disabled

Target 7 ☐ Disabled

Target 8 ☐ Disabled

Target 9 ☐ Disabled

Target 10 ☐ Disabled

Target 11 ☐ Disabled

Target 12 ☐ Disabled

Please select the movement mode:

● AUTO ○ MANUAL

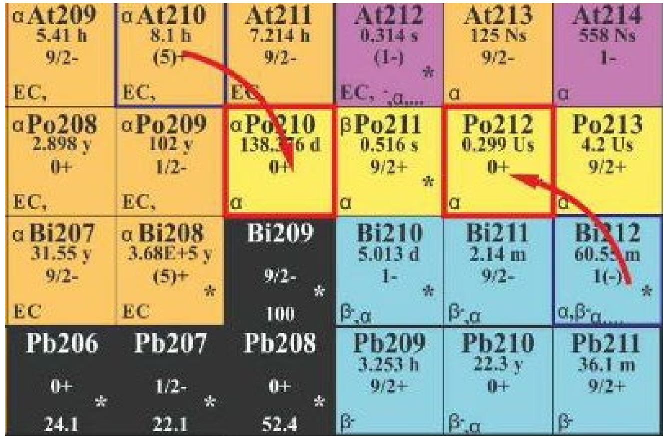
3

4

The Default is set to Auto! The changes are seen immediately in the movement logic.

Special thanks to A. State, M. Cuciuc (ELI-NP)

Planned (and already performed) measurements

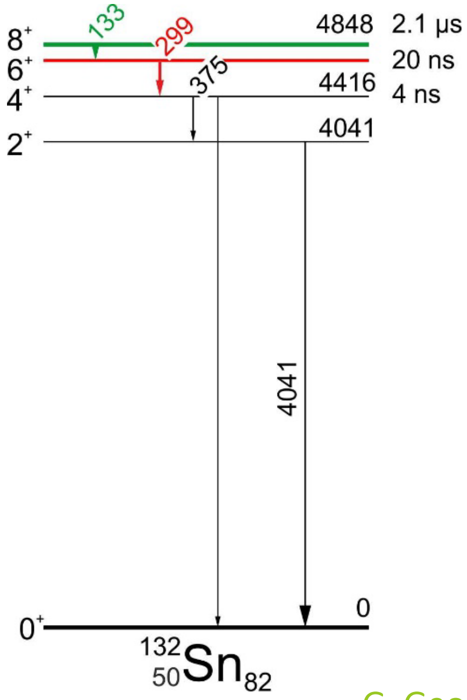


αAt209 5.41 h 9/2- EC,	αAt210 8.1 h (5)+ EC,	At211 7.214 h 9/2- EC	At212 0.314 s (1-) * EC, ⁻,α,...	At213 125 Ns 9/2- α	At214 558 Ns 1- α
αPo208 2.898 y 0+ EC,	αPo209 102 y 1/2- EC,	αPo210 138.376 d 0+ α	βPo211 0.516 s 9/2+ * α	Po212 0.299 Us 0+ α	Po213 4.2 Us 9/2+ α
αBi207 31.55 y 9/2- EC	αBi208 3.68E+5 y (5)+ * EC	Bi209 9/2- * 100	Bi210 5.013 d 1- * β-,α	Bi211 2.14 m 9/2- β-,α	Bi212 60.55 m 1(-) * α,β-α,...
Pb206 0+ * 24.1	Pb207 1/2- * 22.1	Pb208 0+ * 52.4	Pb209 3.253 h 9/2+ β-	Pb210 22.3 y 0+ β-,α	Pb211 36.1 m 9/2+ β-

- **ISOLDE** – IS 673 (Sn isomers) and
  I239 (**seniority vs. cluster structure** around ^{208}Pb)
  isomeric states down to 1.5 ns (?)

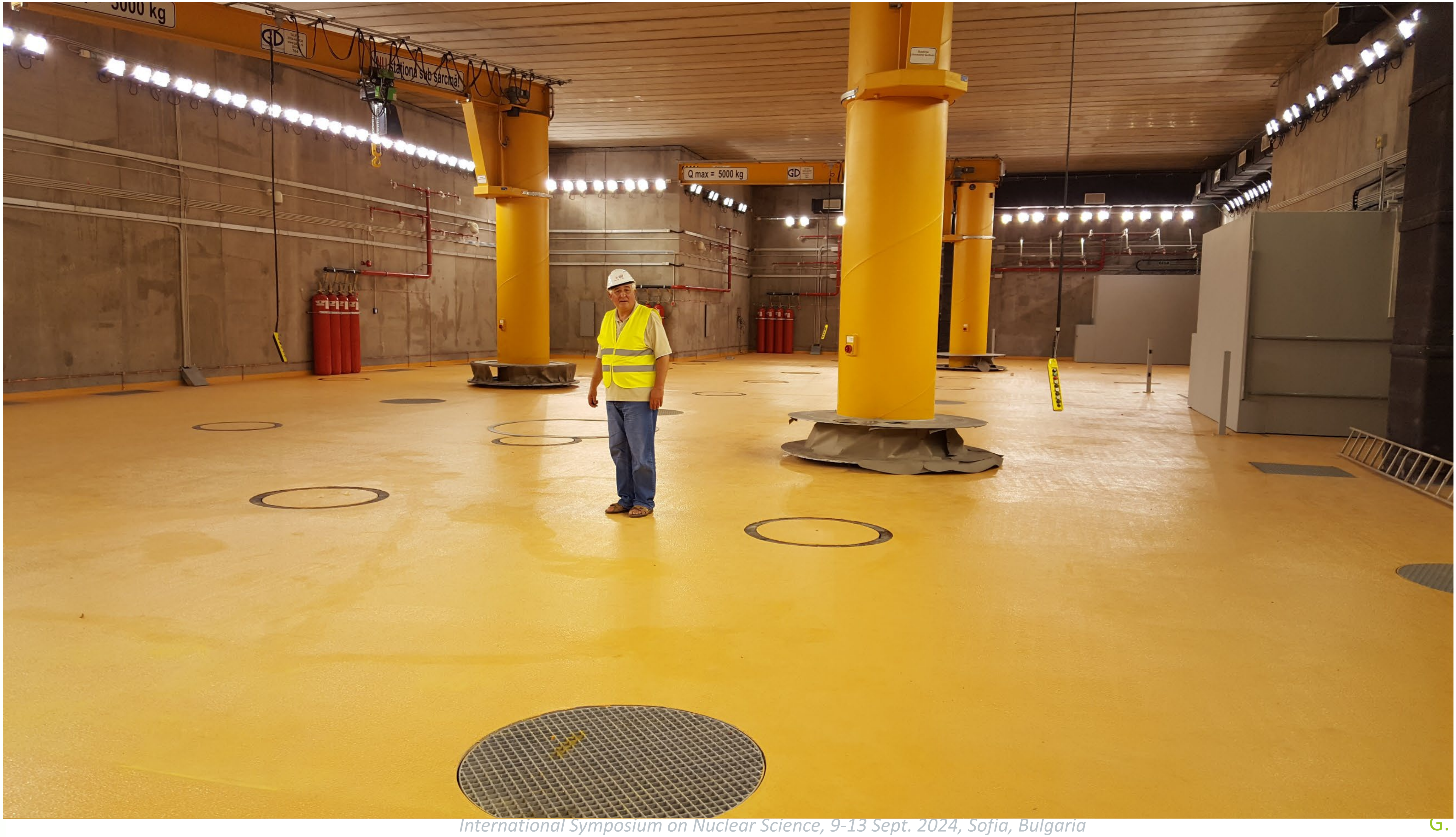
- ILL – ^{98}Y → ***see the talk of Jean-Michel Daugas***

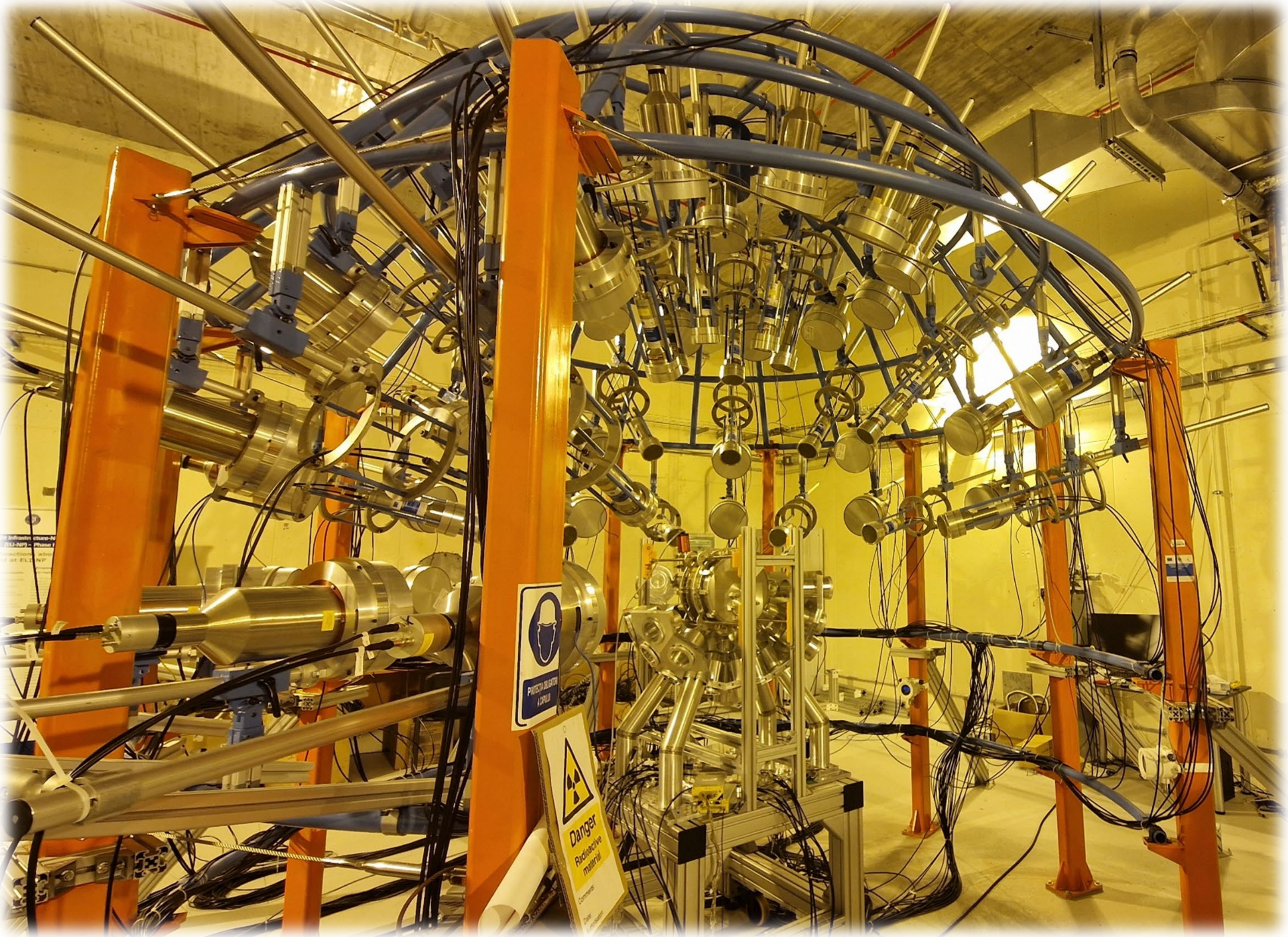
- **RIKEN** – NP2212-RIBF225
  Magnetic moment of ^{132}Sn (6^+) in TDPAC
  experiment scheduled in November 2024

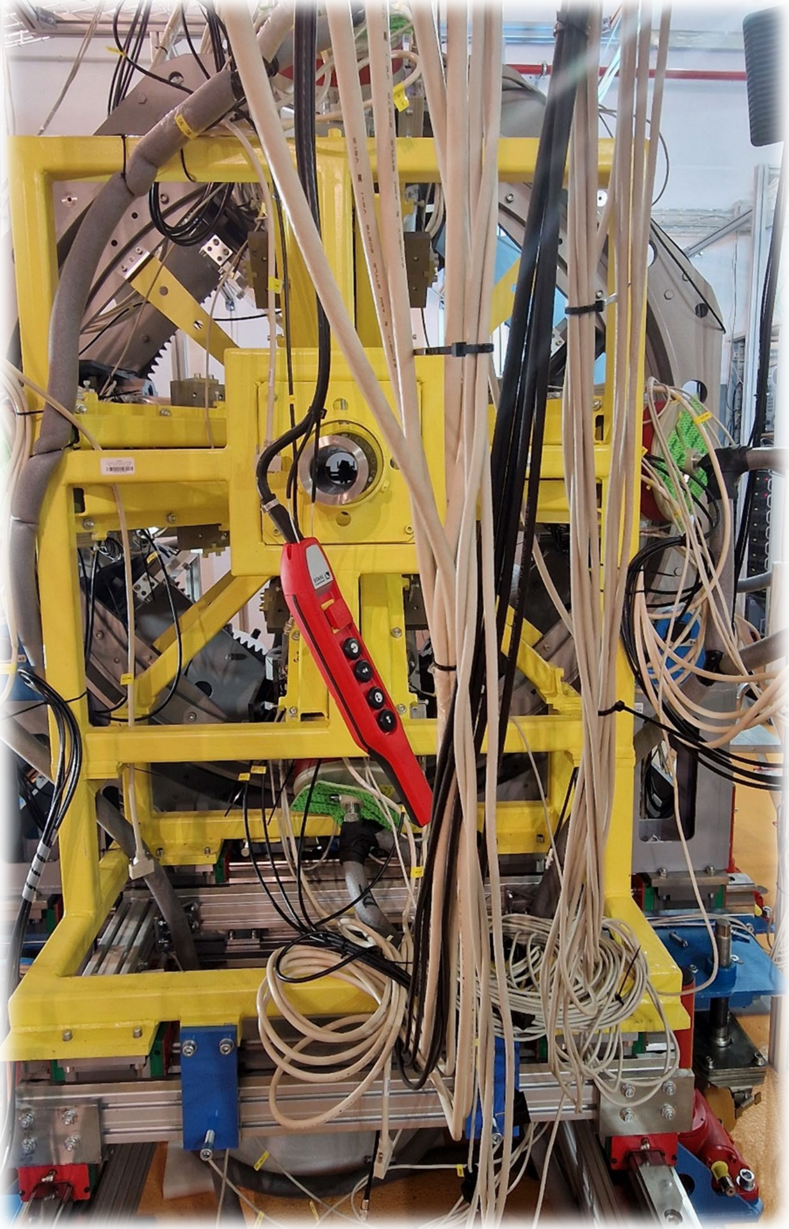


Summary

- TDPAD in projectile fragmentation has provided a numerous results for a number of exotic nuclei throughout the nuclear chart and at several different facilities.
- TDPAC is a technique that can be used both at high energy (fragmentation) and at low-energy facilities (ISOLDE, DESIR etc.) It is complementary to the TDPAD that could be further developed and used for nuclear moment studies of short-lived isomeric states in exotic nuclei.


5000 kg
Nu stationa sub sarcina!
Q max = 5000 kg


Danger
Radioactive material

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Some recent collaborators

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IFIN-HH

ill
NEUTRONS FOR SOCIETY

ISOLDE

RIKEN NISHINA CENTER

NATIONAL AND KAPODISTRIAN UNIVERSITY OF ATHENS

UNIVERSIDAD COMPLUTENSE
MADRID

KU LEUVEN