EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2007-2013

High precision *g*-factor measurements with stable and radioactive nuclei and perspectives for experiments @SPES and @ELI-NP

Aslı KUŞOĞLU[1,2]

[1]ELI-NP, Magurele, Romania
[2]Istanbul University, Istanbul, Turkey
asli.kusoglu@eli-np.ro

Outline

- g factor– how do we measure them and why do we need different methods and approaches?
- Alternative *g*-factor measurements need to be developed for RIB

  g-factor measurements of short-lived excited states:

  Time Differential Recoil In Vacuum (TDRIV) on radioactive geometry

  - ^{24}Mg – proof of principle on H-like ions @ ALTO
  - ^{56}Fe – proof of principle on Na-like ions @ ALTO
- Perspective experiments @SPES and @ELI-NP

Magnetic dipole moments

- Nuclei with non-zero spin have magnetic dipole moment

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

- Source of nuclear magnetism:
  - orbital movement of charged particles
  - intrinsic spin of the nucleus

- Nuclei with non-zero spin have magnetic dipole moment

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

- the contribution of every nucleon

- π/ν g factors:

free-nucleon

$$g_s^\pi = 5.585 \quad g_\ell^\pi = 1$$

$$g_s^\nu = -3.826 \quad g_\ell^\nu = 0$$

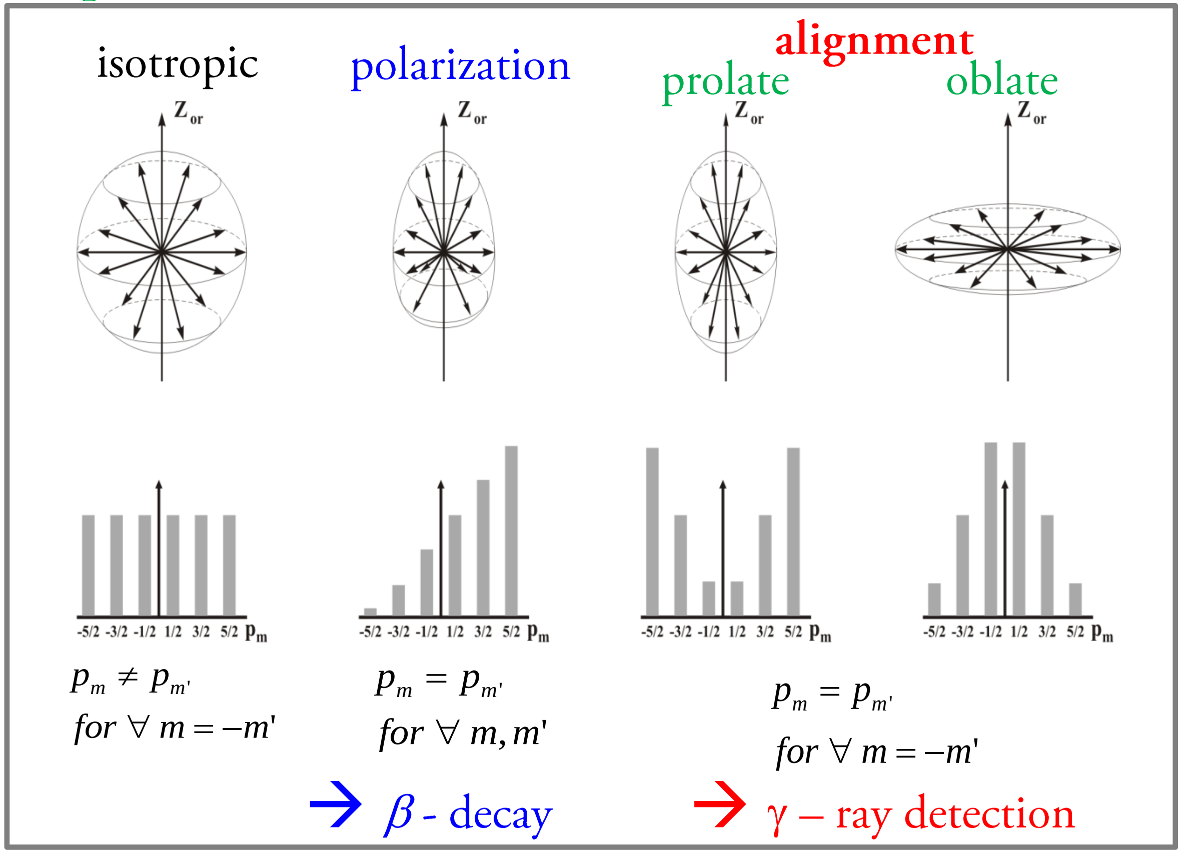
effective

$$g_s^\pi = 0.7 * g_s^\pi \quad g_\ell^\pi = 1$$

$$g_s^\nu = 0.7 * g_s^\nu \quad g_\ell^\nu = 0$$

How to measure *g* factor?

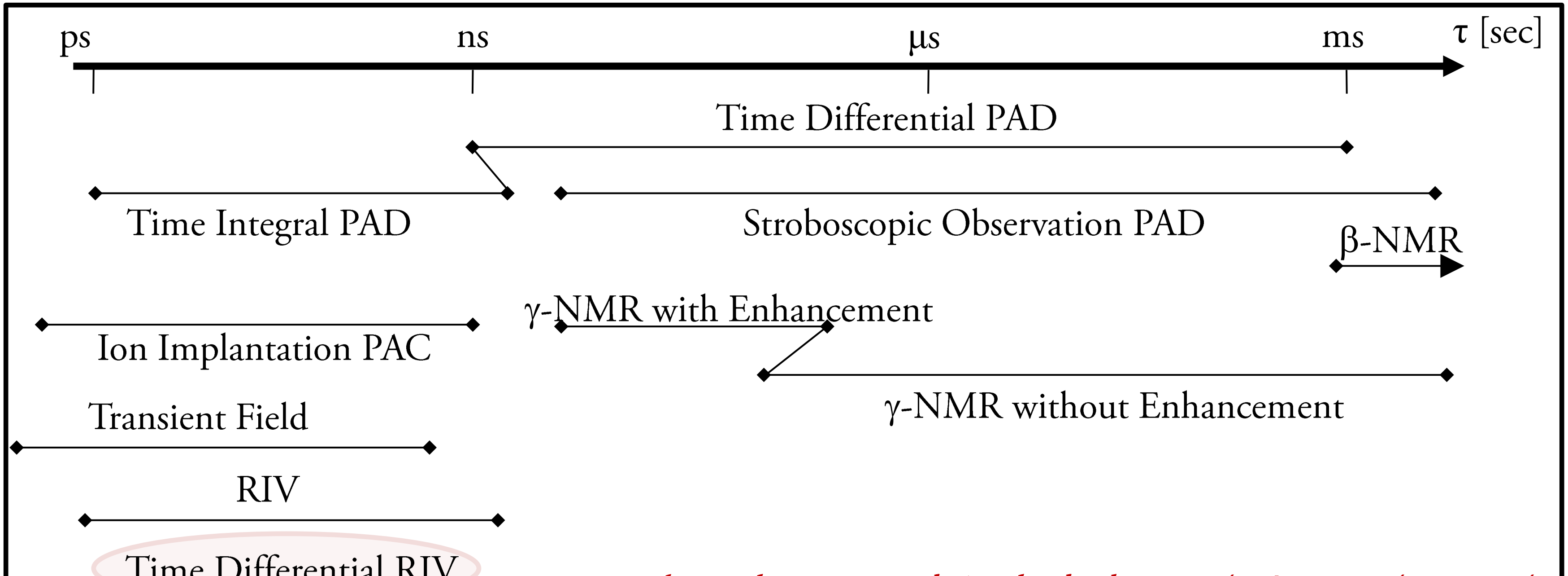
- Obtain nuclear spin-oriented ensemble



- Apply perturbing magnetic field (external or hyperfine field) → $\omega_L = -g \frac{\mu_N}{\hbar} B$
  - Have sufficient time for interaction within the nuclear lifetime
  - Know with a sufficient precision the perturbing field
- Observe modification of the perturbation

Experimental nuclear moment measurement techniques

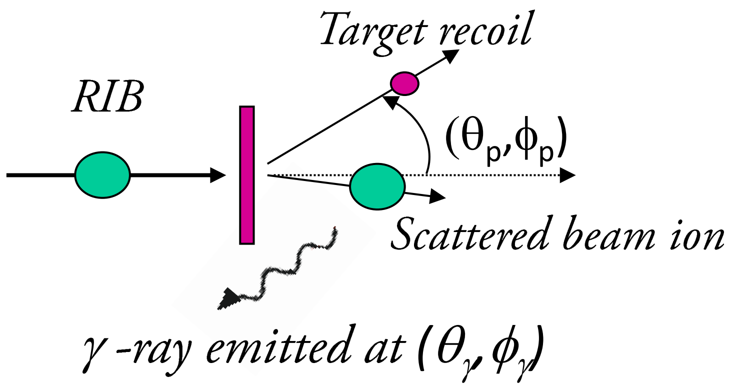
- Different measurement techniques depending on the nuclear state properties (lifetime, spin, production method etc.)



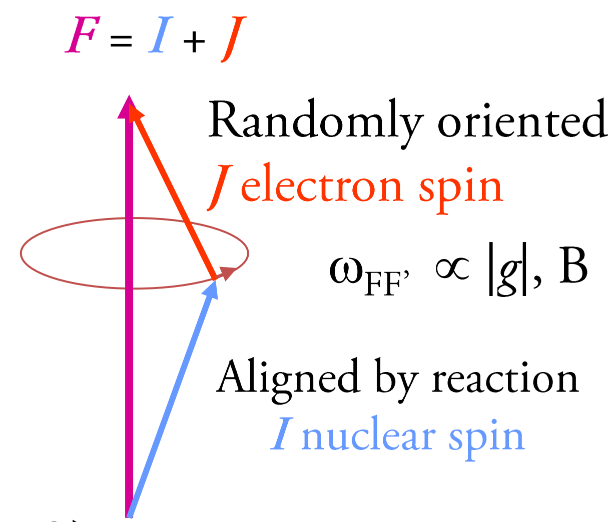
E. Recknagel , Pure and Applied Physics, 40C, 93-141, 1974

- Transient Field (TF) or Recoil In Vacuum (RIV) techniques need calibration measurements with known g factors

RIV (Recoil In Vacuum)



$$B_{ns} = 16.7 \frac{Z^3}{n^3}\left[1+\left(\frac{Z}{84}\right)^{2.5}\right][T]$$



A.E. Stuchbery et al., Hyperfine Interact 220, 29-45, (2013)

Analyze particle-γ angular correlations

$$W(\theta_p,\theta_\gamma,\Delta\phi) = \sum_{kq} B_{kq}(\theta_p) Q_k G_k F_k D_{q0}^{k*}(\Delta\phi,\theta_\gamma,0)$$

$$\underset{(0\le|G_k|\le1)}{G_k(t)} = \sum_{F,F'} C_{FF'} \exp(-\omega_{FF'}t)$$

- attenuation coefficients

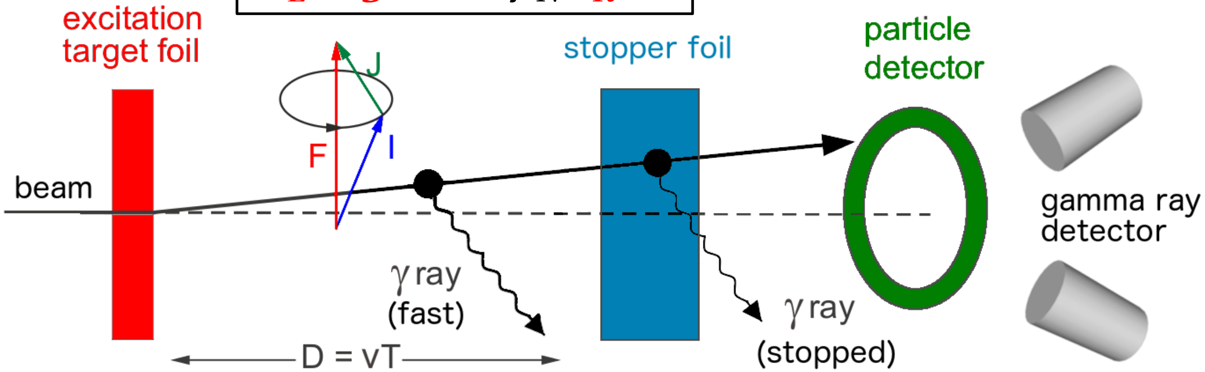
contains information about *g factor*

$$\omega_{FF'} = \frac{\mu_N B}{2\hbar J} g \big(F(F+1) - F'(F'+1)\big)$$

- interaction frequency

TDRIV (Time-Differential Recoil In Vacuum) with stable beam

$$\omega_L = g(2I+1)\mu_N B_{1s}/\hbar$$

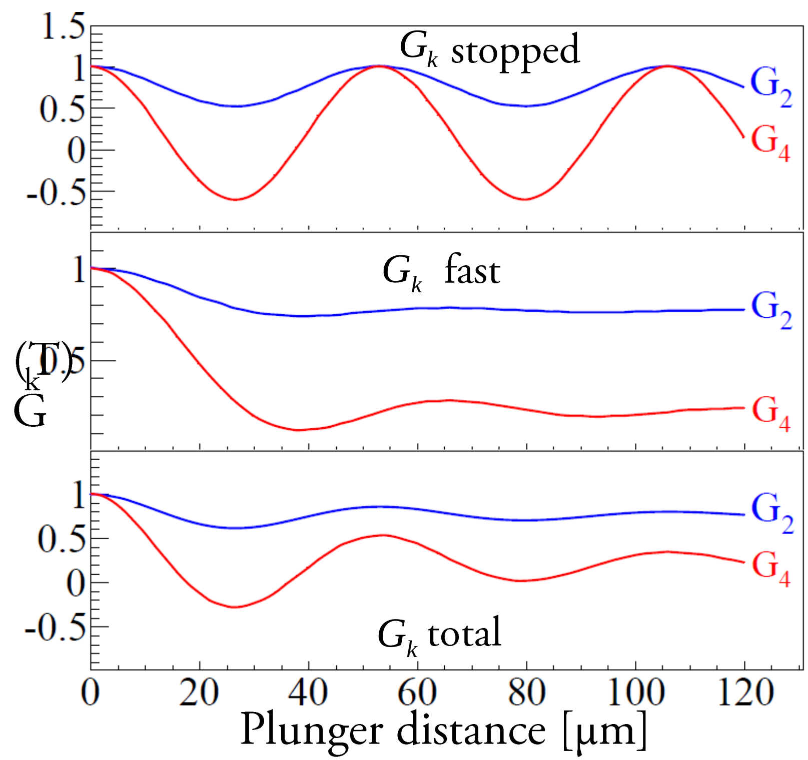


Stable beam geometry!

H-like ions attenuation factors

$^{12}C(^{16}O,\alpha\gamma)^{24}Mg$ @ 41.7 MeV
→ $\beta = 0.056$
→ 15 % H-like charge state
→ $|g(2^+)| = 0.51(2)$

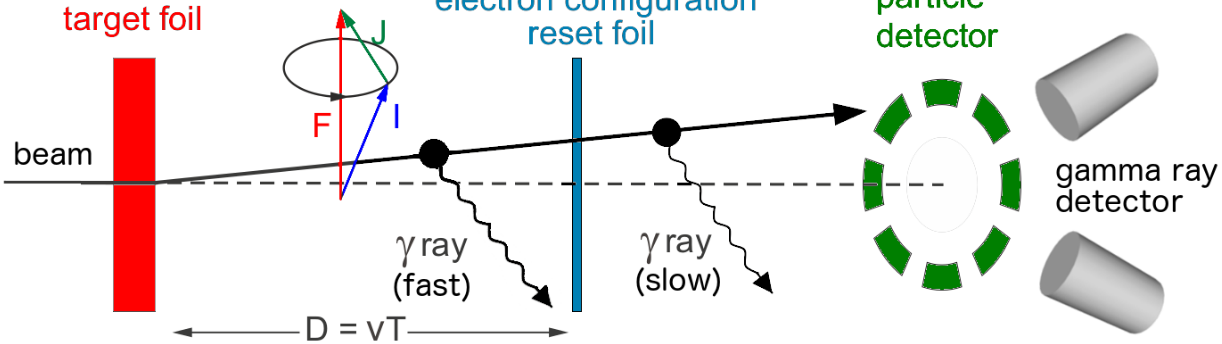
R.E. Horstman et al., Nucl. Phys. A 248, 291 (1975)



- The importance of the use of H-like ions comes from the simplicity of the electron configuration

TDRIV (Time-Differential Recoil In Vacuum) with radioactive beam

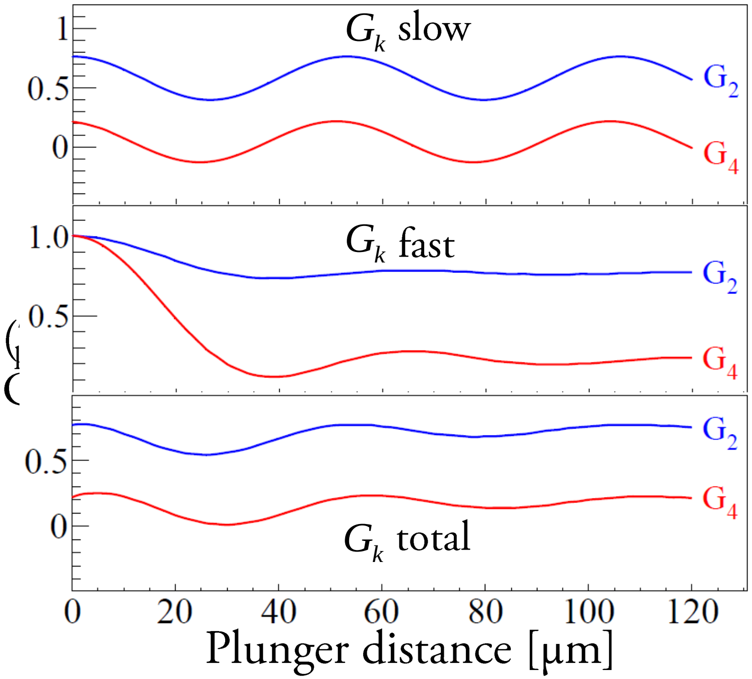
$$\omega_L = g(2I+1)\mu_N B_{1s}/\hbar$$



Attenuation coefficients → $\overline{G_k(T)}$ $G_k(T)\overline{G_k(\infty)}$

Radioactive beam geometry!

H-like ions attenuation factors

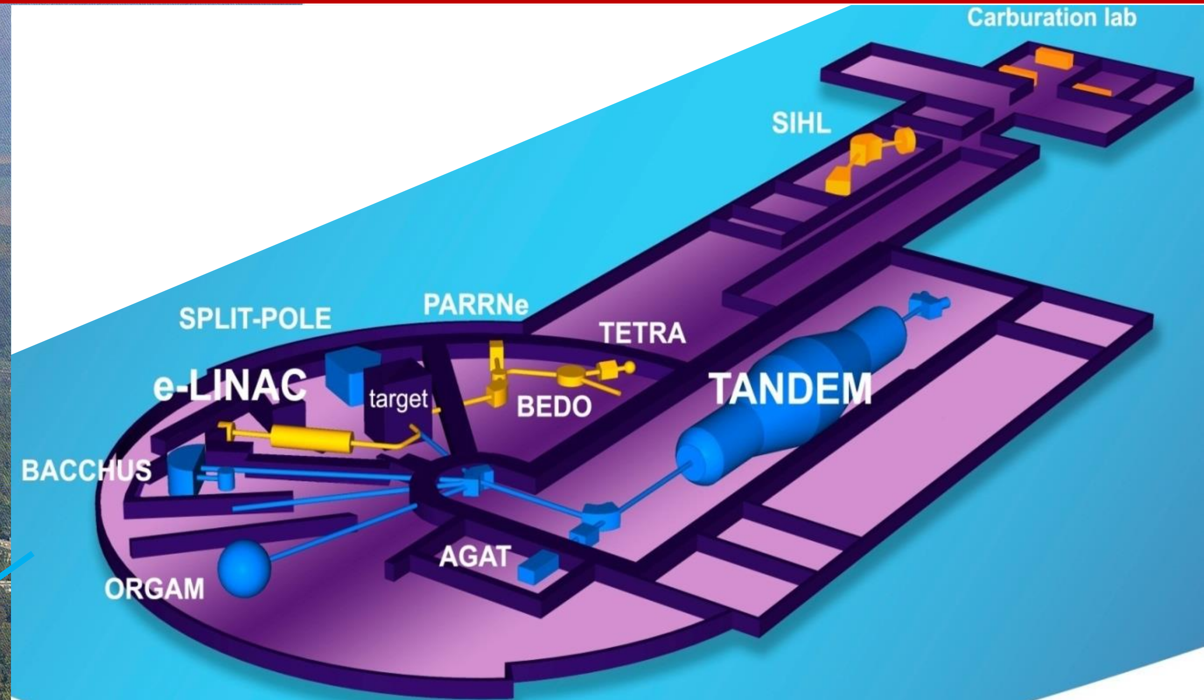


A. E. Stuchbery et al., Phys. Rev. C 71, 047302 (2005)

$$\overline{G_k(T)} = \int_0^T G_k(t)\lambda e^{-\lambda t}dt$$

$$G_k(\infty) = \int G_k(t)\lambda e^{-\lambda t}dt$$

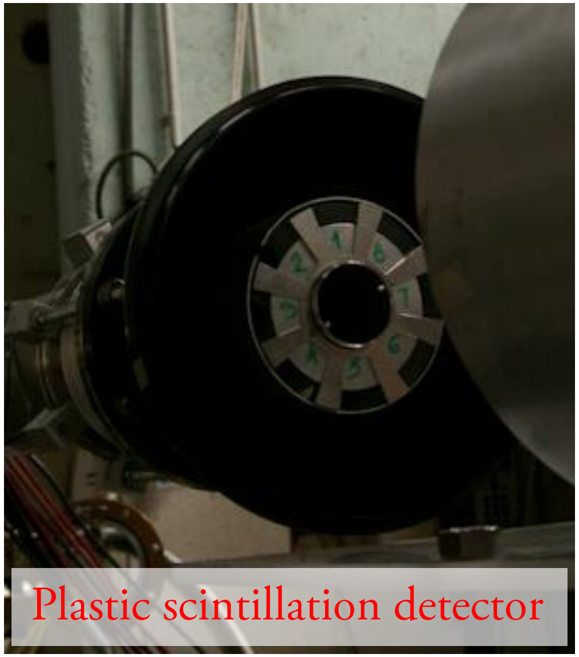
ALTO facility @ IPN

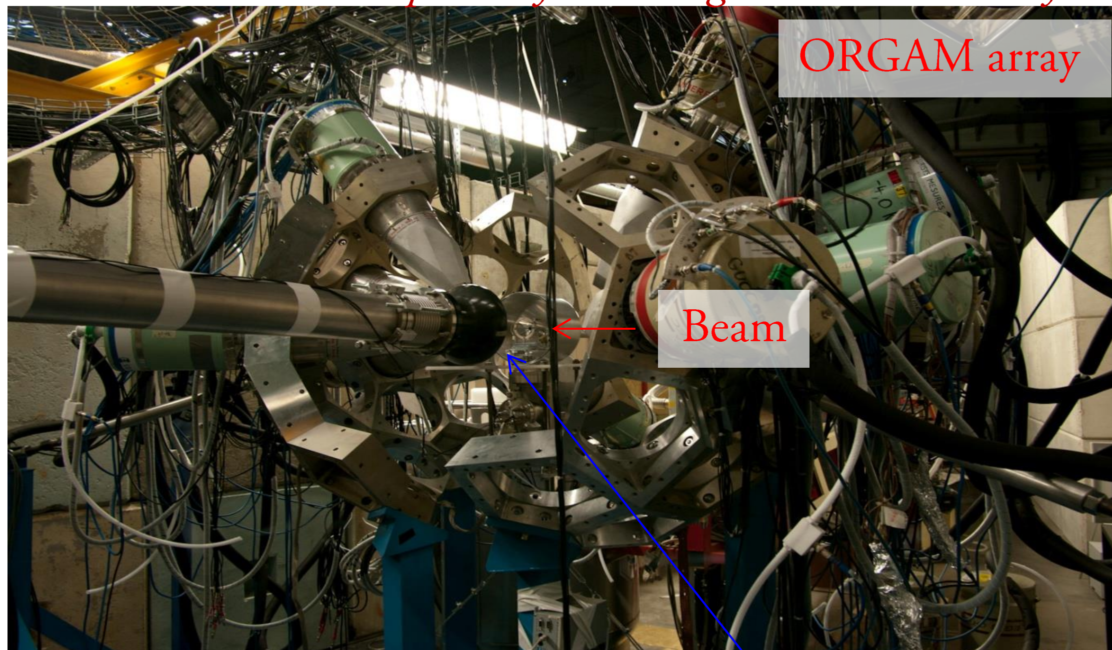


Tandem building
Institut de Physique Nucléaire
Campus of the Paris Sud University
Orsay (France)

TDRIV Experimental Setup for H-like ions @ ALTO

Proposed by G.Georgiev, A.E. Stuchbery et. al





Beam : ^{24}Mg @ 120 MeV (5MeV/u), 0.3 pnA

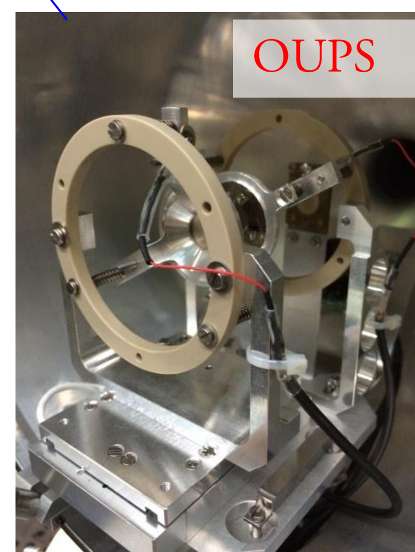
Target : 2.4 mg/cm^2 ^{93}Nb, Glancing collisions

Reset foil: 1.7 mg/cm^2 ^{197}Au

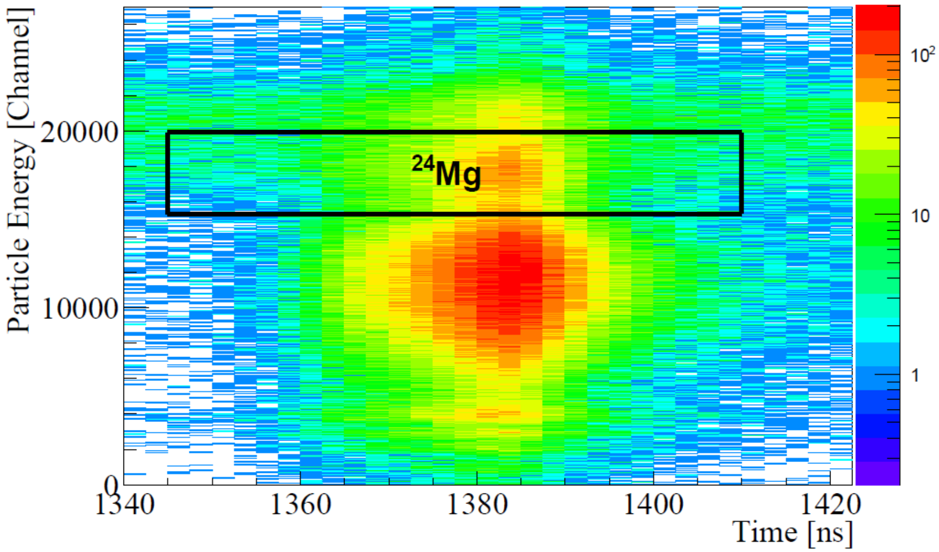
- 13 HPGe in ORGAM array

θ= 46.5°, 72.1°, 85.8°, 94.2°, 108.0°,133.6°, 157.6°

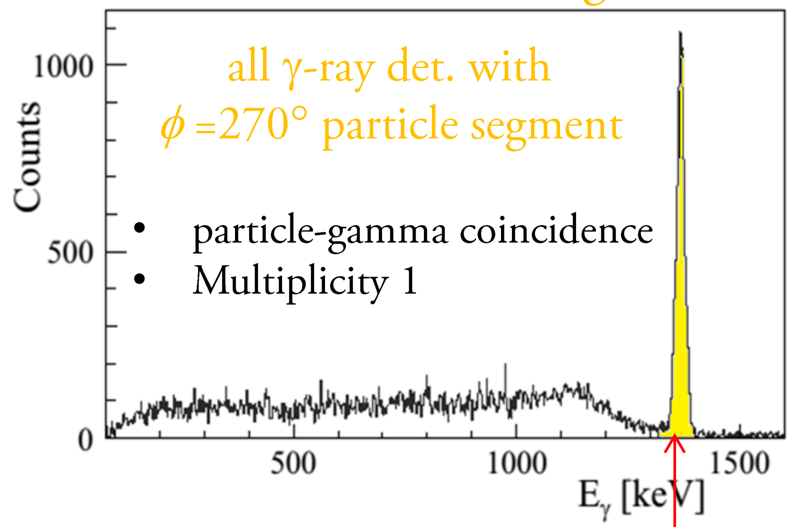
- 8-fold segmented plastic scintillation particle detector ($\Delta\phi_p$ = 30°, θ_p=33° to 38°)
- Plunger: OUPS (24 target-reset foil distance 100 μm)

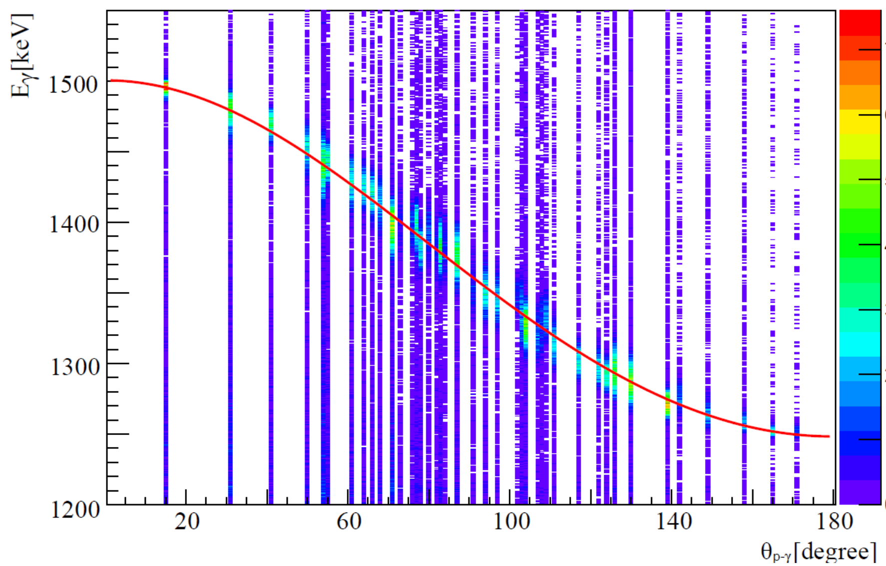


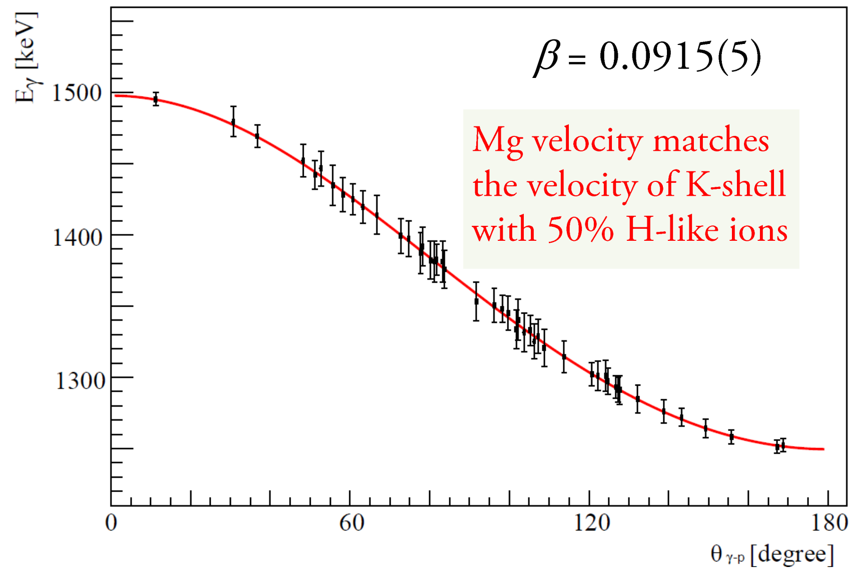
Data Analysis



^{24}Mg: $2^+ \rightarrow 0^+$

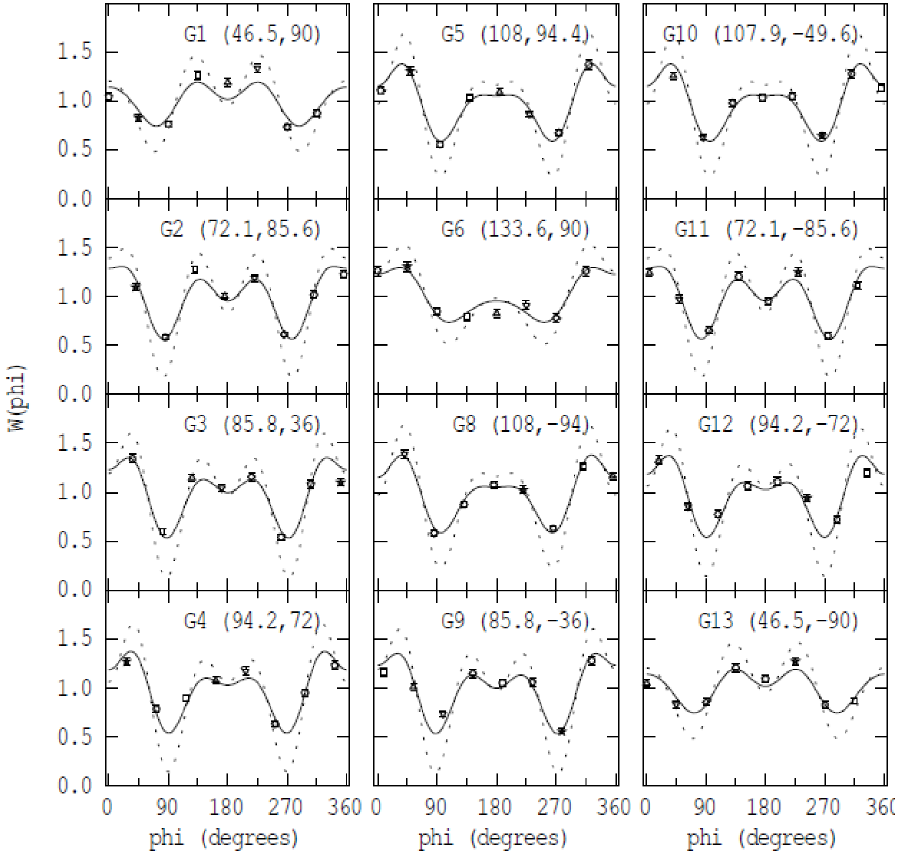


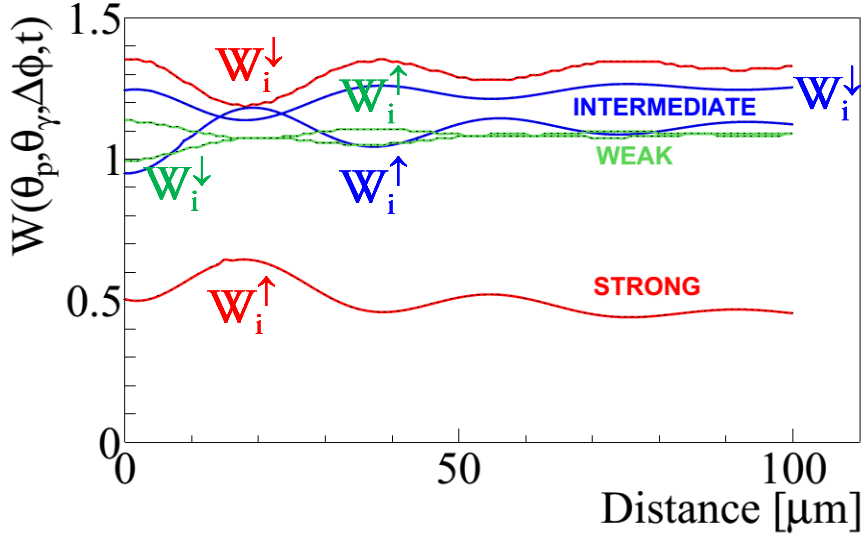




Angular Correlation Analysis

$$W(\theta_p,\theta_\gamma,\Delta\phi,t)=\sum_{kq}B_{kq}(\theta_p)Q_kF_kG_k(t)D^{k*}_{q0}(\Delta\phi,\theta_\gamma,0)$$

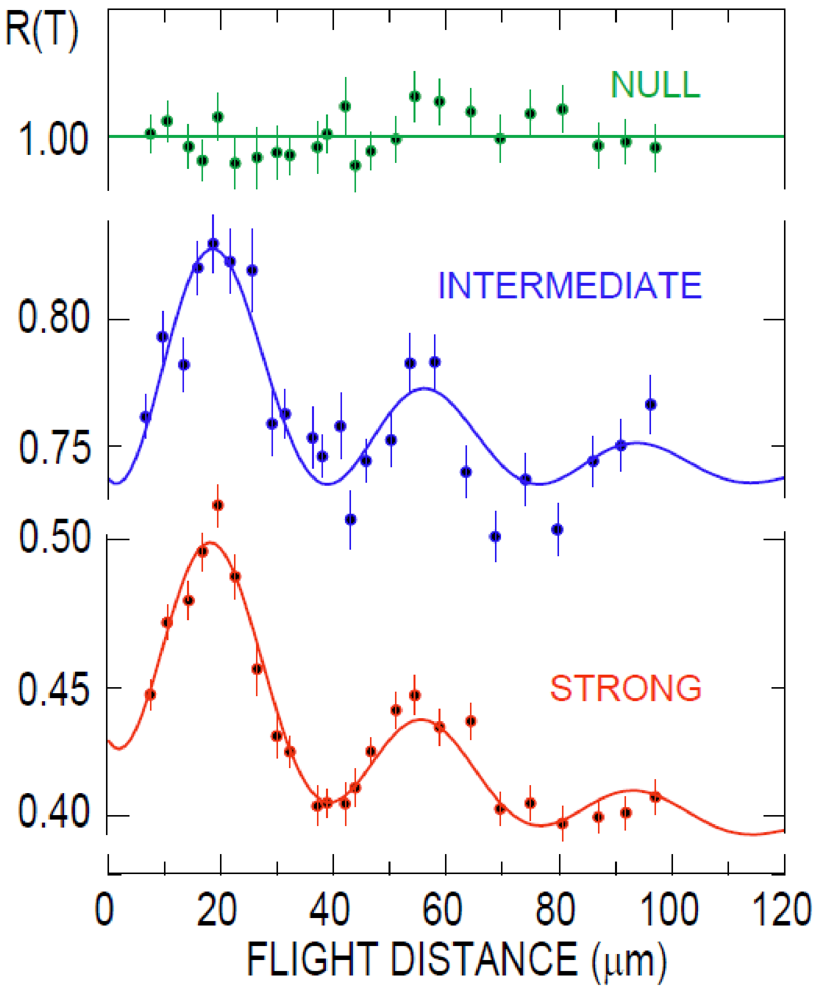


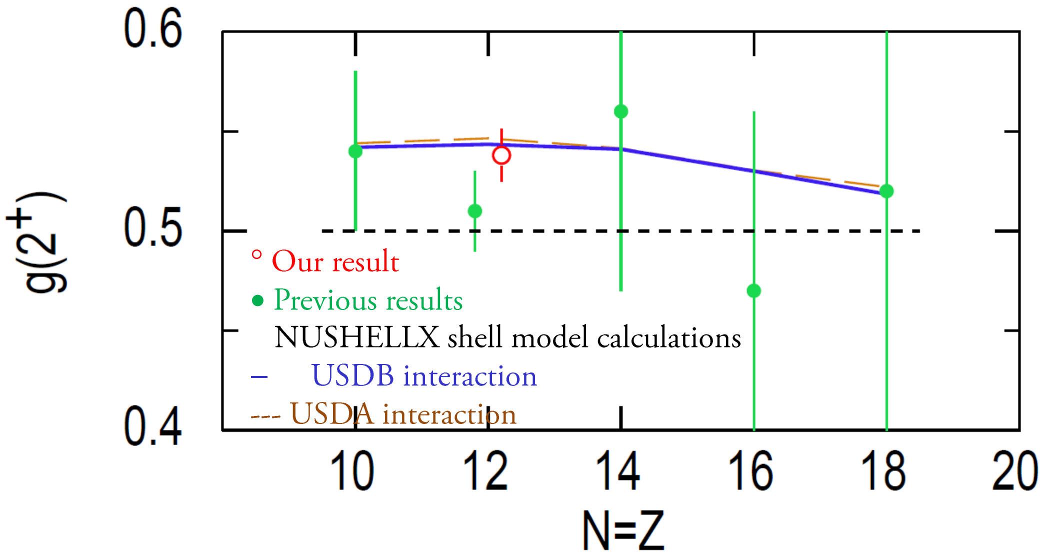


$$N(i,j)=N_0\varepsilon_{pi}\varepsilon_{\gamma j}W(\theta_p,\theta_\gamma,\Delta\phi,t)$$

$$R(T)=\left(\prod_{i=1}^{n}\frac{W_i^{\uparrow}}{W_i^{\downarrow}}\right)^{1/n}$$

A.Kusoglu et al. JPCS, 590, 012041, 2015





*R.E. Horstman et al., Nucl. Phys. **A** 248, 291 (1975)*

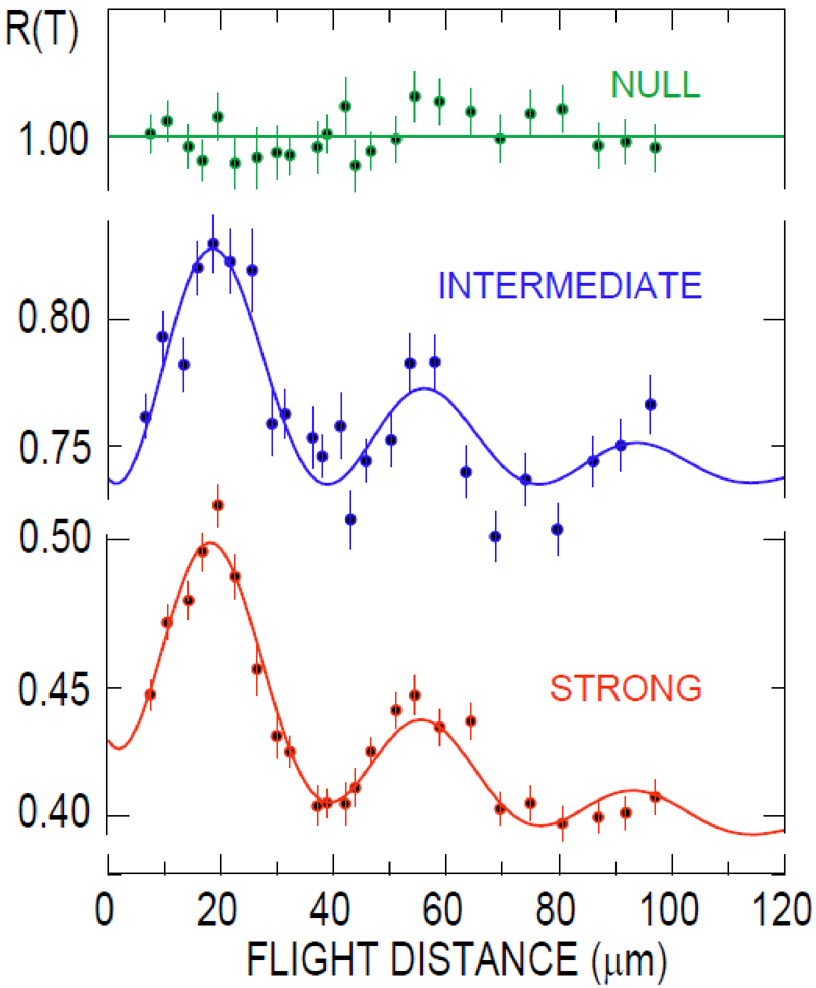
Previous measurement: $|g(2^+)| = 0.51(2)$

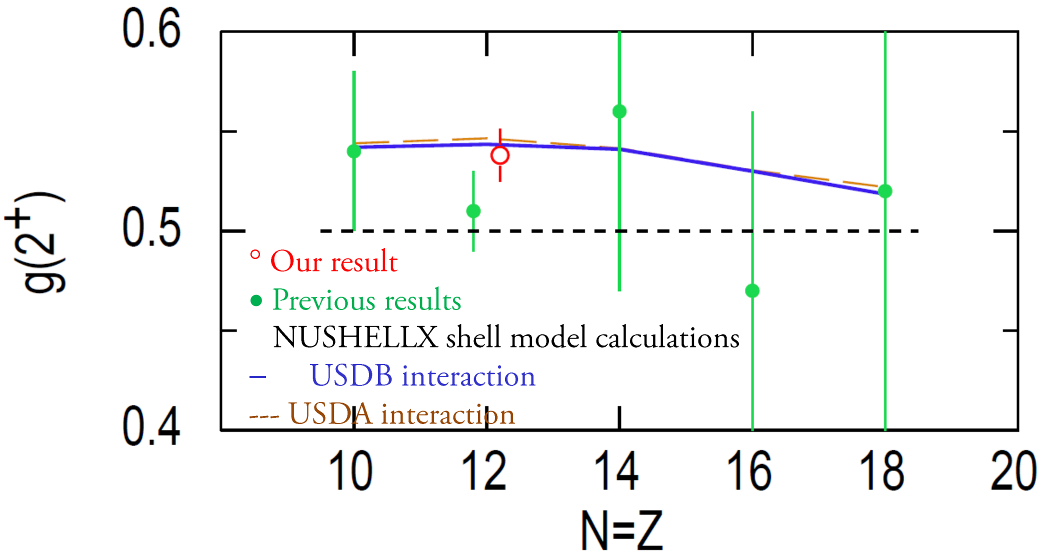
Our result: $|g(2^+)| = 0.538(\mathbf{13})$

A.Kusoglu et al. PRL, 114, 062501, 2015

First high precision measurement of $g(2^+)$ of ^{24}Mg

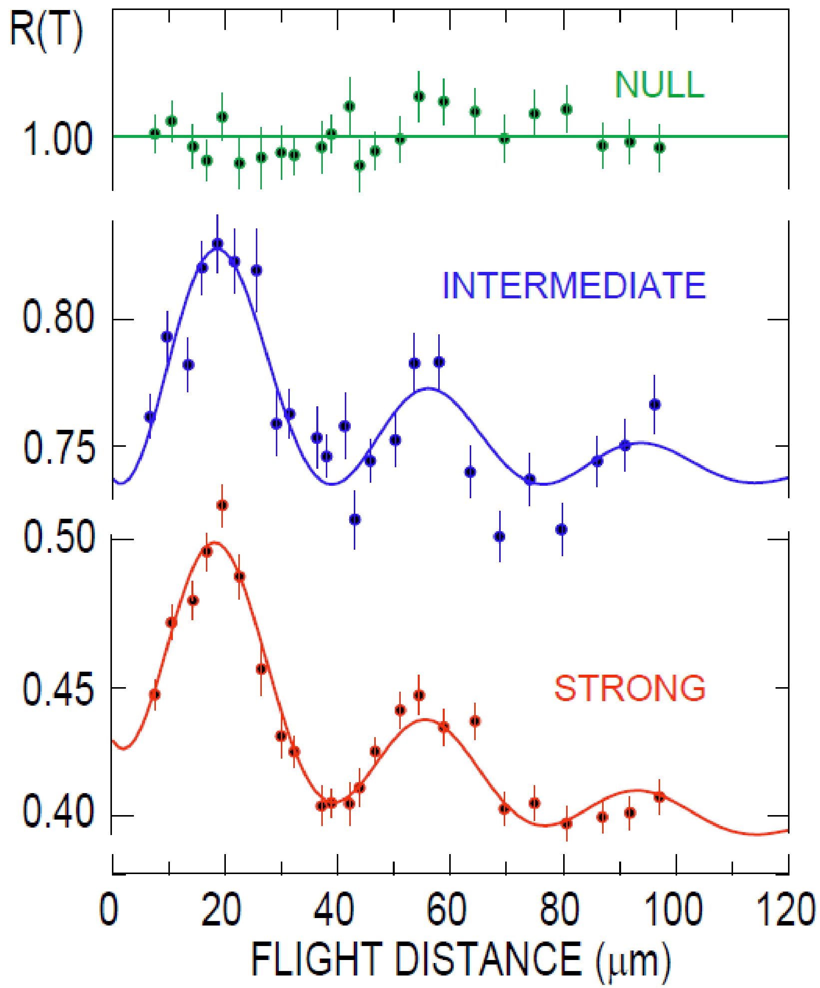
Experimental Results

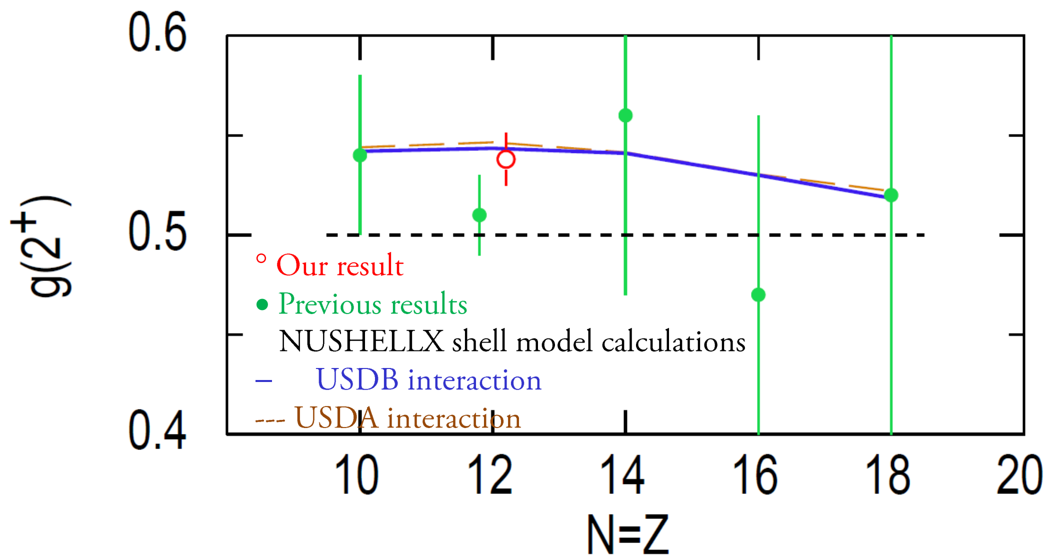




- ❑ Departure from $g = 0.5$
  - ❑ Configuration mixing
  - ❑ Isospin mixing
  - ❑ Meson exchange current

Experimental Results





- Departure from $g = 0.5$
  - Configuration mixing
  - Isospin mixing
  - Meson exchange current
- Open new perspectives:
  - High precision g-factor in stable nuclei
  - Validation of the technique for RIB
  - Extension to $A \geq 20$ to determine **absolute** g factors

Extension to Na-like electronic configurations

Method works for H-like ions

⇩

Does it work for ions with more than 1 electron?

$$B_{ns} = 16.7 \frac{Z^3}{n^3}\left[1+\left(\frac{Z}{84}\right)^{2.5}\right][T]$$

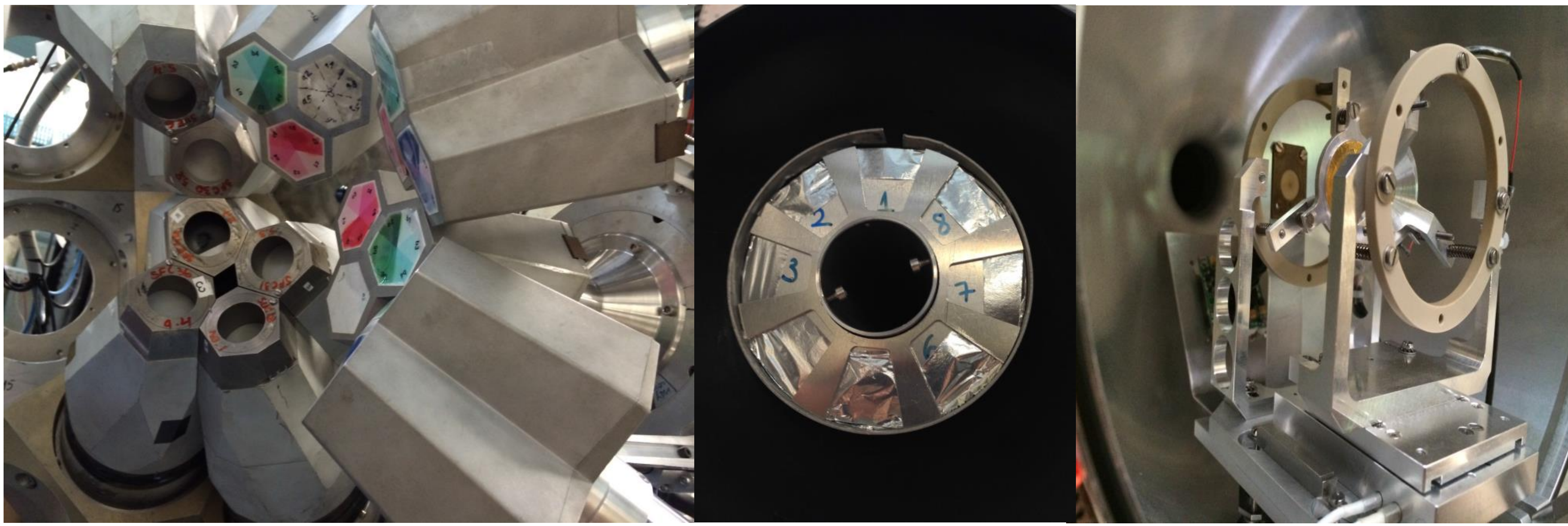
Proposed experiment with Na-like ions using $^{56}Fe^{15+}$

- Is it possible to observe oscillation?
- (if yes) Precise and independent *g*-factor measurement of ^{56}Fe, 2^+
- (if yes) Confront ab initio hyperfine field calculations

TDRIV Experimental Setup for Na-like ions @ ALTO

Proposed by A.E. Stuchbery et. al

- 8 MINIBALL Cluster: 144 Segments
- 12 ORGAM detectors
- 8 fold segmented plastic detector
- OUPS plunger



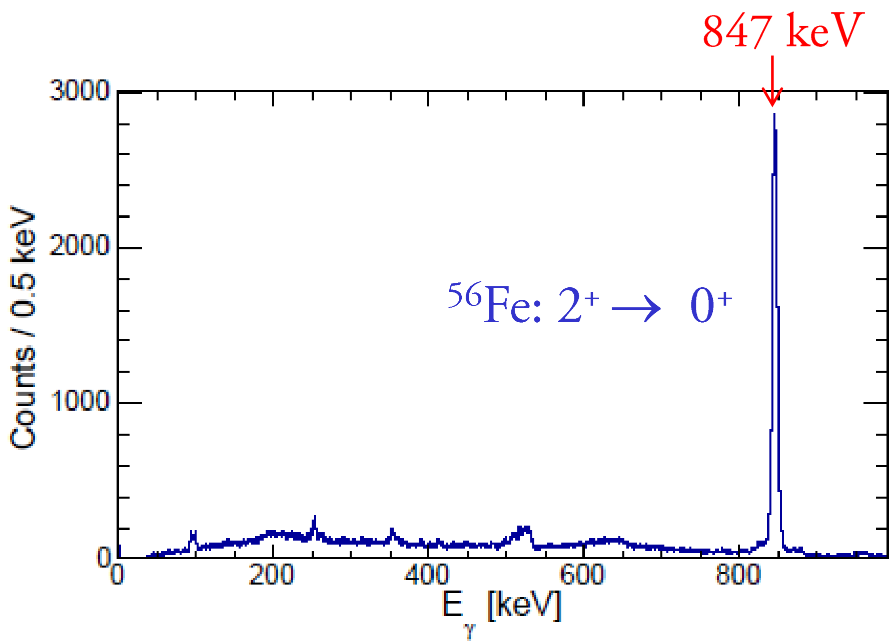
Beam : $^{56}Fe^{15+}$ @ 130 MeV,

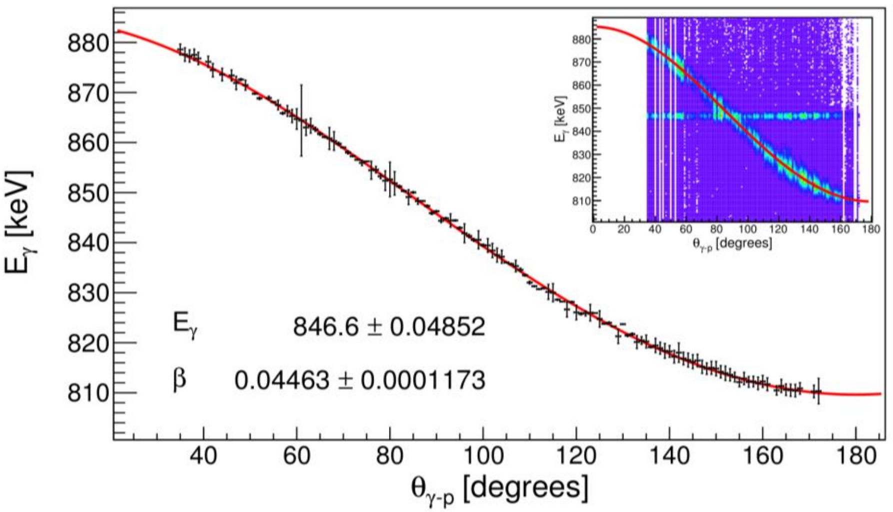
Target : 230 µm/cm^2 of ^{12}C deposited on 0.5 µm ^{nat}Ni foil

Coulomb excitation first 2^+ (E_x = 847 keV, τ= 9.6 ps)

Stopper : 5.8 mg/cm^2 ^{nat}Ni

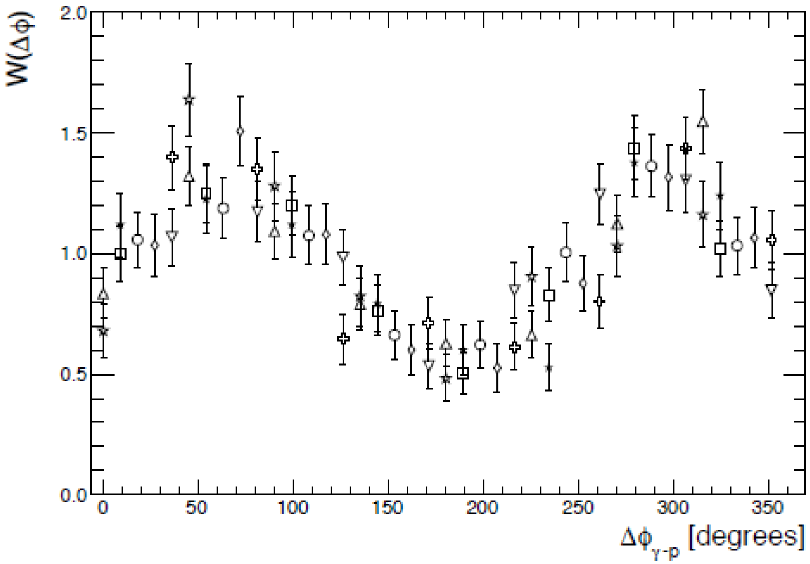
Preliminary results



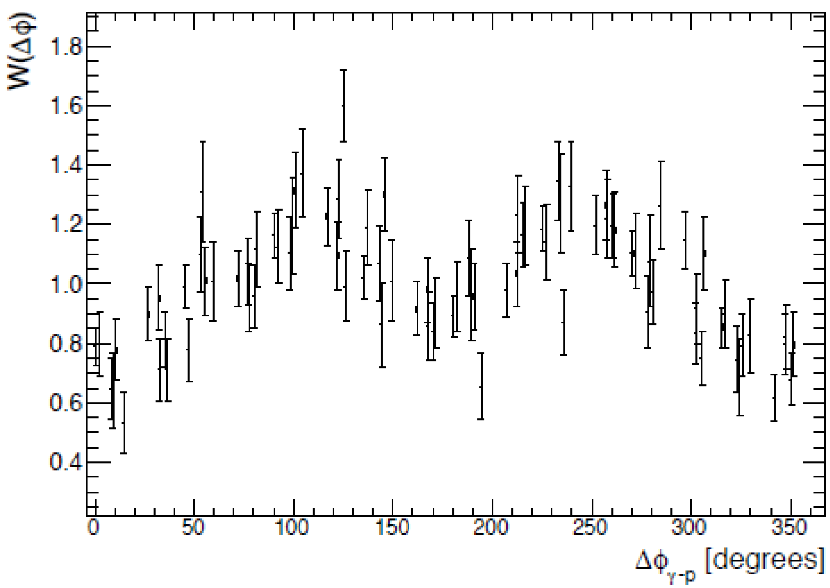


- Development of a ^{12}C for plunger
- Beam energy tuned to optimize the charge state distribution
- Several conditions to clean the spectrum from:
  - Reactions with the C foil
  - Coulomb excitation in the Ni foil

Analysis by A. Goasduff

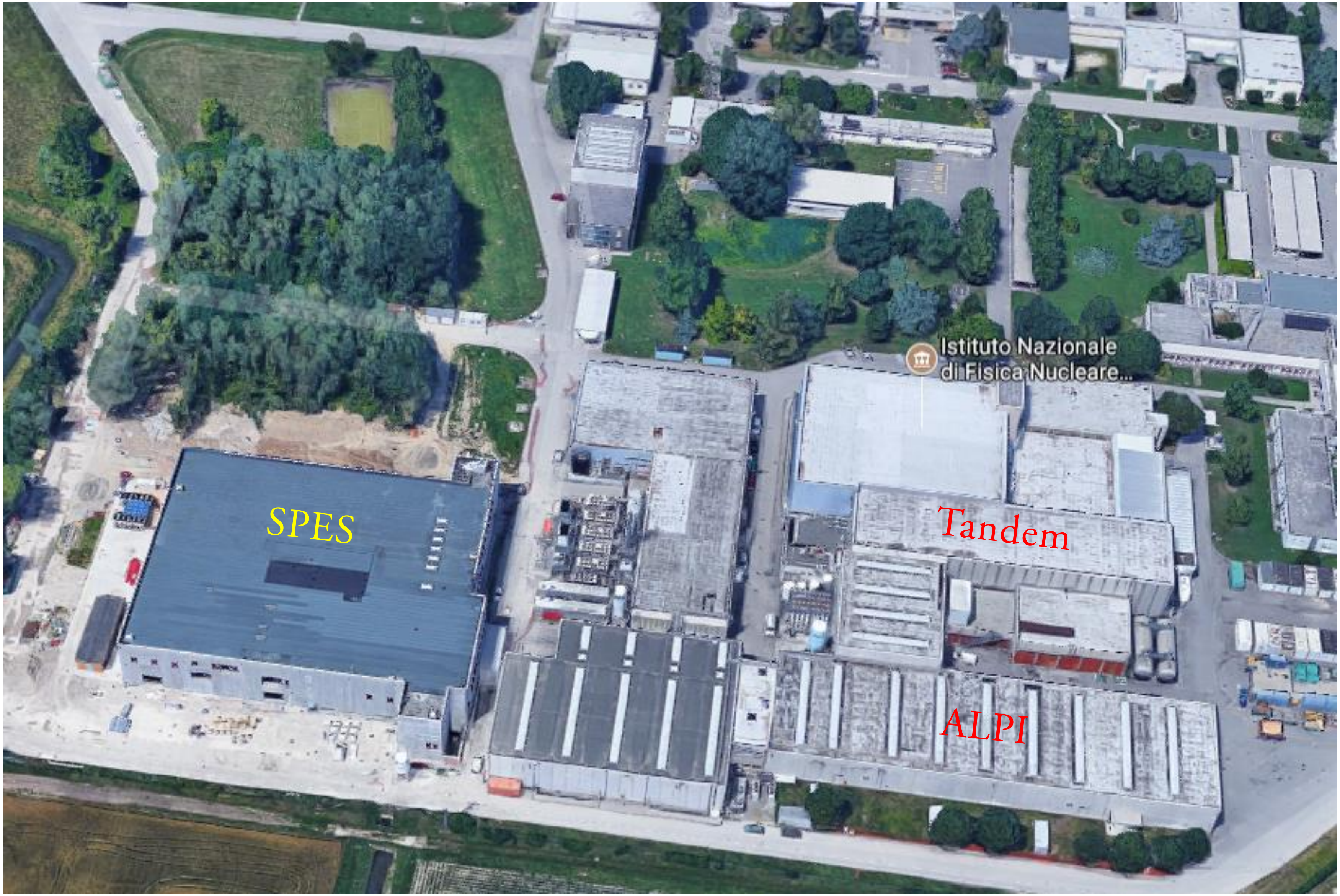


- Angular correlations for ORGAM detectors
  - For stopped and in-flight component
  - For all plunger distances



- Analysis of MINIBALL performed segment by segment

LNL facilities



Possibilities of TDRIV @ LNL

Essential ingredients:

- ❑ γ-ray transparency

→ GALILEO array (phase1 2.4% at 1.3 MeV)

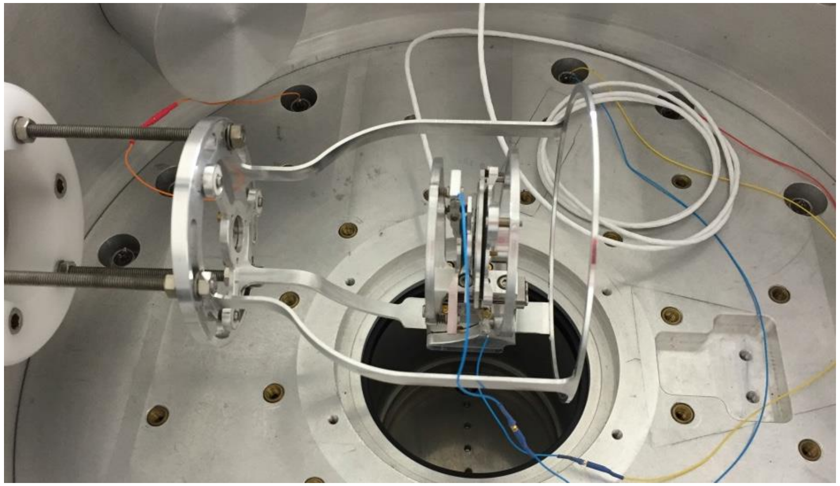
- ❑ Observe changes in the radiation pattern as a function of time

→ IKP-LNL plunger

- ❑ Stable beam and post-accelerated SPES beam

- ❑ Segmentation in both θ, ϕ

→ Particle detector (under development)



Letter of Intent: *High precision electromagnetic moment measurements with stable and radioactive nuclei with GALILEO and GALILEO plunger*

GALILEO + Plunger + Recoil detector

A. Goasduff, A. Kusoglu et. al

LNL Particle detector

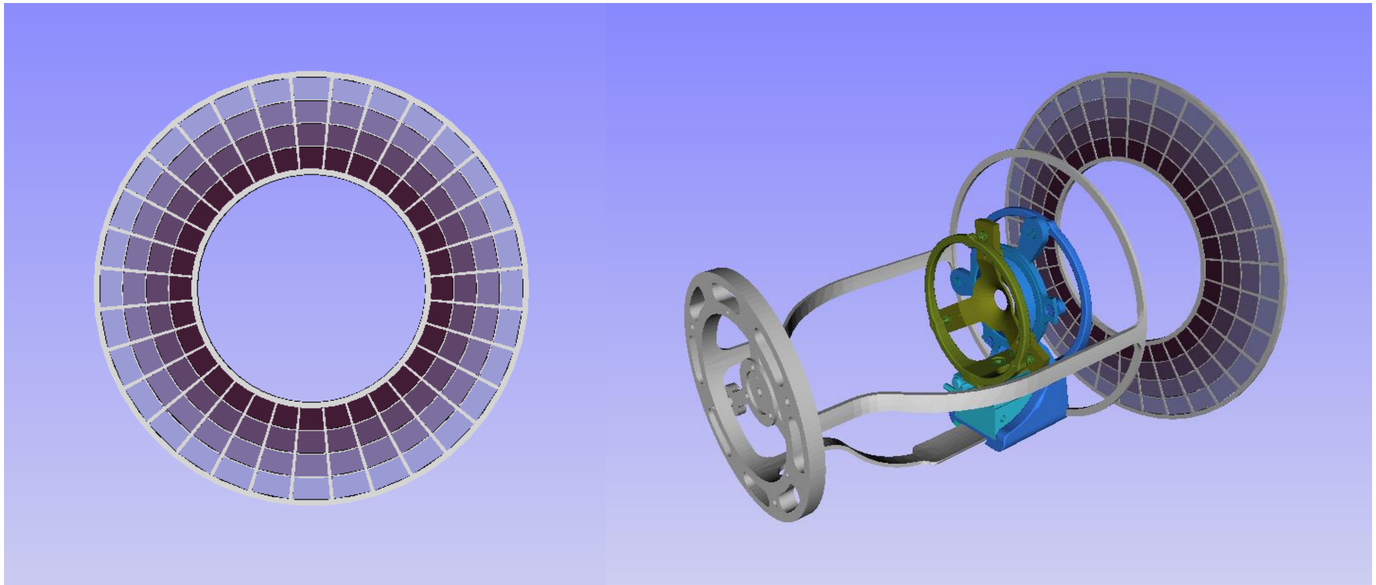
- Segmentation in both θ, ϕ

$\rightarrow$ Increased sensibility for g-factor and Doppler correction

- High counting rate capabilities and radiation hardness

$\rightarrow$ To be used with both stable and radioactive beams

- Coupling with the plunger and existing mechanics



Collaboration CSNSM (France), ANU (Australia), Istanbul University (Turkey) and INFN (Italy)

Perspectives Experiments @ LNL

- Development of new recoil detector at forward angle:
  - high precision g-factor measurements taking advantage of:
    - Large efficiency of the GALILEO array at 90 degrees
    - PIAVE-ALPI beams (^{22}Ne,…)
    - High quality Mg beams
    - Exploration of the fp-shell nuclei to give calibration points to transient-field technique
  - Paving the way for the study of g-factor measurements in exotic nuclei with SPES RIBs beams
    - Post accelerated SPES beam $\geq 10^5$ pps (neutron rich Zn, Ge and Se isotopes)
    - Study the evolution of the N=50 shell-closure towards ^{78}Ni

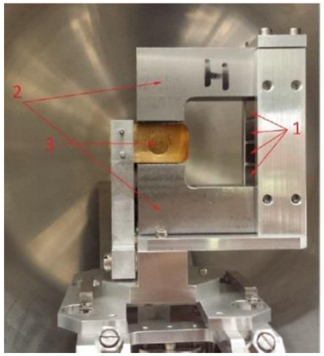
Letter of Intent for SPES: *Electromagnetic moment measurements with radioactive ion beams using GALILEO-ray array A. Goasduff, A. Kusoglu et. al*

ELI-NP facility

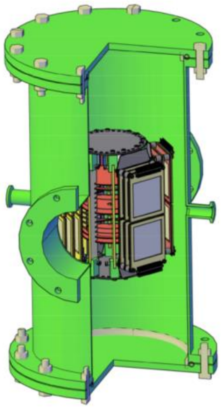
Perspective Experiments @ELI-NP

- ELIADE array covers the backward angles
  - Triple and higher fold γγ-coincidence
- ELI-BIC can be mounted at forward angles
- Fast-timing $LaBr_3$ detectors
- *g*-factor magnets
- Fission plunger

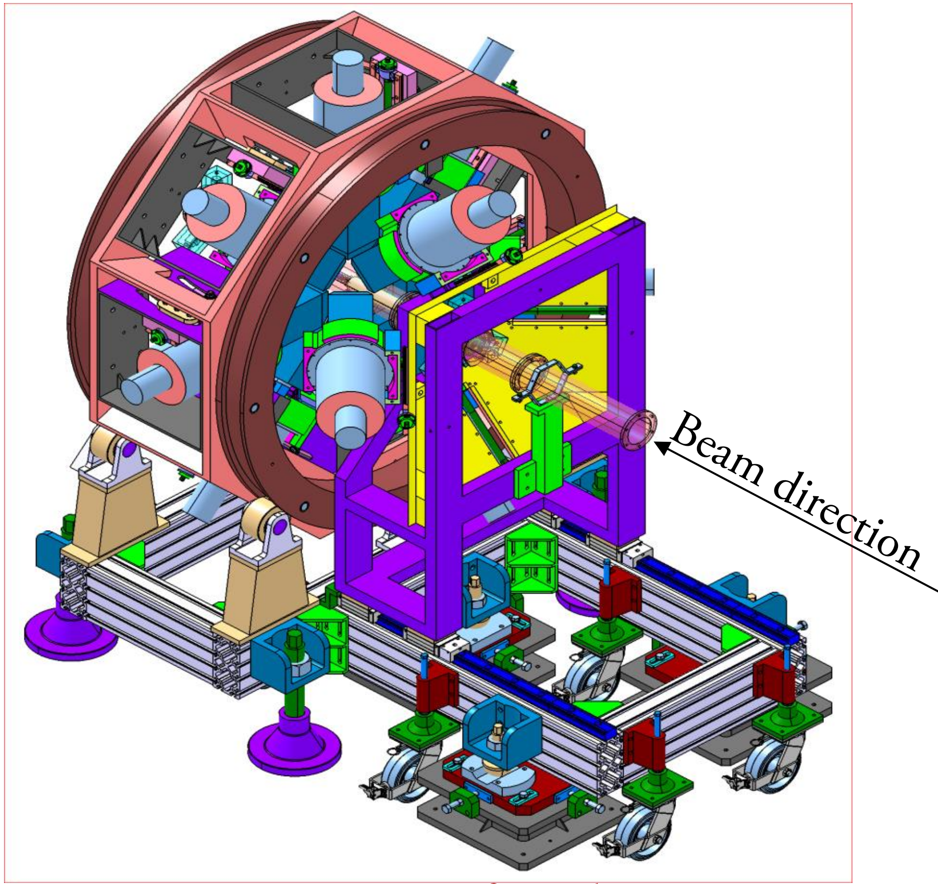
Permanent magnet



ELI-BIC



ELIADE Array



courtesy of C. Petku ELI-NP

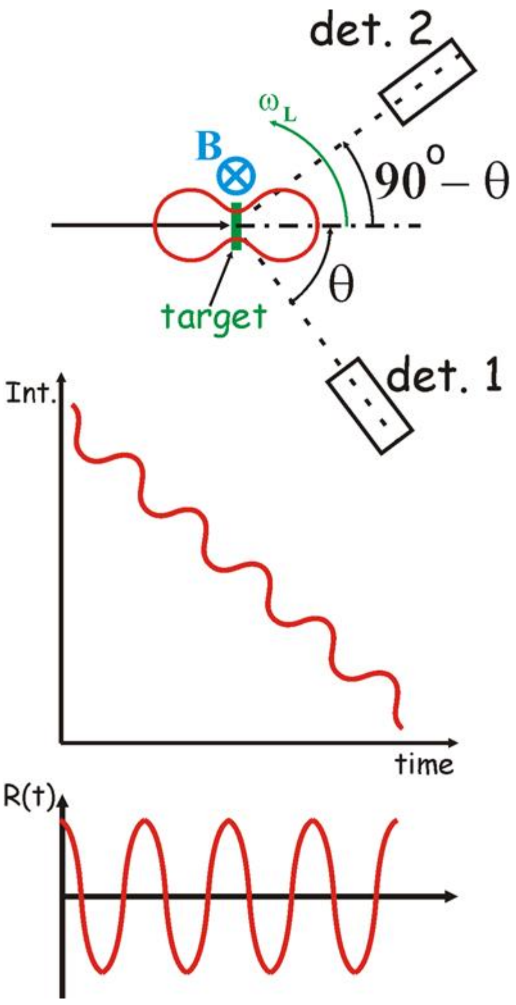
- *g*-factors of short-lived nanosecond isomers can be studied via in-beam γ-ray spectroscopy of fission fragments, using ELIADE array

Remember talk of G. Suliman

D.L. Balabanski et al., Romanian Rep. in Phys. Vol 68, S621-S698 (2016)

Perspective Experiments @ELI-NP

- Suitable Technique for isomeric lifetimes Time Differential Perturbed Angular Distribution (TDPAD)



$$I(t,\theta,B) = I_0 e^{-t/\tau} W(t,\theta,B)$$

$$W(t,\theta,B) = \sum_{k=even} A_k B_k P_k \cos(\theta - \omega_L t)$$

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

A_2 – angular distribution coefficient;
B_2 – nuclear orientation coefficient

- γ-decay of excited states using photo fission of ^{232}Th or ^{238}U
- understanding of the deformed *A* ~ 100 and *A* ~ 150 mass regions
  - ^{93,94,95}Rb, ^{95,97}Sr, ^{99}Zr
  - Vicinity of doubly-magic ^{132}Sn (^{130,131,132}Sn, ^{131}Sb, ^{133}Te, ^{132,134,135}Te)

Collaboration

ALTO TDRIV in ^{24}Mg

- A.E. Stuchbery – *Department of Physics, RSPE, Australian National University, Canberra ACT 0200, Australia*
- G.Georgiev, A. Goasduff, J. Ljungvall, C. Sotty - *CSNSM, CNRS/IN2P3; Université Paris-Sud 11, UMR8609, F-91405 ORSAY-Campus*
- B.A. Brown - *National Superconducting Cyclotron Laboratory, Department of Physics and Astronomy , Michigan State University, East Lansing, Michigan 48824, USA*
- D. L. Balabanski - *Extreme Light Infrastructure-Nuclear Physics Facility, MG-G Bucharest Magurele, Romania*
- M. Bostan - *Istanbul University, Vezneciler/Fatih, 34134, Istanbul, Turkey*
- L. Atanasova, P. Detistov - *Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, BG-1784, Sofia, Bulgaria*
- M. Danchev, K. Gladnishki - *Faculty of Physics, University of Sofia, Bulgaria*
- I. Matea, I. Stefan, D.Verney - *IPN, Orsay, France*
- D. Radeck - *IKP, University of Cologne, D-50937 Cologne, Germany*
- D.T. Yordanov - *ISOLDE, CERN, Switzerland*

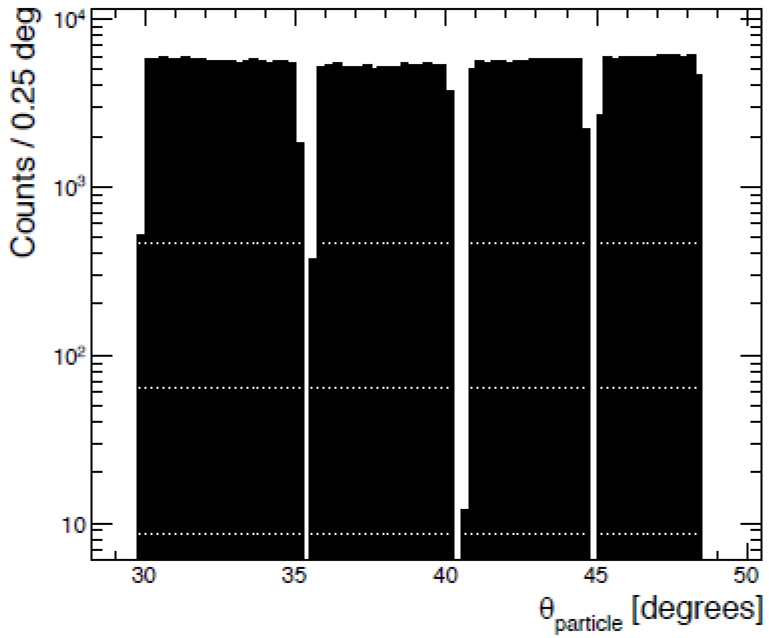
ALTO TDRIV in ^{56}Fe

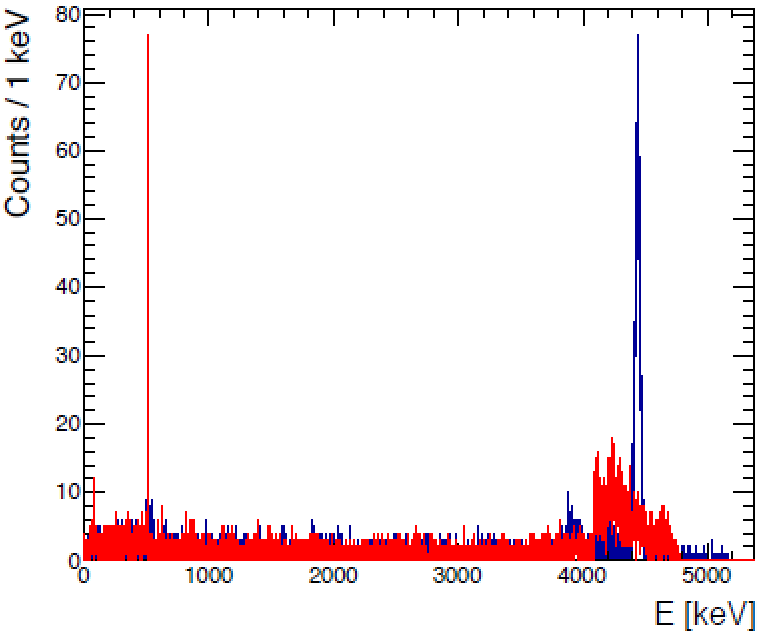
- A.E. Stuchbery – *Department of Physics, RSPE, Australian National University, Canberra ACT 0200, Australia*
- G.Georgiev, A. Goasduff, J. Ljungvall, T. Konstantinopoulos - *CSNSM, CNRS/IN2P3; Université Paris-Sud 11, UMR8609, F-91405 ORSAY-Campus*
- I. Matea, A. Gottardo, D. T. Yordanov- *IPN, Orsay, France*
- K. Gladnishki - *Faculty of Physics, University of Sofia, Bulgaria*
- N. Warr - Institut für Kernphysik, Universitiat zu Köln, D-50937 Köln, Germany

THANK YOU!

Particle detector : Monte-Carlo simulations

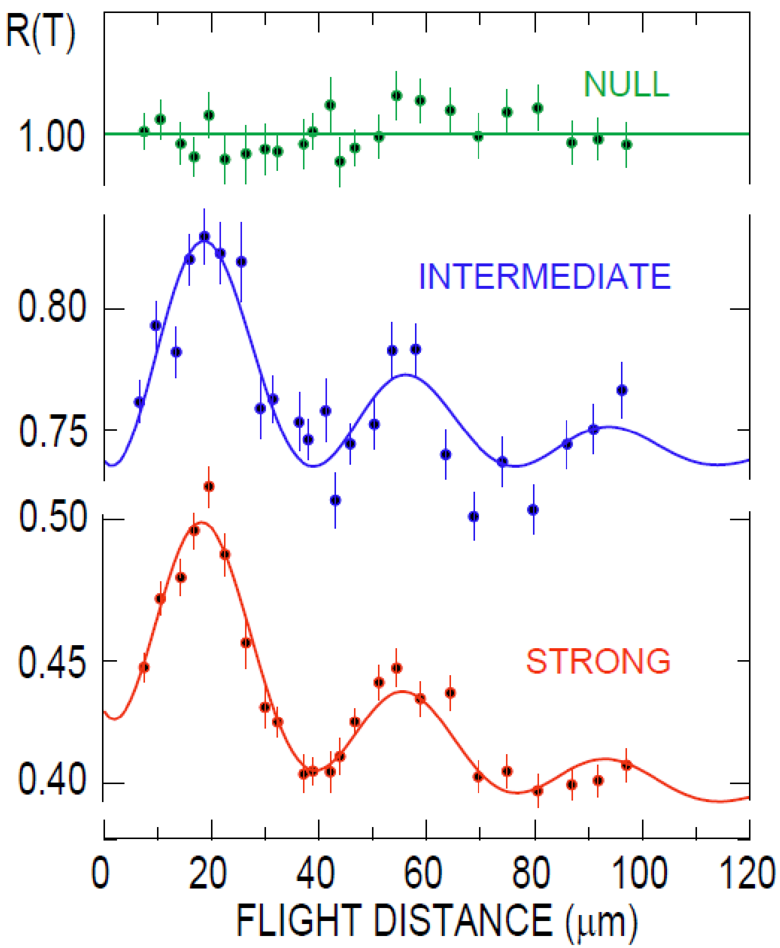
- ^{12}C Coulomb Excitation reaction on ^{208}Pb target 5 mg/cm^2





- FWHM of 44 keV is achievable for the $2^+ \rightarrow 0^+$ transition of ^{12}C (4.4 MeV)

Results



45% H-like, 43 % bare ions or He-like,
12 % L-shell contribution
B_{1s} = 29.09 kTesla with GRASP2K

A.Kusoglu et al. PRL, 114, 062501, 2015

Resulting *g*-factor with statistical error

Ratio of particle-γ combination	Label	*Resulting g- factor*
n=14	strong	0.538(13)
n=17	intermediate	0.539(24)
n=18	weak	0.54(3)
Total weighted average:		**0.538(11)**

Source of systematic error	Value	*Resulting g* factor
Target to particle distance	61.0(1.5) mm	±0.0045
lifetime	1.97(5) ps	±0.0040
υ/c	0.0915(5)	±0.0035
Distribution of hyperfine fields		±0.0010
Total weighted average:		**±0.0070**

$|g(2^+)|$ = 0.538(13)

Total uncertainty < 3%

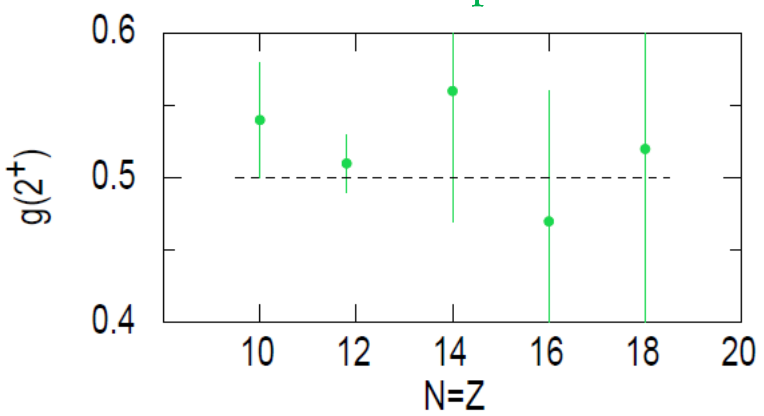
TDRIV using H-like ^{24}Mg ions @ ALTO, Orsay

$$\mu = gI = g_{\ell_o}\langle \ell_0 \rangle + g_{s_o}\langle s_0 \rangle$$

$$I = \langle \ell_0 \rangle + \langle s_0 \rangle \qquad \langle s_0 \rangle = 0$$

$$g_{\ell_p} = 1 \quad g_{\ell_n} = 0 \qquad g_{\ell_o} = \frac{g_{\ell_p} + g_{\ell_n}}{2} = 0.5$$

• Previous exp. results



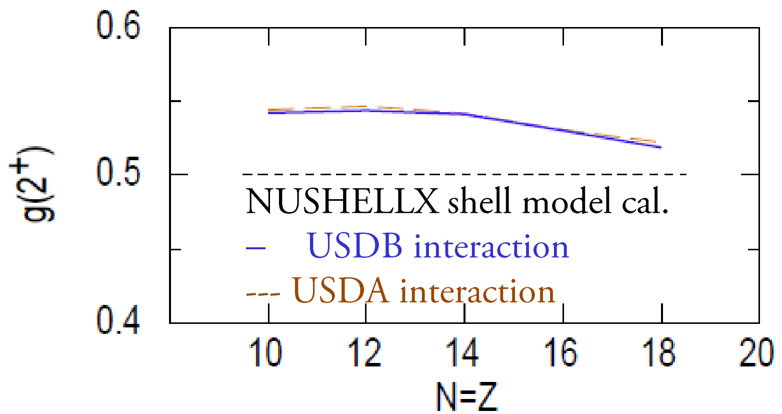
Experimentally little departure from g = 0.5 for the g factors of the first-excited states of even-even nuclei with N = Z.

Brown B. A. JPG 8(5), 679, 1982.

Recent shell-model calculations predict departures from g = 0.5 by up to 10% for the first-excited 2^+ states in the N = Z *sd*-shell nuclei from ^{20}Ne to ^{36}Ar.

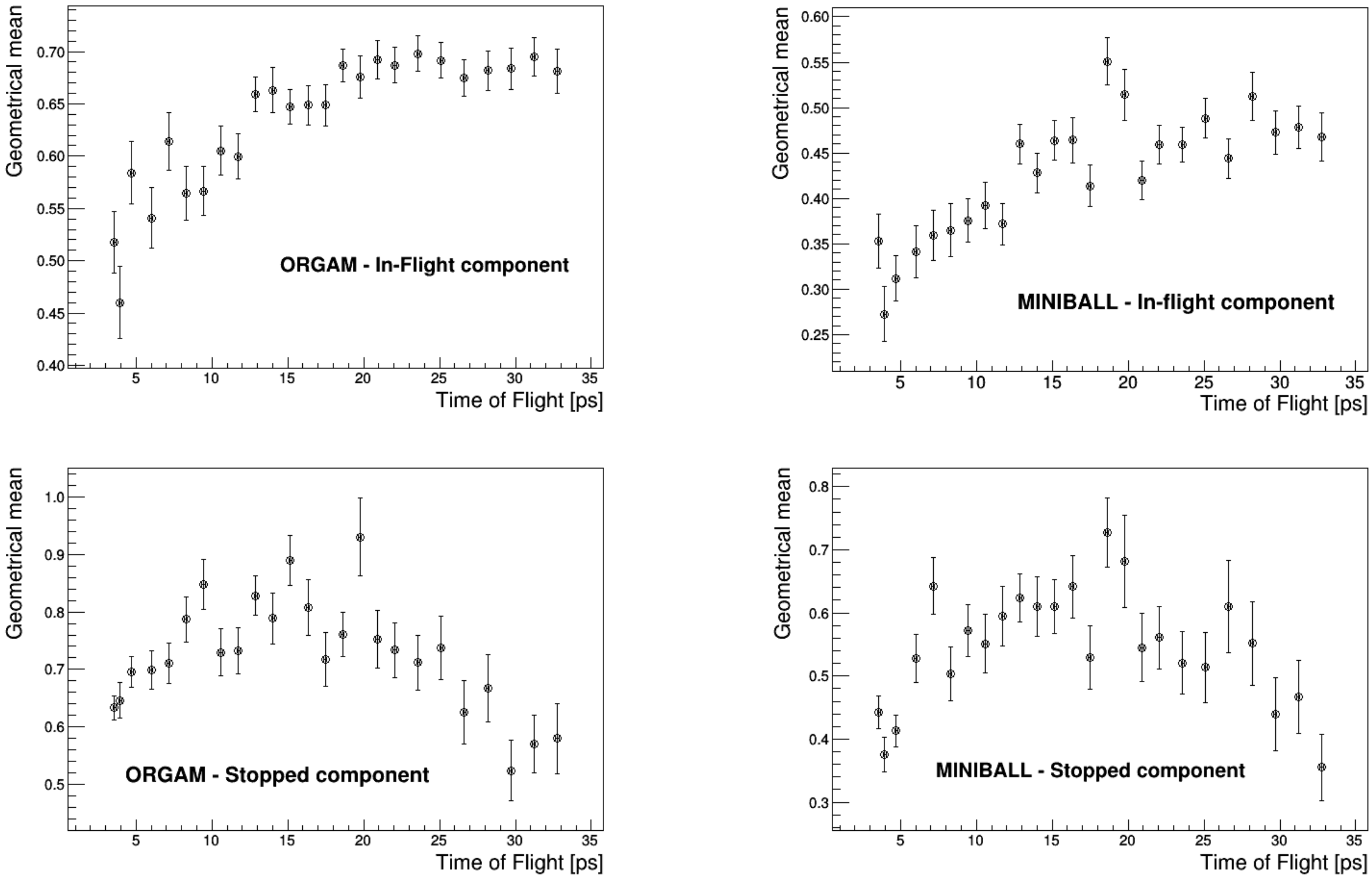
Richter W.A., PRC, 78, 064302, 2008

These departures:
- configuration mixing
- isospin mixing
- meson exchange



Preliminary results

❑ Similar behavior for ORGAM and MINIBALL detectors



Analysis by A. Goasduff