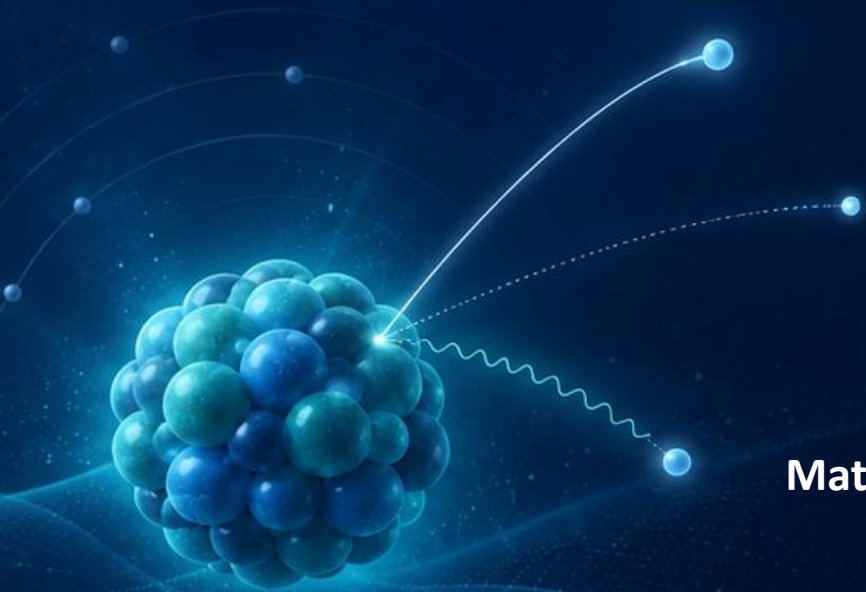


GAIAS: Precision Measurements of Forbidden Non-Unique Beta Spectra for the Investigation of the Axial-Vector Coupling Constant



GAIAS

GAxial Analysis with Scintillators

gaias.web.roma2.infn.it

Mattia Atzori Corona *on behalf of the GAIAS Collaboration*
INFN Roma Tor Vergata

ESNT Workshop, 21-25/09/2026, CEA



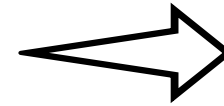
Seminar Outline

1

The g_A quenching problem

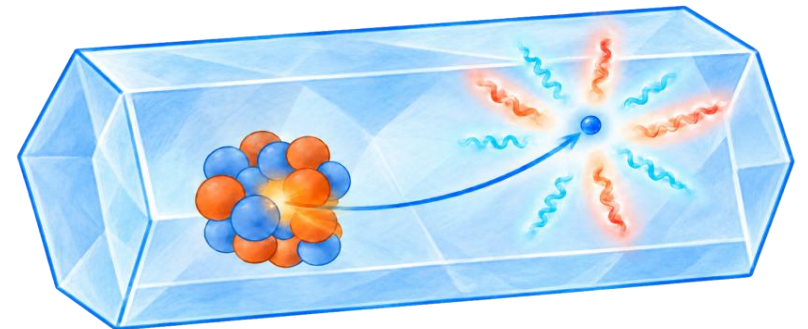
2

Phenomenology of forbidden non-unique β decays for g_A measurements



3

The GAIAS Experiment



Nuclear Beta Decays

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

At nuclear energies, $q^2 \ll m_W^2$, **β decay** is described by the effective **Fermi interaction**

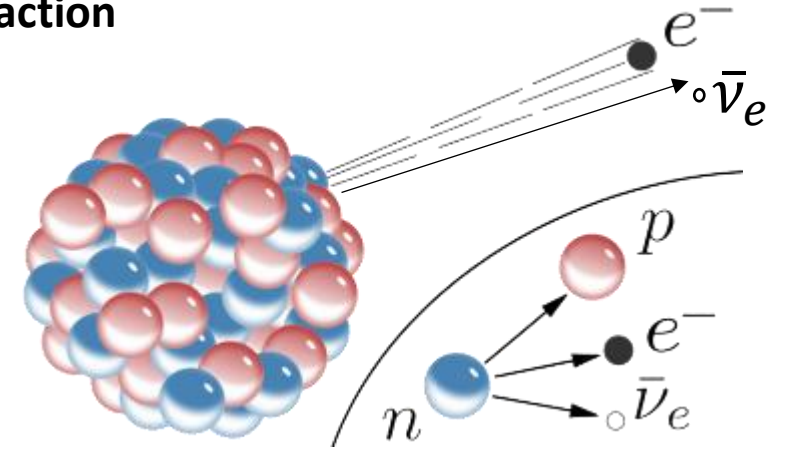
$$H_{\beta,\text{eff}} = \frac{G_F V_{ud}}{\sqrt{2}} J_\mu^{\text{lep}} J_\mu^{\text{had}} + h.c.$$

The currents encode the $V - A$ **structure** of the interaction:

Leptonic current $J_\mu^{\text{lep}} = \bar{e} \gamma_\mu (1 - \gamma^5) \nu_e$

Single-nucleon hadronic current $J_\mu^{\text{had}} = \bar{p} \gamma_\mu (g_V - g_A \gamma^5) n$

Vector and **axial-vector** coupling constants



➤ **Conserved Vector Current (CVC)** fixes $g_V(0) \simeq 1$, while the axial current is only **partially conserved** (PCAC).

➤ The free-neutron β decay $n \rightarrow p + e^- + \bar{\nu}_e$ measures the ratio $\lambda \doteq \frac{g_A}{g_V} \Rightarrow |g_A^{\text{free}}| \simeq 1.2753(13)$ [PDG 2026](#)

What is the effective value of g_A inside nuclei?

From g_A^{free} to g_A^{eff} : The Quenching Problem

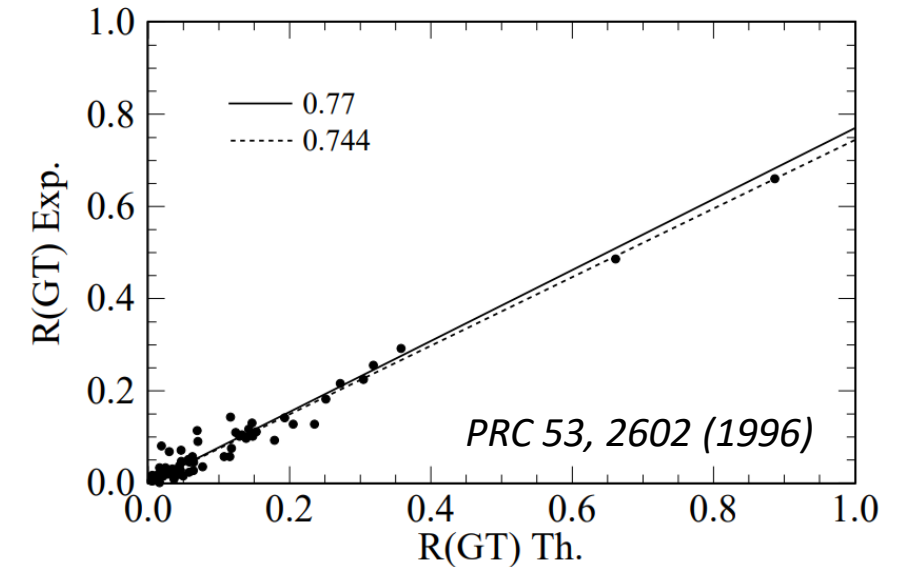
- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

- The axial coupling constant in nuclear β -decays can be affected by e.g. **many-body correlations, two-body weak currents** and **nuclear medium effects** which might modify the axial strength.
- These effects are commonly parametrized through an effective axial-vector coupling (while $g_V = 1$):

$$g_A^{eff} = q g_A^{free}$$

where $q < 1$ corresponds to **quenching** and $q > 1$ to **enhancement**.

➡ The **effective value** of g_A can depend on the nucleus, transition, observable and nuclear model. Understanding this apparent modification remains an open challenge.



Historical evidence for the apparent quenching of g_A : experimental Gamow–Teller matrix elements are systematically smaller than shell-model predictions. The fit (dashed line) suggests $g_A^{eff} = 0.74 g_A$

Ab initio calculations including **many-body correlations** and **two-body weak currents** agree with Gamow–Teller data from light- and medium-mass nuclei up to ^{100}Sn . (Nature Physics 15, 428 (2019))

Implications for Fundamental Physics

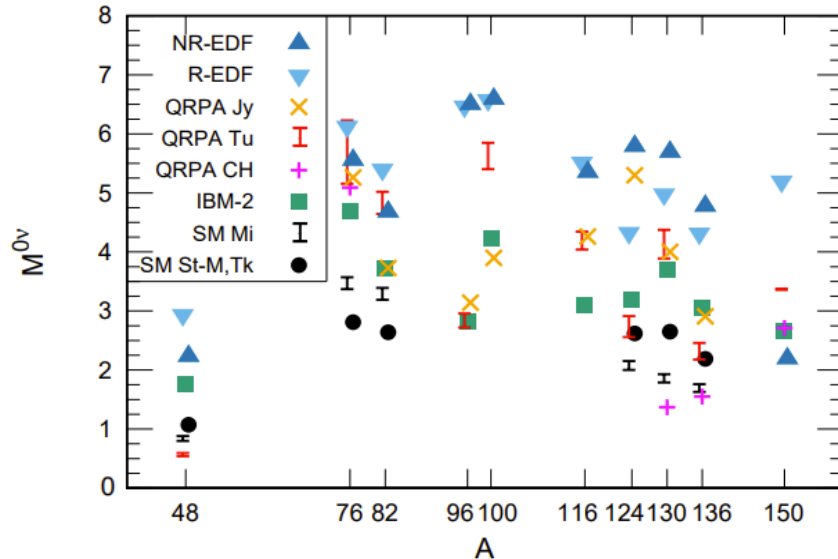
- The quenching of g_A
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The observation of $0\nu\beta\beta$ decay would prove lepton number violation and establish the Majorana nature of neutrinos. The decay rate of $0\nu\beta\beta$ is given by

$$\frac{\Gamma^{0\nu}}{\ln(2)} = \frac{N_A}{M(^A X)} G^{0\nu} \left| M^{0\nu} (g_A^{eff})^2 \right|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

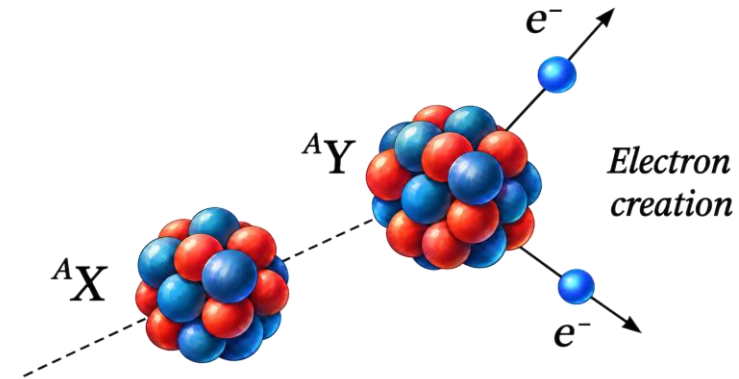
Phase space factor $\rightarrow G^{0\nu}$

$\updownarrow$ $M^{0\nu}$



Theoretical spread on the nuclear matrix element $M^{0\nu}$

J. Engel, J. Menéndez, Rept.Prog.Phys. 80 (2017) 4, 046301



$$[T_{1/2}^{0\nu}]^{-1} \propto (g_A^{eff})^4$$

The strong dependence on g_A^{eff} represents a major source of theoretical uncertainty. A reliable extraction of $m_{\beta\beta}$ therefore requires better control of both g_A^{eff} and the nuclear matrix elements.

Implications for Fundamental Physics

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

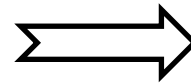
Nuclear Process	Momentum Transfer	g_A^{eff} dependence
$0\nu\beta\beta$	~ 100 MeV	$(g_A^{eff})^4$
$2\nu\beta\beta$	few MeV	$(g_A^{eff})^4$
β decay transition (GT)	few MeV	$(g_A^{eff})^2$
Forbidden non-unique β decay	few MeV	g_A^{eff} and $(g_A^{eff})^2$
Neutrino interaction with matter	$\sim 10 - 100$ MeV	g_A^{eff} or $(g_A^{eff})^2$

The finite momentum transfer plays a crucial role in the interaction:

$$g_V(q^2) = \frac{g_V}{(1 + q^2/M_V^2)^2}$$

$$g_A(q^2) = \frac{g_A}{(1 + q^2/M_A^2)^2}$$

$$M_V \simeq 840 \text{ MeV}, M_A \simeq 1 \text{ GeV}$$

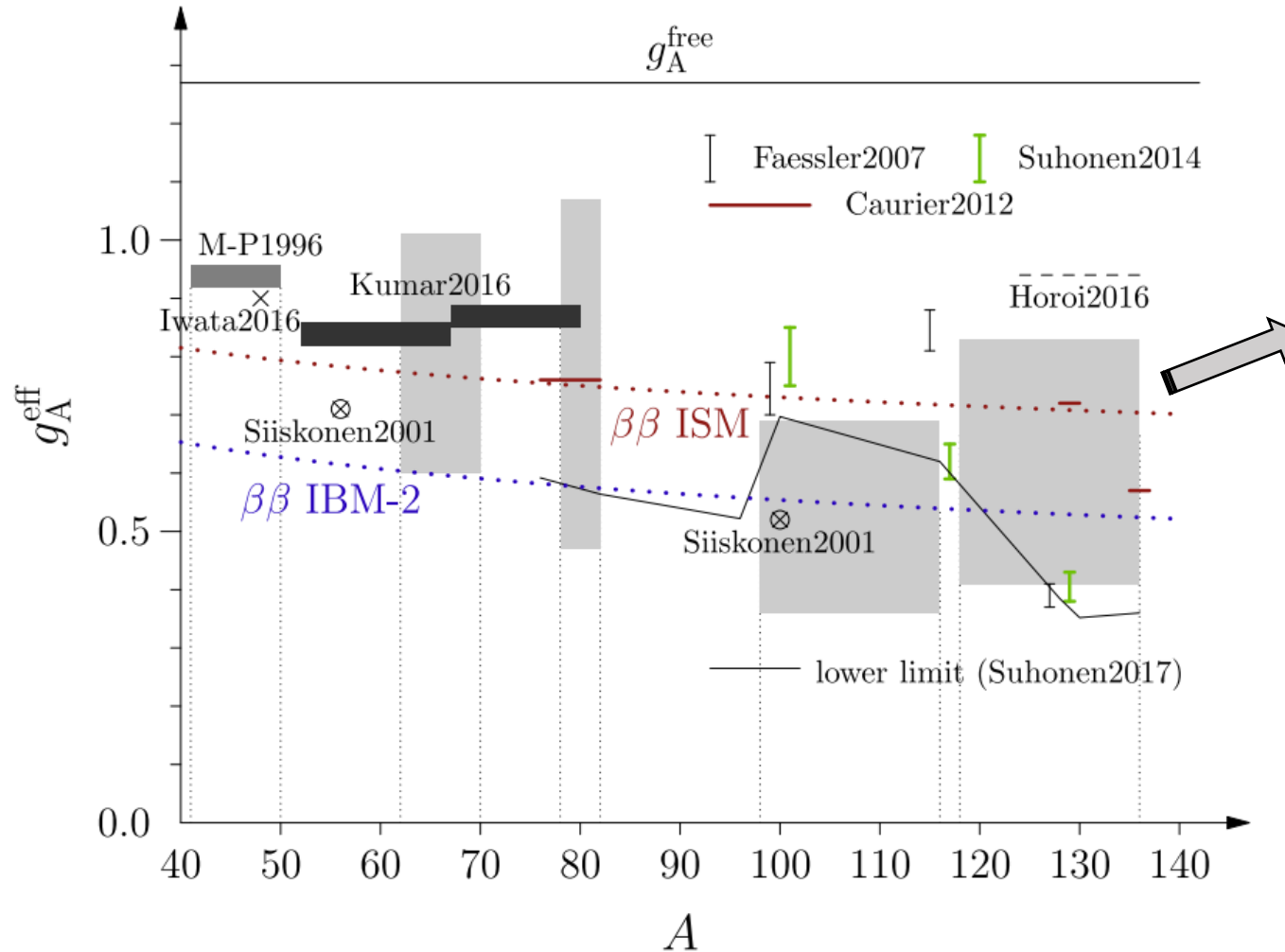


Different weak processes probe different momentum transfers and nuclear multipoles. Therefore, g_A^{eff} values inferred from **low-energy FNU β decay** cannot be **directly** transferred to $0\nu\beta\beta$ calculations.

H. Ejiri, J. Suhonen and K. Zuber, Physics Reports 797 (2019) 1

Dependence of g_A^{eff} on mass number

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment



- Effective g_A values extracted from theoretical analyses of β and $2\nu\beta\beta$ decays across $A = 41-136$, using different nuclear models.
- The inferred quenching factor generally decreases with increasing mass number A

What can **forbidden non-unique β decays** reveal about g_A quenching?

H. Ejiri, J. Suhonen and K. Zuber, Physics Reports 797 (2019) 1

Classification of β Decays

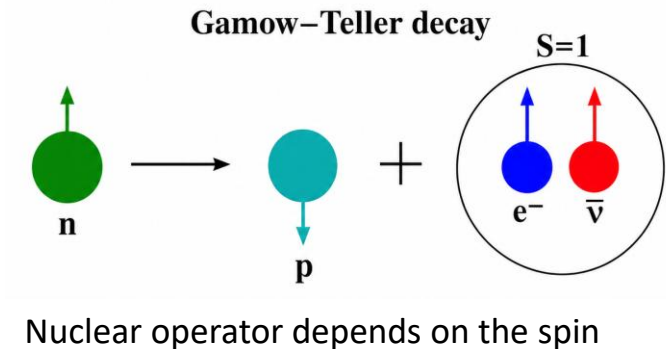
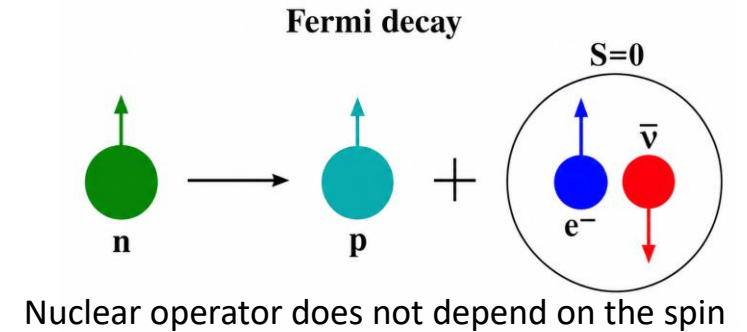
- The quenching of g_A
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Angular momentum in the β decay: $\vec{J}_i = \vec{J}_f + \vec{L} + \vec{S}$; with $\vec{L} = \vec{l}_e + \vec{l}_\nu$ and $\vec{S} = \vec{s}_e + \vec{s}_\nu$

- | | | | |
|------------------------------|-----------------|-------------------------------------|-----------------|
| • Allowed decays if | $ \vec{L} = 0$ | • Fermi decays (F) if | $ \vec{S} = 0$ |
| • Forbidden decays if | $ \vec{L} > 0$ | • Gamow-Teller decay (GT) if | $ \vec{S} = 1$ |

Parity change: $\Delta\pi = (-1)^L$

- **Allowed F:** $|\vec{L}| = 0; |\vec{S}| = 0;$ $J_i = J_f;$
 $\Delta J^{\Delta\pi} = 0^+$
- **Allowed GT:** $|\vec{L}| = 0; |\vec{S}| = 1;$ $J_i = J_f; J_i = J_f \pm 1;$
 $\Delta J^{\Delta\pi} = 0^+, 1^+$
(not the case $0^+ \rightarrow 0^+$)



Forbidden β Decays Classification

- The quenching of g_A

- Forbidden non-unique β decays

- The GAIAS Experiment

Forbidden unique (FU)

- For FU beta decay $\Rightarrow \Delta J = L + 1$
- The transition is governed by a **single** nuclear matrix element (NME)
- At leading order, the spectrum is proportional to $(g_A^{eff})^2$

$$\frac{dR}{dE_e} \sim \mathbf{g_A^2} f(E_e)$$
$$T_{1/2} \propto \mathbf{g_A^{-2}}$$

- Normalized spectral shape independent of g_A at leading order

Forbidden non-unique (FNU)

- For FNU beta decay $\Rightarrow \Delta J = L$. **FNU also allow $\Delta J = 0$.**
- Several NMEs contribute and **interfere**
- g_A^{eff} modifies the spectral shape of the energy distribution

$$\frac{dR}{dE_e} \sim g_V^2 f_V(E_e) + 2g_V \mathbf{g_A} f_{VA}(E_e) + \mathbf{g_A^2} f_A(E_e)$$

- **FNU** can show strong dependence on the details of nuclear structure, enhancing the sensitivity to the axial coupling constant.

Spectrum Shape Method

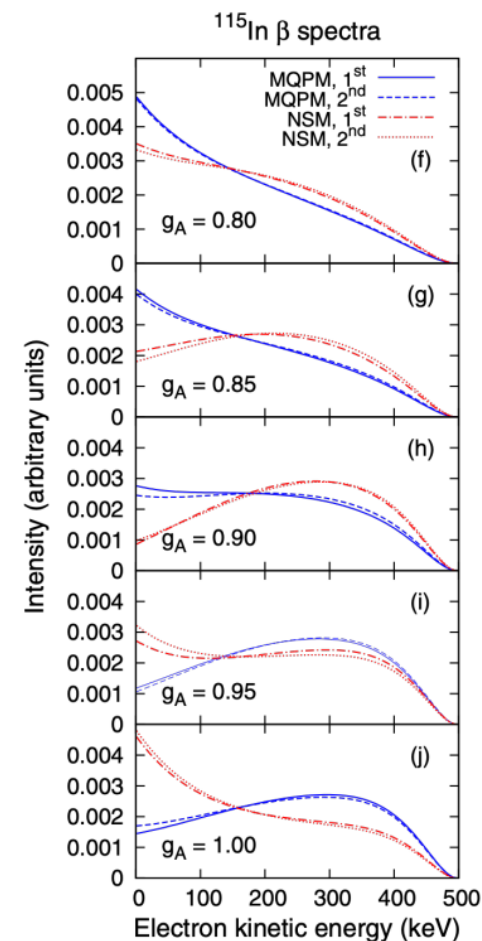
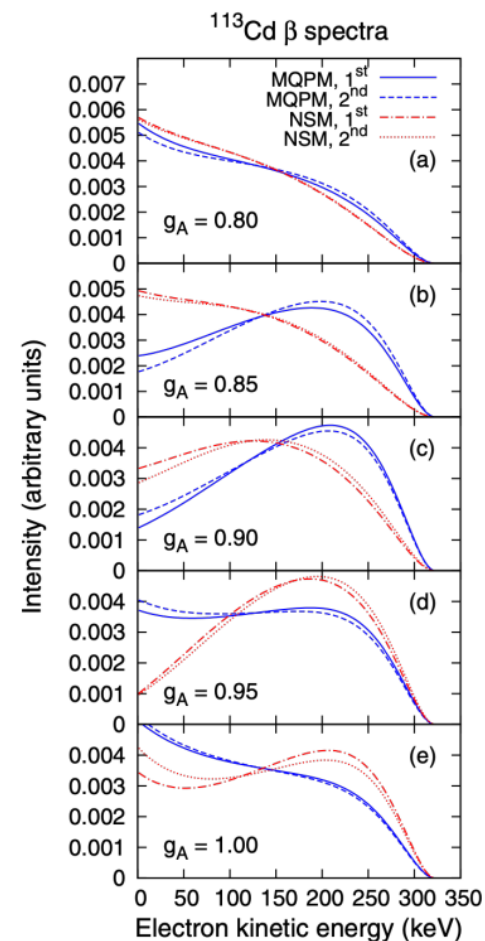
- The quenching of g_A
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Spectrum Shape Method (SSM)



See J. Suhonen's talk!

- g_A^{eff} is extracted by comparing the measured β -spectrum shape with theoretical predictions.
- Theoretical spectra are calculated for different g_A^{eff} values and nuclear models.
- The extracted g_A^{eff} generally shows a **mild** nuclear-model dependence.
- Measurements of **different forbidden transitions** are therefore essential to validate nuclear models at **low momentum-transfer**.



M. Haaranen, P. C. Srivastava and J. Suhonen PRC 93 (2016) 034308

FNU measurements to extract g_A^{eff}

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

^{113m}Cd

$^{113m}\text{Cd}(11/2^-) \rightarrow ^{113}\text{In}(9/2^+)$
1st FNU

Belli et al. Phys. Rev. C 112 (2025) 045503

^{113}Cd

$^{113}\text{Cd}(1/2^+) \rightarrow ^{113}\text{In}(9/2^+)$ **4th FNU**

- *Belli et. al., Phys. Rev. C 76, (2007) 064603; Haaranen et al. Phys. Rev. C 93 (2016) 034308*
- *Kostensalo et al. Phys. Lett. B 822 (2021) 136652*
- *Bandac et al. Eur. Phys. J. C (2024) 84:1158*

^{115}In

$^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(1/2^+)$ **4th FNU**

- *Pagnanini et al. PRL 133 (2024) 122501*
- *Leder et al. PRL 129 (2022) 232502*

^{87}Rb

$^{87}\text{Rb}(3/2^-) \rightarrow ^{87}\text{Sr}(9/2^+)$ **3rd FNU**

Belli et al. EPJA 62 (2026) 16



See also X.
Mougeot's talk!

^{99}Tc

$^{99}\text{Tc}(9/2^+) \rightarrow ^{99}\text{Ru}(5/2^+)$ **2nd FNU**

- *M. Paulsen et al., Phys. Rev. C 110, 055503(2024)*
- *Song et al, arXiv:2506.17544*
- *Nava et al, arxiv 2609.05640*



See also M.
Rodrigues' talk!

Significant progress has been made, but **many complementary FNU transitions** remain **unexplored**.

The GAIAS Experiment

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

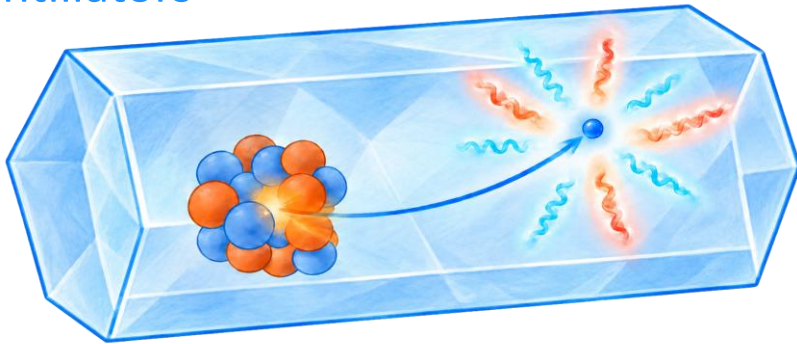
The **GAIAS Experiment** (gaias.web.roma2.infn.it) aims to investigate g_A^{eff} through precision measurements of selected **forbidden non-unique β decays** using **crystal scintillators**.



International Collaboration

- *~ 20 members from 4 Institutions*
- *Started in 2026*
- *Operating at LNGS*

Crystal Scintillators



Experimental Approach

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

Main Features

- ✓ **“Source = detector”**: high detection efficiency and near-complete β -energy containment.
- ✓ **High light yield**, good energy resolution
- ✓ **Stable detector** response
- ✓ **High radiopurity**: low background
- ✓ **Flexible composition** for incorporating selected β isotopes

Methodology

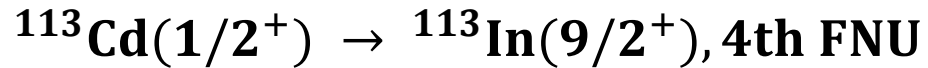
- **Isotope Selection**: high β branching ratio, suitable Q_β , dependence of the beta-spectrum shape on g_A
- **Engineer the crystal**: natural abundance or controlled isotope incorporation
- **Measure the spectrum**: low background and stable long-term operation. Reduce statistical uncertainties
- **Calibration** to reduce systematic uncertainties
- **Extract g_A^{eff}** : compare data with nuclear-model predictions
- **Monte Carlo** full-setup simulation to characterize backgrounds

GAIAS offers a distinctive **source=detector approach** to measure **FNU transitions**. The **low threshold** enhances the sensitivity to g_A^{eff}

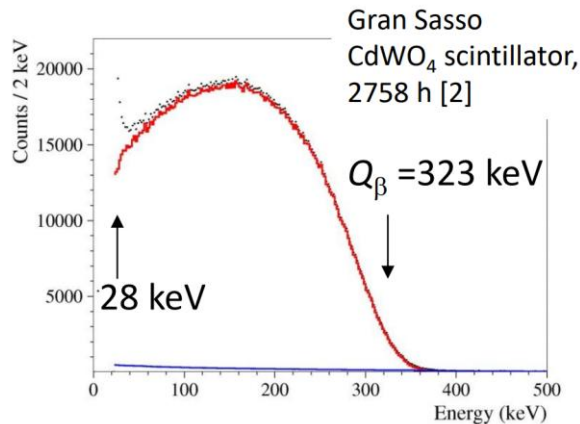
Experimental Proof of Concept: ^{113}Cd

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

GAIAS builds on **previous low-background measurements** of different FNU transitions.



- **Low-background CdWO_4** crystal scintillator ($\varnothing$ 40 mm x 43 mm, mass of 434 g)
 $\rightarrow$ ^{113}Cd naturally present with $\delta \approx 12.2\%$
- Stored in the Solotvina underground Laboratory (Ukraine) on a depth of 1000 m w.e. for ~ 10 years
- The detector was measured in the lowbackground DAMA/R&D set-up at LNGS over 2758 h.
- Activity of ^{113}Cd : 558(4) mBq/kg

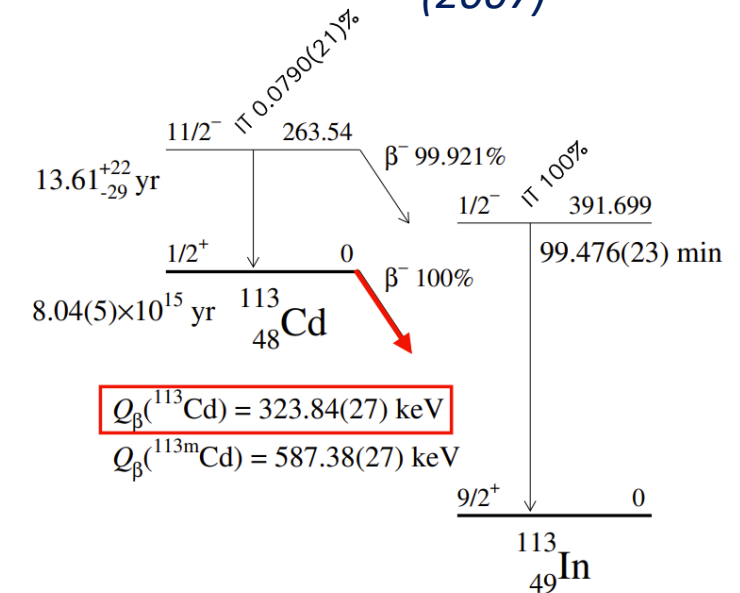


^{113}Cd - 4th FNU

CdWO_4 , threshold $\sim 28 \text{ keV}$
 $T_{1/2} = (8.04 \pm 0.05) \times 10^{15} \text{ yr}$



P. Belli et al., PRC 76, 064603 (2007)

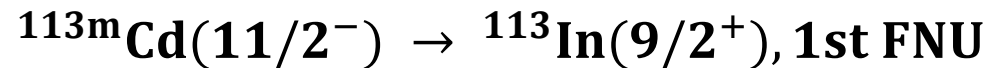


Extraction of $g_A^{eff} \simeq 0.92$
M. Haaranen, J. Kotila, and J. Suhonen,
Phys.Rev.C 95 (2017) 2, 024327

Experimental Proof of Concept: ^{113m}Cd

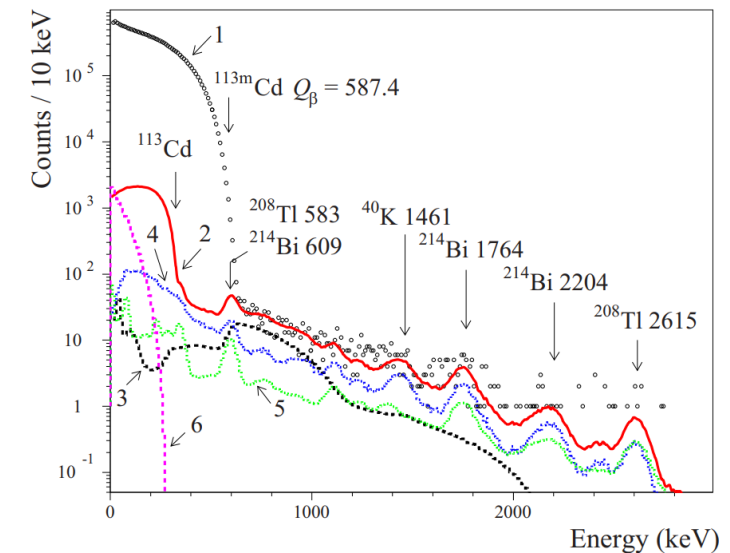
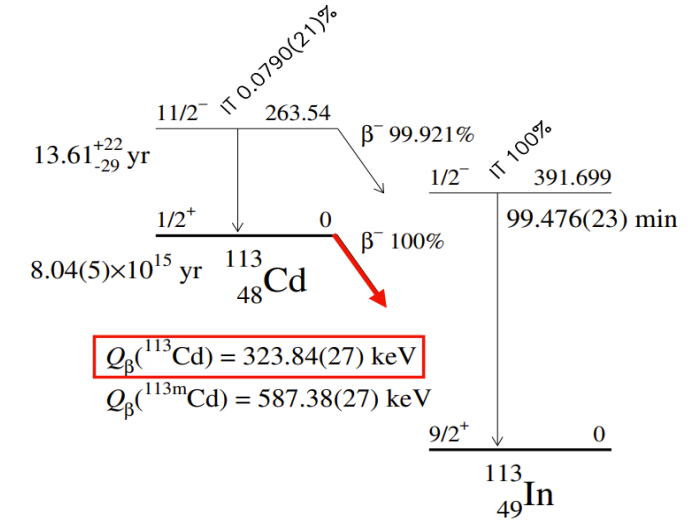
- The quenching of g_A
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GAIAS builds on **previous low-background measurements** of different FNU transitions.



Belli et al. Phys. Rev. C 112 (2025) 045503

- **Technique:** ^{106}Cd — enriched CdWO_4 crystal scintillator operated at LNGS; data collected in 2009, 2015 and 2023
- **Measured half-life:** $T_{1/2} = 13.61^{+0.22}_{-0.29}$ years (threshold ~ 28 keV)
- **Spectrum shape:** first measurement of the first-forbidden non-unique β spectrum of ^{113m}Cd ; the comparison favours $g_A^{eff} \approx 0.8$ or lower.



Experimental Proof of Concept: ^{87}Rb

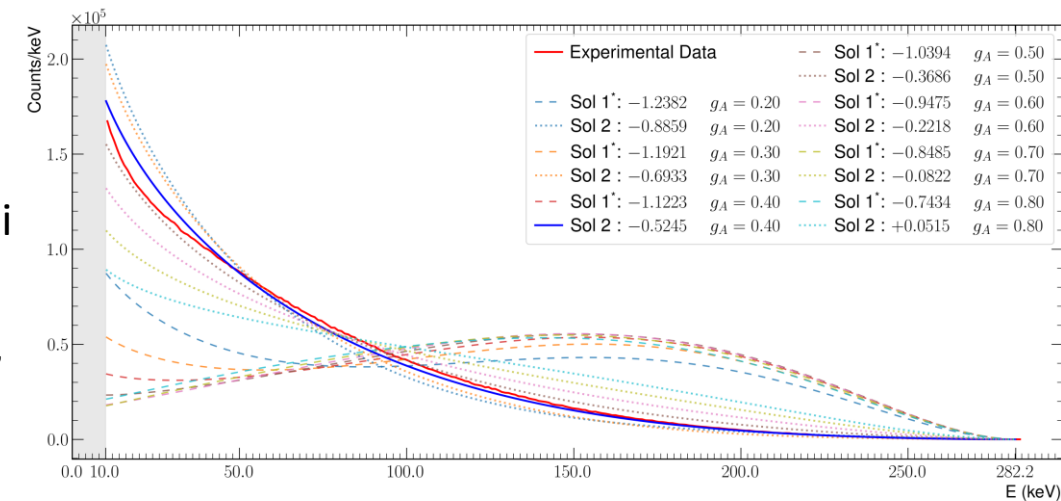
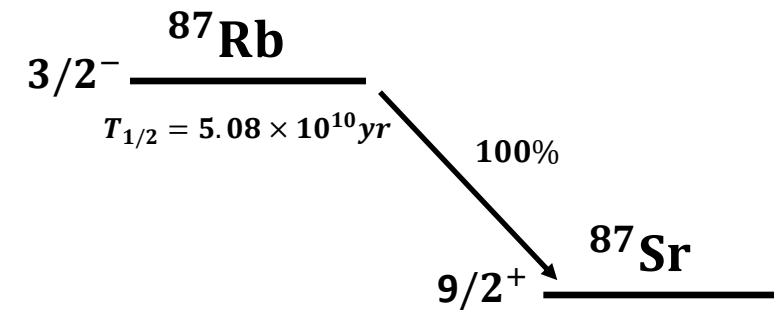
- The quenching of g_A
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- The GAIAS Experiment

GAIAS builds on **previous low-background measurements** of different FNU transitions.



Belli et al., EPJ A 62 (2026) 16

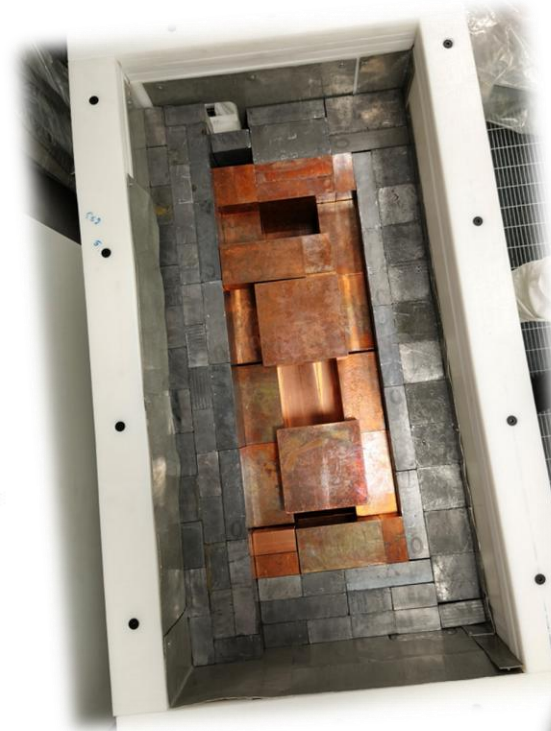
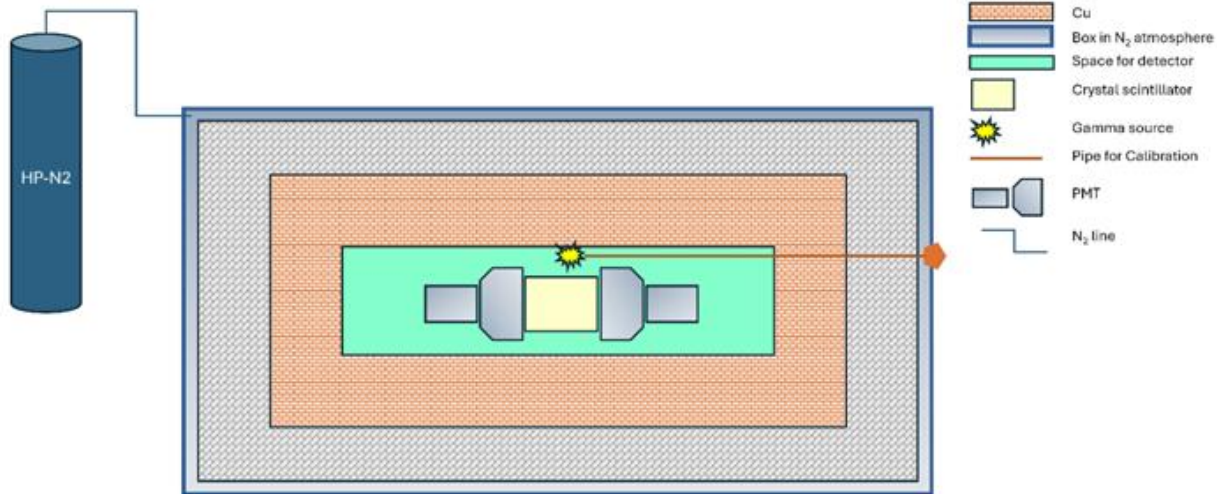
- **Technique:** 0.465-g Rb_2ZrCl_6 crystal scintillator operated at LNGS in a source = detector configuration; 10-keV threshold.
- **Model:** Enhanced Spectrum-Shape Method using the shell-model interactions jj44b, jun45 and glbepn, together with MQPM; the sNME is fitted to reproduce the measured half-life.
- **Spectrum shape:** $g_A^{eff} = 0.4 - 0.6$, depending on the nuclear model, indicating strong axial-coupling quenching.
- **Measured Half-life:** $T_{1/2} = 5.08 \pm 0.13 \times 10^{10} \text{ yr}$



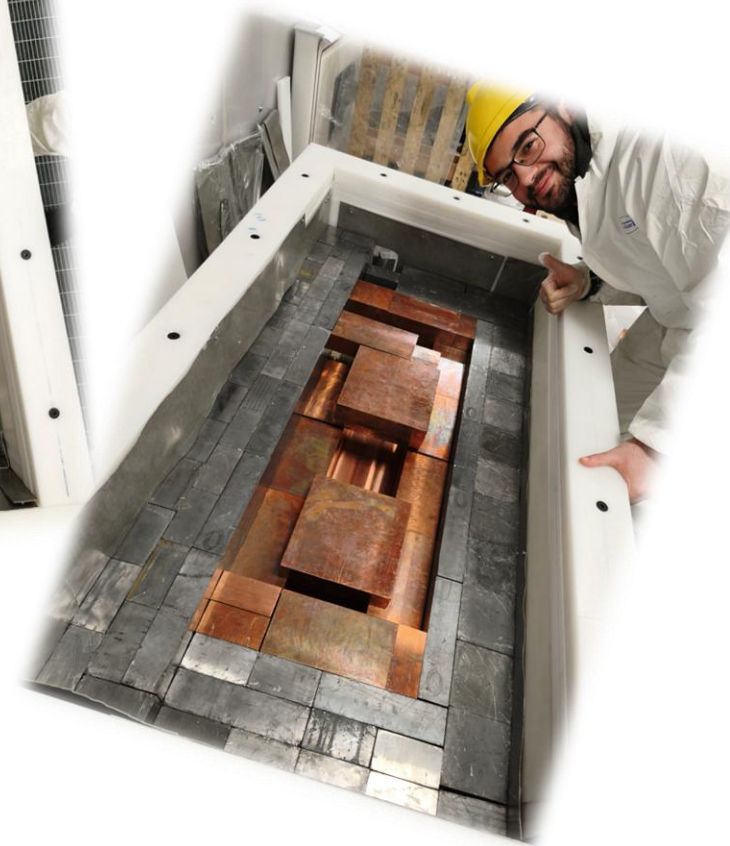
GAIAS Experimental Apparatus

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

- **Crystal housed in a PTFE container** filled with high-purity silicone oil
- **Readout performed by two PMTs**
- **Passive shielding:** 10 cm of Cu and 15 cm of Pb
- **Sealed low-radioactivity PTFE box**, flushed with high-purity N_2
- **Two calibration pipes**
- **Control of temperature** inside the setup



GAIAS-I

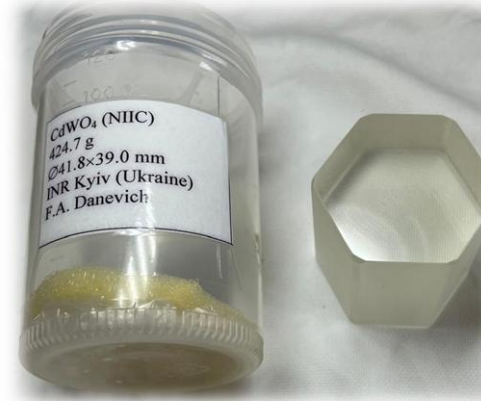


A Closer Look at the GAIAS Detector

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

Fourth-forbidden non-unique β decay of ^{113}Cd

- Hexagonal CdWO_4 crystal scintillator, mass 361.2 g, ^{113}Cd naturally present with $\delta \approx 12.2\%$ installed in GAIAS-I
- The **hexagonal geometry** and **optically diffused surfaces** improve light collection.
- Data taking started in **July 2026** and is **currently ongoing**.



A higher light collection and energy resolution of hexagonal crystals were demonstrated in

- NIMA 744 (2014) 41–47
- NIMB 336 (2014) 26–30
- Nuclear Physics and Atomic Energy 16 (2015) 329.

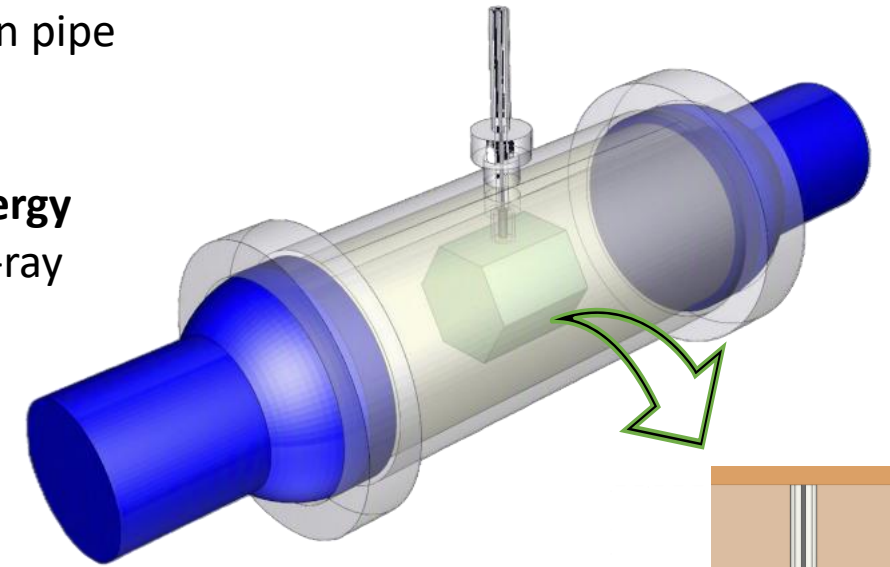
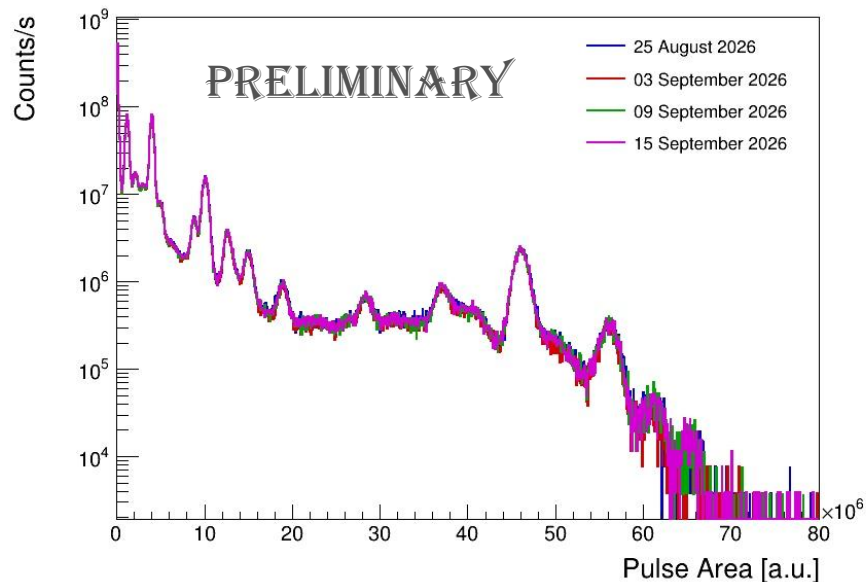


Detector Stability and Calibration

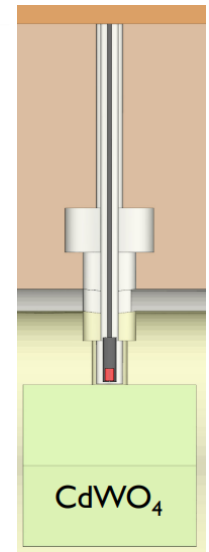
- The quenching of g_A
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- ^{228}Th calibrations are performed $\sim$ weekly through a PTFE insertion pipe to monitor the detector energy scale without opening the setup or interrupting PMT operation ($E > 80$ keV)
- We plan to use additional calibration sources to monitor the **low-energy region**, e.g. ^{57}Co source (~ 14.4 keV line), and ^{241}Am (~ 18 keV L X-ray and 59.5 keV of ^{241}Am)

^{228}Th calibrations show stable detector response throughout the data-taking campaign.



Wire source positioned close to the crystal



Preliminary energy resolutions:

- FWHM/E $\sim 7\%$ at the 662 keV ^{137}Cs γ line.
- FWHM/E $\sim 4\%$ at the 2615 keV ^{208}Tl γ line

The GAIAS Experimental Apparatus

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

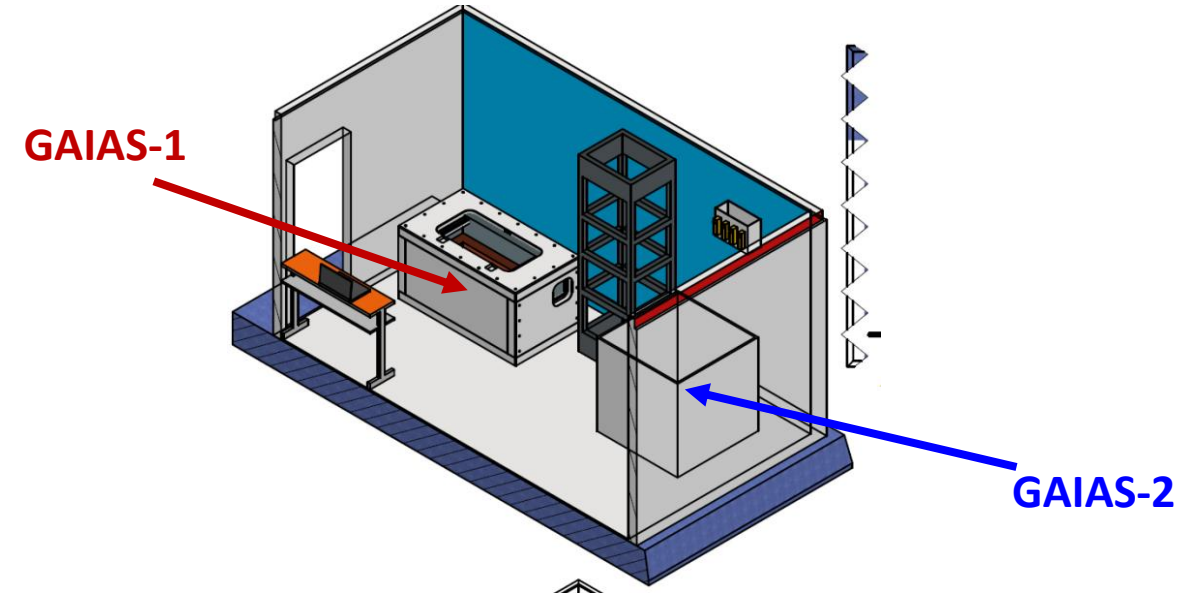
GAIAS-2 Shield

- 2 cm thick polyethylene box flushed with high-purity N_2
- Passive shield (65 cm x 65 cm x 130 cm) composed of:
 - 20 cm of Pb, 15 cm Cu, Cd foil;
 - inner volume for detector displacement : 20 cm x 20 cm x 20 cm
 - 1 calibration pipe

Environmental sensors continuously monitored

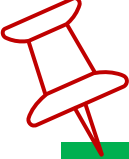
- Temperature (2 sensors)
- Humidity, pressure
- N_2 flow

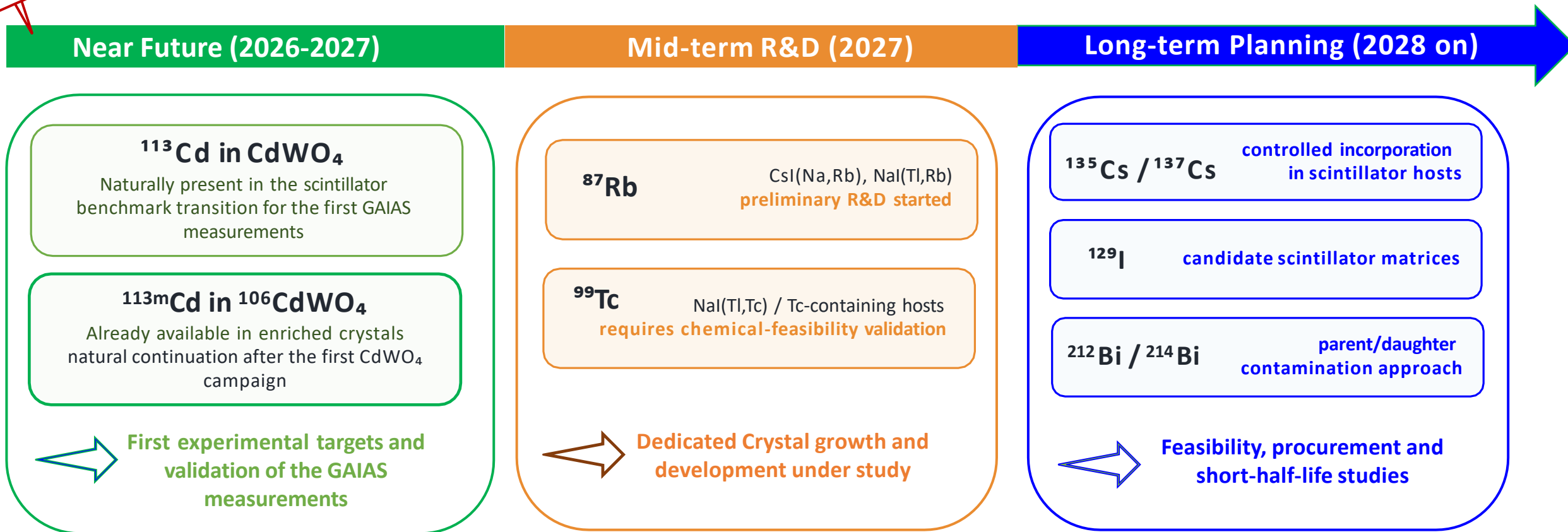
This enables us to ensure stable operating conditions and identify possible sources of systematic variations in the detector response.



GAIAS Scientific Plan

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

 **Beginning of 2026: start of the experiment!**



Different transitions probe g_A^{eff} differently, motivating a systematic multi-isotope program to validate nuclear models, with dedicated experimental apparatus

The GAIAS Collaboration

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

Institution	Name	Position
INFN–Roma Tor Vergata (Italy)	Riccardo Cerulli (PI & spokesperson)	Senior Researcher
	Vincenzo Caracciolo	Associate Professor at Tor Vergata University & INFN associate
	Pierluigi Belli	Director of research
	Alice Leoncini	Post-doc at Tor Vergata University & INFN associate
	Mattia Atzori Corona	Post-doc INFN
	Vittorio Merlo	Former Senior Lecturer
	Andrea Bussolotti	INFN Technician
INFN–Roma (Italy)	Fabio Cappella (PI Roma1)	Senior Researcher
	Antonella Incicchitti	Director of research
	Alessio Giarnetti	Post-doc INFN
	Angelo Mattei	INFN Technician
INR–Kyiv (Ukraine)	Fedor Danevich (PI)	Director of research
	Volodymyr Tretyak	Director of research
	Vladislav Kobychiev	Director of research
	Dmytro Kasperovych	Senior Researcher
	Volodymyr Klavdiienko	Junior Researcher
University of Jyväskylä (Finland)	Jouni Suhonen (PI)	Full Professor
	Jenni Kotila	Senior Researcher
	Aagrah Agnihotri	Post-doc
	Marlom Ramalho	Post-doc



*See J. Suhonen's talk
for more details on
the theory!*

Conclusions and Outlook

- The quenching of g_A
- Forbidden non-unique β decays
- The GAIAS Experiment

- ✓ GAIAS exploits crystal scintillators in a source = detector configuration to investigate g_A^{eff} across different isotopes.
- ✓ **Two low-background** stations, including the DAQ and environmental monitoring systems, have been commissioned at LNGS in 2026.
- ✓ The **first CdWO₄** detector has been taking data since July 2026, showing good performance and **a stable response** across the full energy range.
- ✓ Measurements with CsI(Na,Rb) and R&D on Rb- and Tc-containing crystals, and studies of other candidate isotopes, will extend GAIAS toward a multi-isotope study of complementary forbidden non-unique transitions.

Supported by a collaboration combining experimental and theoretical expertise, the three-year program will provide new data to benchmark nuclear models and constrain g_A^{eff} with implications for fundamental physics.

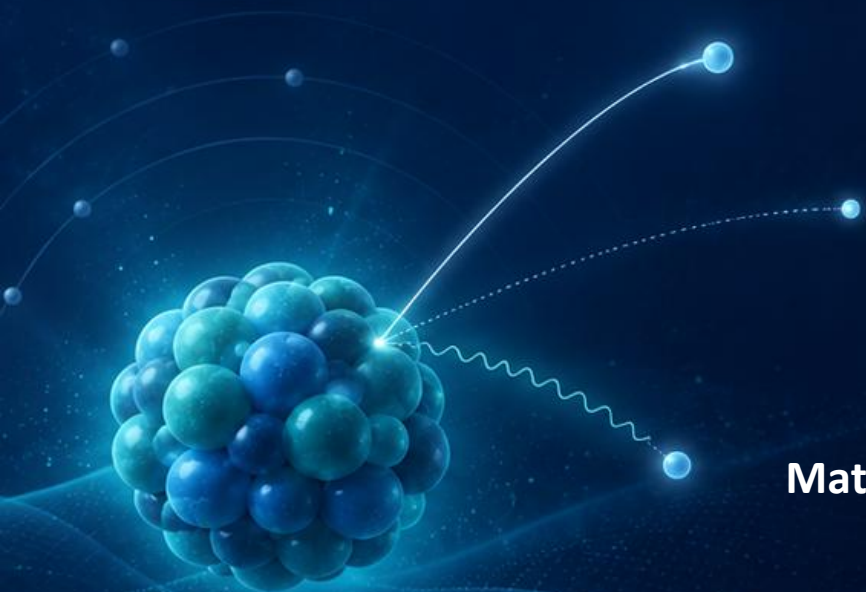
**We will provide data to
validate nuclear models**



**Exciting times for nuclear weak-
interaction and neutrino physics!**
Open to explore even more isotopes!



Thank you for your attention!



GAIAS

GAXial Analysis with Scintillators

gaias.web.roma2.infn.it

Mattia Atzori Corona *on behalf of the GAIAS Collaboration*
INFN Roma Tor Vergata

ESNT Workshop, 21-25/09/2026, CEA



Towards a Multi-Isotope Program

Transition	Forbiddenness	Q_b (keV) d (%)	Half-life	Activity ¹	Possible scintillator
$^{113}\text{Cd} \rightarrow ^{113}\text{In}$	$1/2^+ \rightarrow 9/2^+$ (100%, 4 FNU)	323.84(27) 12.2227(7)	$8.04(5) \times 10^{15}$ yr	1.8 mBq/g of Cd	CdWO_4
$^{113\text{m}}\text{Cd} \rightarrow ^{113}\text{In}$	$11/2^- \rightarrow 9/2^+$ (~100%, 1 FNU)	587.38(27) Synthetic	$13.61^{+0.22}_{-0.29}$ yr	65-130 mBq/g of $^{106}\text{CdWO}_4$	$^{106}\text{CdWO}_4$
$^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$	$3/2^- \rightarrow 9/2^+$ (100%, 3 FNU)	282.275(6) 27.83(2)	$5.08(13) \times 10^{10}$ yr	867 Bq/g of Rb	$\text{CsI}(\text{Na}, \text{Rb})$, $\text{NaI}(\text{Tl}, \text{Rb})$
$^{99}\text{Tc} \rightarrow ^{99}\text{Ru}$	$9/2^+ \rightarrow 5/2^+$ (100%, 2 FNU)	297.5(9) Synthetic	$2.111(12) \times 10^5$ yr	6.33×10^8 Bq/g of ^{99}Tc	$\text{NaI}(\text{Tl}, ^{99}\text{Tc})$, $\text{CsI}(\text{Na}, ^{99}\text{Tc})$
$^{115}\text{In} \rightarrow ^{115}\text{Sn}$	$9/2^+ \rightarrow 1/2^+$ (100%, 4 FNU)	497.489(10) 95.719(52)	$4.41(25) \times 10^{14}$ yr	0.25 Bq/g of In	$\text{CsI}(\text{In})$, LiInSe_2 , InI
$^{212}\text{Bi} \rightarrow ^{212}\text{Po}$	$1^- \rightarrow 0^+$ (55.37%, 1 FNU)	2251.5(17) daughter of ^{212}Pb (^{232}Th chain)	60.55(6) min	5.4×10^{17} Bq/g of ^{212}Bi	$\text{GAGG}:\text{Ce}$, CdWO_4 fast $\beta - \alpha$ sequence
$^{135}\text{Cs} \rightarrow ^{135}\text{Ba}$	$7/2^+ \rightarrow 3/2^+$ (100%, 2 FNU)	268.70(29) Synthetic	$2.3(3) \times 10^6$ yr	4.3×10^7 Bq/g of ^{135}Cs	$\text{CsI}(\text{Tl})$
$^{137}\text{Cs} \rightarrow ^{137}\text{Ba}$	$7/2^+ \rightarrow 3/2^+$ (5.6%, 2 FNU)	1175.63(17) Synthetic	30.04(4) y	3.2×10^{12} Bq/g of ^{137}Cs	$\text{CsI}(\text{Tl})$
$^{129}\text{I} \rightarrow ^{129}\text{Xe}$	$7/2^+ \rightarrow 3/2^+$ (100%, 2 FNU)	189(3) (10^{-13} - 10^{-12})	$1.57(4) \times 10^7$ yr	0.7-7 mBq/g of I	CsI
$^{36}\text{Cl} \rightarrow ^{36}\text{Ar}$	$2^+ \rightarrow 0^+$ (98.1%, 2 FNU)	709.53(4) ($\sim 7 \times 10^{-13}$)	$3.013(15) \times 10^5$ yr	≈ 1 mBq/g of Cl	CeCl_3
$^{214}\text{Bi} \rightarrow ^{214}\text{Po}$	$1^- \rightarrow 0^+$ (19.2%, 1 FNU)	3269(11) daughter of ^{226}Ra (^{238}U chain)	19.71(2) min	1.6×10^{18} Bq/g of ^{214}Bi	CaWO_4 , $\text{NaI}(\text{Tl})$, $\text{CsI}(\text{Tl})$, $\text{SrI}_2(\text{Eu})$, LaCl_3 , ...,
.....					

¹ specific activity for 1 g of the element in the cases of natural radioactive nuclides, and activity partially to be added to in scintillator in the cases of synthetic elements

FNU Sensitive to g_A^{eff}

Transition	$J_i^{\pi_i} (gs)$	$J_f^{\pi_f} (n_f)$	Branching	K	Sensitivity	Nuclear model
$^{50}\text{V} \rightarrow ^{50}\text{Cr}$	6^+	$2^+ (1)$	~ 0	4	Weak	ISM
$^{59}\text{Fe} \rightarrow ^{59}\text{Co}$	$3/2^-$	$7/2^- (gs)$	0.18%	2	Moderate	ISM
$^{60}\text{Fe} \rightarrow ^{60}\text{Co}$	0^+	$2^+ (1)$	100%	2	Moderate	ISM
$^{85}\text{Br} \rightarrow ^{85}\text{Kr}$	$3/2^-$	$9/2^+ (gs)$	~ 0	3	Moderate	MQPM
$^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$	$3/2^-$	$9/2^+ (gs)$	100%	3	Moderate	MQPM, ISM
$^{94}\text{Nb} \rightarrow ^{94}\text{Mo}$	6^+	$4^+ (2)$	100%	2	Strong	NSM
$^{96}\text{Zr} \rightarrow ^{96}\text{Nb}$	6^+	$5^+ (1)$	10%	5	Strong	ISM
$^{97}\text{Zr} \rightarrow ^{97}\text{Nb}$	$1/2^+$	$9/2^+ (gs)$	~ 0	4	Strong	MQPM
$^{98}\text{Tc} \rightarrow ^{98}\text{Ru}$	6^+	$4^+ (3)$	100%	2	Strong	ISM
$^{99}\text{Tc} \rightarrow ^{99}\text{Ru}$	$9/2^+$	$5/2^+ (gs)$	100%	2	Strong	MQPM, ISM
$^{101}\text{Mo} \rightarrow ^{101}\text{Tc}$	$1/2^+$	$9/2^+ (gs)$	~ 0	4	Strong	MQPM
$^{113}\text{Cd} \rightarrow ^{113}\text{In}$	$1/2^+$	$9/2^+ (gs)$	100%	4	Strong	MQPM, ISM, IBFM-2
$^{113\text{m}}\text{Cd} \rightarrow ^{113}\text{In}$	$11/2^-$	$9/2^+ (gs)$	100%	1	Strong	ISM, NSM

FNU Sensitive to g_A^{eff}

Transition	$J_i^{\pi_i}(\text{gs})$	$J_f^{\pi_f}(n_f)$	Branching	K	Sensitivity	Nuclear model
$^{115}\text{Cd} \rightarrow ^{115}\text{In}$	$1/2^+$	$9/2^+ (\text{gs})$	~ 0	4	Strong	MQPM
$^{115}\text{In} \rightarrow ^{115}\text{Sn}$	$9/2^+$	$1/2^+ (\text{gs})$	100%	4	Strong	MQPM, ISM, IBFM-2
$^{117}\text{Cd} \rightarrow ^{117}\text{In}$	$1/2^+$	$9/2^+ (\text{gs})$	~ 0	4	Strong	MQPM
$^{119}\text{In} \rightarrow ^{119}\text{Sn}$	$9/2^+$	$1/2^+ (\text{gs})$	~ 0	4	Strong	MQPM
$^{123}\text{Sn} \rightarrow ^{123}\text{Sb}$	$11/2^-$	$1/2^+ (4)$	~ 0	5	Weak	MQPM
$^{136}\text{Te} \rightarrow ^{136}\text{I}$	0^+	$(1^-) (\text{gs})$	8.7%	1	Strong	ISM
$^{137}\text{Xe} \rightarrow ^{137}\text{Cs}$	$7/2^-$	$5/2^+ (1)$	30%	1	Strong	ISM
$^{138}\text{Cs} \rightarrow ^{138}\text{Ba}$	3^-	$3^+ (1)$	44%	1	Strong	ISM
$^{141}\text{Ce} \rightarrow ^{141}\text{Pr}$	$7/2^-$	$5/2^+ (\text{gs})$	31%	1	Weak	MQPM
$^{210}\text{Bi} \rightarrow ^{210}\text{Po}$	1^-	$0^+ (\text{gs})$	100%	1	Strong	ISM

Classification of β Decays

- The quenching of g_A

- Forbidden non-unique β decays

- The GAIAS Experiment

			$\Delta J^{\Delta\pi}$	
	L	$\Delta\pi$	F S=0	GT S=1
Super-allowed	0	+	0^+	
Allowed	0	+		$0^+, 1^+$
First-forbidden	1	-	$0^-, 1^-$	$0^-, 1^-, 2^-$
Second-forbidden	2	+	2^+	$2^+, 3^+$
Third-forbidden	3	-	3^-	$3^-, 4^-$
Fourth-forbidden	4	+	4^+	$4^+, 5^+$
....	...	...	...	...

The total change in angular momentum is:

- In **FU beta decay** $\Rightarrow \Delta J = L + 1$
- In **FNU beta decay** $\Rightarrow \Delta J = L$
- Exception:** first FNU also allow $\Delta J = 0$

- Allowed**
- Forbidden non-unique (FNU)**
- Forbidden unique (FU)**

Transition type	$\Delta J^{\Delta\pi}$	$\Delta\pi$	Forbiddenness
Allowed	$0^+, 1^+$		
Forbidden non-unique	$0^-, 1^-, 2^+, 3^-, 4^+, \dots$	$(-1)^{\Delta J}$	ΔJ
Forbidden unique	$2^-, 3^+, 4^-, \dots$	$(-1)^{\Delta J - 1}$	$\Delta J - 1$

Forbidden β Decays

- If $\Delta J^{\Delta\pi} = 3^+$

- $\Delta J = 3 \rightarrow L = 2, 3, 4$ 
- L is even

- $L = 2; S = 1$ GT transition
($L = 4$ gives negligible contributions)

2nd-Forbidden Unique (2-FU)

$$M^2 = g_A^2 |M_{GT}|^2$$

- If $\Delta J^{\Delta\pi} = 3^-$

- $\Delta J = 3 \rightarrow L = 2, 3, 4$ 
- L is odd

- $L = 3; S = 0$ F transition
- $L = 3; S = 1$ GT transition

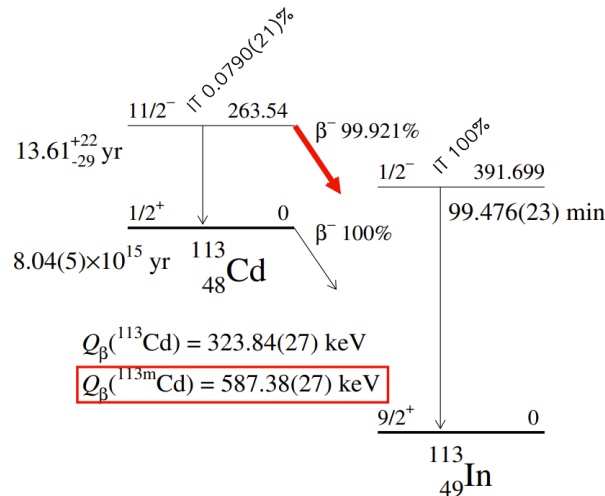
3rd-Forbidden Non-Unique (3-FNU)

$$M^2 = |g_V M_F + g_A M_{GT}|^2 = g_V^2 |M_F|^2 + 2g_V g_A \text{Re}(M_F^* M_{GT}) + g_A^2 |M_{GT}|^2$$

FNU measurements to extract g_A^{eff}

	Nuclear transition	Experimental approach	Nuclear model adopted	g_A^{eff}	Reference
^{87}Rb	$^{87}\text{Rb}(3/2^-) \rightarrow ^{87}\text{Sr}(9/2^+)$ 3 rd FNU	Rb_2ZrCl_6 crystal scintillator at LNGS	NSM + MQPM	$\approx 0.40 - 0.60$	Belli et al. EPJA 62 (2026) 16
	$^{113\text{m}}\text{Cd}(11/2^-) \rightarrow ^{113}\text{In}(9/2^+)$ 1 st FNU	$^{106}\text{CdWO}_4$ crystal scintillator enriched in ^{106}Cd contaminated by $^{113\text{m}}\text{Cd}$ at LNGS	NSM/KSHELL	≈ 0.80	Belli et al. Phys. Rev. C 112 (2025) 045503
$^{113\text{m}}\text{Cd}$ & ^{113}Cd	$^{113}\text{Cd}(1/2^+) \rightarrow ^{113}\text{In}(9/2^+)$ 4 th FNU	CdWO_4 crystal scintillator at LNGS	MQPM, ISM, IBFM-2	≈ 0.90	Belli et. al., Phys. Rev. C 76, (2007) 064603, Haaranen et al. Phys. Rev. C 93 (2016) 034308
	$^{113}\text{Cd}(1/2^+) \rightarrow ^{113}\text{In}(9/2^+)$ 4 th FNU	COBRA: CdZnTe semiconductor detectors at LNGS	ISM, MQPM, IBFM-2	$0.828(140) - 0.993(63)$	Kotensalo et al. Phys. Lett. B 822 (2021) 136652
	$^{113}\text{Cd}(1/2^+) \rightarrow ^{113}\text{In}(9/2^+)$ 4 th FNU	CdWO_4 bolometer at Canfranc (Spain)	NSM, MQPM, IBFM-2	$0.998(6) - 1.160(19)$	Bandac et al. Eur. Phys. J. C (2024) 84:1158
	$^{99}\text{Tc}(9/2^+) \rightarrow ^{99}\text{Ru}(5/2^+)$ 2 nd FNU	Artificial ^{99}Tc source embedded in a 4π Au absorber and measured with a Metallic Magnetic Calorimeter	NSM, ISM, MQPM	$1.0 - 1.2$	Song et al, arXiv:2506.17544v1 [nucl-ex]
^{99}Tc	$^{99}\text{Tc}(9/2^+) \rightarrow ^{99}\text{Ru}(5/2^+)$ 2 nd FNU	Silicon Drift Detectors	RSM (Realistic Shell Model)	$g_A^{eff} \approx 0.51(1)$ $g_V^{eff} \approx 0.47(1)$	Nava et al., arXiv: 2609.05640 [nucl-ex]
	$^{99}\text{Tc}(9/2^+) \rightarrow ^{99}\text{Ru}(5/2^+)$ 2 nd FNU	ASPECT-BET: ^{99}Tc source deposited on Si substrate and measured with Silicon Drift Detector (SDD)	RSM	Not value quoted	Nava et al., Sensors 24 (2024) 8202
	$^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(1/2^+)$ 4 th FNU	ACCESS: InI cryogenic calorimeter	ISM best fit; MQPM, IBFM-2 cross-check	$0.964^{+0.010}_{-0.006}$	Pagnanini et al. PRL 133 (2024) 122501
^{115}In	$^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(1/2^+)$ 4 th FNU	High-resolution LiInSe ₂ bolometer	ISM, IBM, MQPM	$0.830(2) - 0.936$	Leder et al. PRL 129 (2022) 232502

$^{113}\text{Cd}(1/2^+) \rightarrow ^{113}\text{In}(9/2^+)$, 4th FNU



COBRA, PLB 800, 135092 (2020)

- **Technique:** CdZnTe semiconductor detectors operated at LNGS.
- **Spectrum shape:** $g_A^{eff} = 0.915 \pm 0.007$ (ISM), 0.911 ± 0.013 (MQPM) and 0.955 ± 0.022 (IBFM-2).
- **Half-life:** not independently extracted from this normalized spectrum-shape analysis

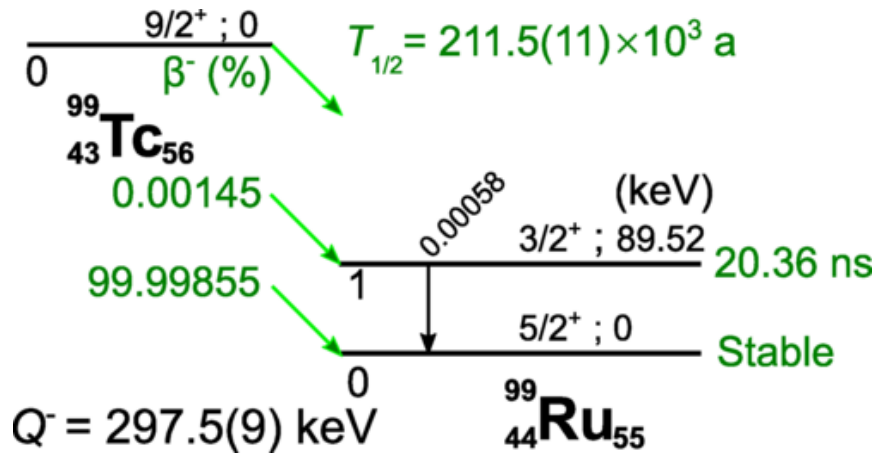
P. Belli et al., PRC 76, 064603 (2007)

- **Technique:** 434-g CdWO_4 crystal scintillator operated at LNGS for 2758 h (^{113}Cd naturally present with $\delta \approx 12.2\%$)
- **Measured half-life:** $T_{1/2} = (8.04 \pm 0.05) \times 10^{15}$ yr (threshold ~ 28 keV)
- **Spectrum shape:** Extraction of $g_A^{eff} \simeq 0.92$ M. Haaranen, J. Kotila, and J. Suhonen, Phys.Rev.C 95 (2017) 2, 024327

Bandac et al., EPJC 84, 1158 (2024)

- **Technique:** 0.43-kg CdWO_4 crystal operated as a cryogenic scintillating bolometer at Canfranc for 26 days.
- **Spectrum shape + half life:** $g_A^{eff} \approx 1.0\text{--}1.16$, depending on the nuclear model.
- **Half-life:** $T_{1/2} = 7.73^{+0.60}_{-0.57} \times 10^{15}$ yr.

$^{99}\text{Tc}(9/2^+) \rightarrow ^{99}\text{Ru}(5/2^+)$, 2nd FNU



M. Paulsen et al., Phys. Rev. C 110, 05503(2024)

- **Technique:** two independent metallic magnetic calorimeters, cross-checked with silicon detectors.
- **Model:** nuclear shell model (NuShellX/GLEKPN), with the sNME fixed through CVC.
- **Spectrum shape:** $g_A = 1.526(92)$ - enhanced, assuming $g_V = 1$!
- **Including the half-life:** $g_A^{\text{eff}} = 0.574(36)$ and $g_V^{\text{eff}} = 0.376(5)$.

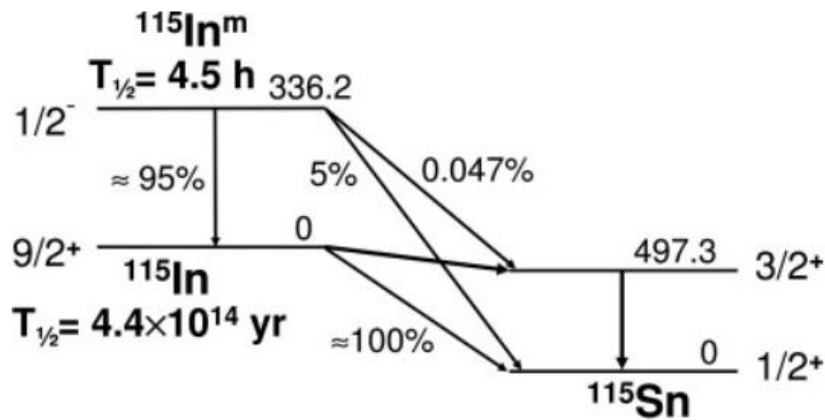
Song et al. 2506.17544

- **Technique:** metallic magnetic calorimeter.
- **Model:** nuclear shell-model (glekpn and jj45pnb) and MQPM.
- **Spectrum shape:** $g_A^{\text{eff}} \simeq 1.0 - 1.2$, corresponding to mild-to-moderate quenching ($q \simeq 0.78 - 0.94$).
No evidence for the previously reported enhancement $g_A/g_V = 1.526(92)$.

Nava et al. 2609.05640

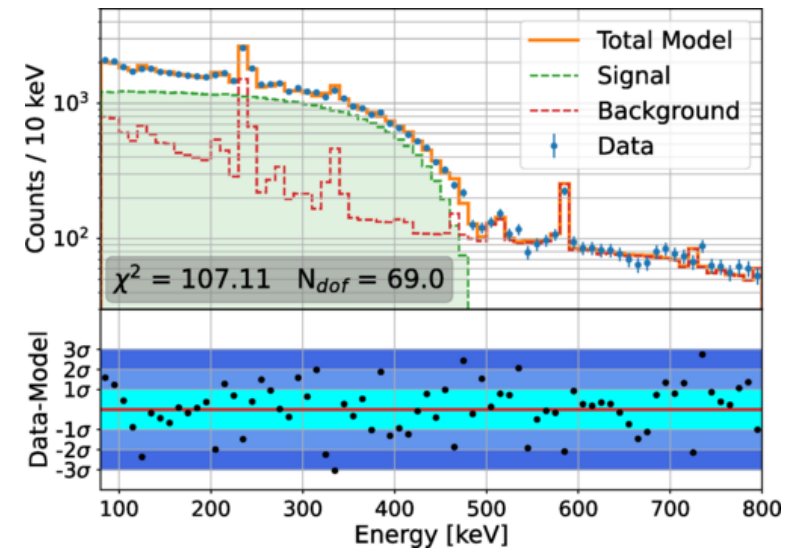
- **Technique:** Silicon Drift Detector with LYSO-SiPM in-situ calibration
- **Model:** Realistic shell model
- **Spectrum shape + half life:** $q(g_A) = 0.40(1)$ and $q(g_V) = 0.47(1)$, corresponding to $g_A^{\text{eff}} \approx 0.51$, $g_V^{\text{eff}} \approx 0.47$, and $g_A/g_V \approx 1.08$

$^{115}\text{In}(9/2^+) \rightarrow ^{115}\text{Sn}(1/2^+)$ 4th FNU



Leder et al. PRL 129 (2022) 232502

- **Technique:** 10.3-g LiInSe₂ scintillating bolometer at Orsay; 39.7 g·day exposure and 160-keV analysis threshold.
- **Model:** Spectrum-Shape Method using ISM, IBM and MQPM calculations
- **Spectrum shape:** $g_A^{eff} = 0.830 \pm 0.002$ (ISM), 0.845 ± 0.006 (IBM) and 0.936 ± 0.003 (MQPM)
- **Half-life:** $T_{1/2} = 5.18 \pm 0.06(\text{stat})_{-0.015}^{+0.005}(\text{syst}) \times 10^{14}$ yr from the ISM analysis



Pagnanini et al., PRL 133 (2024) 122501

- **Technique:** 1.91-g InI cryogenic calorimeter operated at LNGS for 128.8 h; ^{115}In embedded in the detector.
- **Model:** ISM, MQPM and IBFM-2 calculations.
- **Spectrum shape:** $g_A^{eff} = 0.964_{-0.006}^{+0.010}$ - moderate quenching
- **Half-life:** $T_{1/2} = (5.26 \pm 0.06) \times 10^{14}$ yr.