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## $\beta$ decay of $^{113m}\text{Cd}$

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# The rare $\beta$ decay

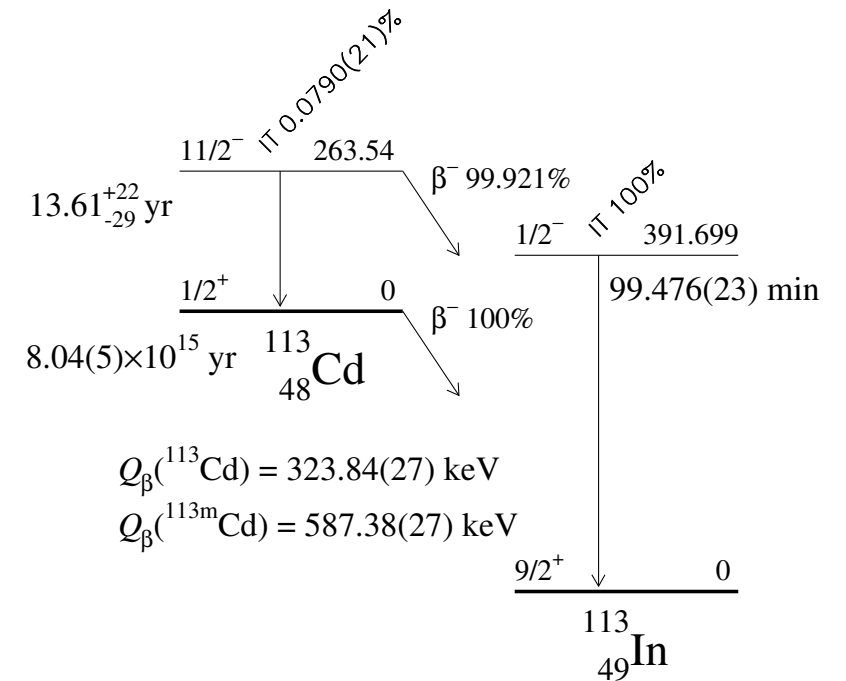
- ❖ **Beta electrons are crucial in modern nuclear and particle physics:** antineutrino flux from nuclear reactors and the related anomalies; background in rare-event experiments (e.g., dark matter,  $2\beta$  decay).
- ❖ **The effective value of  $g_A$  in finite nuclei is uncertain:**  $g_A^{free} \simeq 1.2723$ , but inside a nucleus  $g_A \sim A^{-\alpha}$ , with  $\alpha = 0.15 - 0.25$ , depending on the nuclear model adopted to infer the  $g_A$  value.
  - Key parameter in modeling  $\beta$  and  $2\beta$  decays.
  - Directly impacts predictions for  $0\nu 2\beta$  decay sensitivity.
  - The quenching of  $g_A$  can depend on the process type and momentum transfer.
- ❖ **Forbidden non-unique  $\beta$  decays** are especially informative: study electron spectral shapes of  $\beta$  decays can be used to extract the value of  $g_A$ .

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

# $\beta$ decay of $^{113m}\text{Cd}$

| Experiment description  | Total time followed (yr) | Half-life (yr)          | Year [Reference] |
|---|--------------------------|-------------------------|------------------|
| $^{113m}\text{Cd}$ created by thermal neutron fission of $^{235}\text{U}$ , methane flow proportional counter | 7                        | $14 \pm 2$              | 1959 [1]         |
| 20 mg/cm <sup>2</sup> sample of $^{113}\text{Cd}$ , end-window gas-flow proportional counter                  | 11                       | $13.6 \pm 0.2$          | 1965 [2]         |
| Same experimental technique as in [1]   | 18                       | $14.6 \pm 0.5$          | 1972 [3]         |
| Table value   |                          | $14.1 \pm 0.5$          | 2010 [4]         |
| Solution of $^{113m}\text{Cd}$ extracted from Cd irradiated by neutrons, liquid scintillation counting        | 0.9                      | $13.97 \pm 0.13$        | 2011 [5]         |
| $^{113m}\text{Cd}$ in $^{106}\text{CdWO}_4$ crystal scintillator, low-background scintillation counting       | 14                       | $13.61^{+0.22}_{-0.29}$ | This work        |

- $^{113m}\text{Cd}$  decays via first-forbidden non-unique  $\beta$  transition ( $\Delta J = 1^-$ ) to  $^{113}\text{In}$ .
- Offers complementary information to the ground-state decay of  $^{113}\text{Cd}$  ( $\Delta J = 4+$ ).

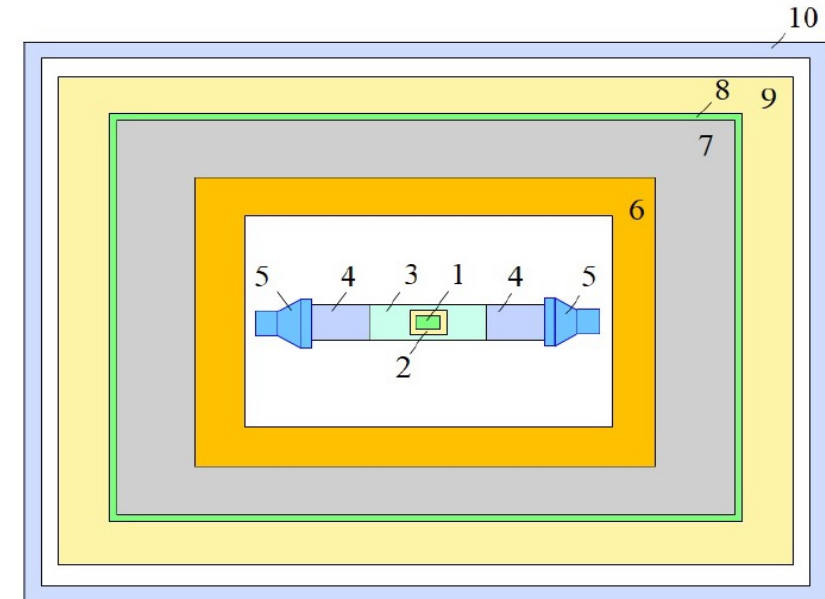


[1] A.C. Wahl, J. Inorg. Nucl. Chem. 10, 1 (1959).  
 [2] K.F. Flynn et al. Nucl. Sci. Eng. 22, 416 (1965).

[3] A.C. Wahl, J. Inorg Nucl. Chem. 34, 1767 (1972).  
 [4] J. Blachot, Nucl. Data Sheets 111, 1471 (2010).  
 [5] K. Kossert et al. Appl. Radiat. Isot. 69, 500 (2011).

# Stages of the low-background measurements at LNGS

| Stage of experiment                                    | 1   | 2  | 3  |
|--|---|--|--|
| Measurement dates                                      | 09 – 23 Nov 2009  | 30 Apr – 19 May 2015   | 20 Sep – 05 Oct 2023   |
| Specific modifications                                 | Reference setup with quartz light guides and original electronics [6] | Crystal etched to remove $^{207}\text{Bi}$ surface contamination [7,8] | Quartz light guides removed; new low-background Hamamatsu PMTs; improved light collection efficiency [8] |
| Live time (h)  | 248.0(10)   | 392(6)   | 340.9(34)  |
| Mass of $^{106}\text{CdWO}_4$ crystal scintillator (g) | 215.8   | 215.4  | 215.4  |
| Energy resolution at 587 keV ( $\sigma$ , keV)         | 31.1(2)   | 31.8(4)  | 23.2(3)  |
| Energy threshold accepted in analysis (keV)            | 39  | 64   | 26   |
| Background in (0.8 – 2.0) MeV (counts/day)             | 66(2)   | 119(3)   | 105(2)   |
| Signal-to-background ratio in (100 – 580) keV          | 549   | 398  | 294  |



Schematic cross-sectional view of the experimental set-up used to measure  $^{113\text{m}}\text{Cd}$   $\beta$  spectrum in 2009. The  $^{106}\text{CdWO}_4$  crystal scintillator (1) is fixed in a cavity filled by silicon oil (2) inside polystyrene plastic light guide (3) and viewed through quartz light guides (4) by PMTs (5). The passive shield consisted of high-purity copper (6), low-radioactive lead (7), cadmium (8), polyethylene/paraffin (9), and a poly(methyl methacrylate) box flushed with  $\text{N}_2$  gas (10).

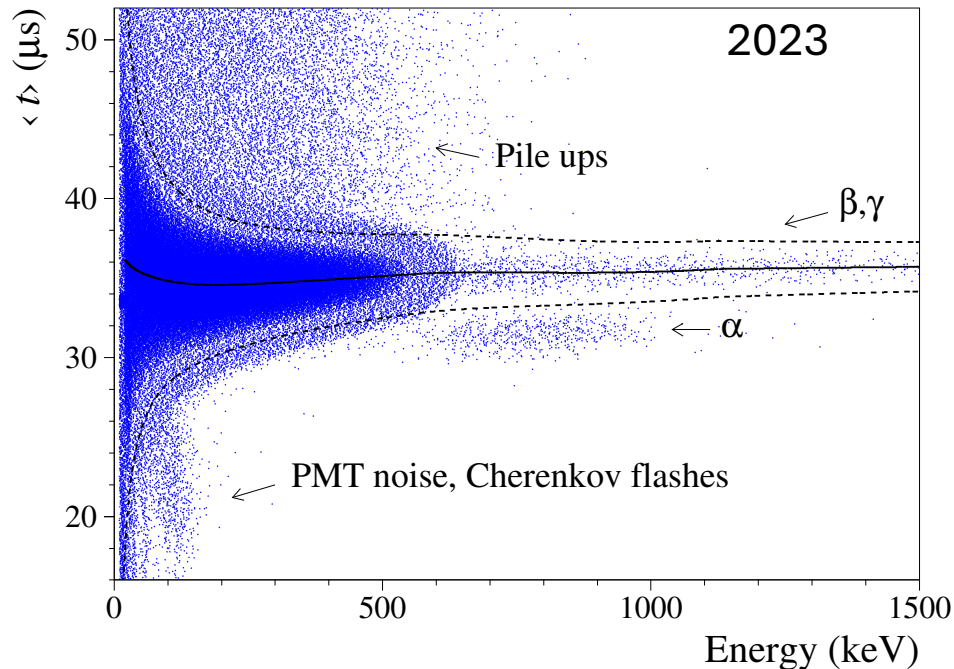
[6] P. Belli et al., Phys. Rev. C 85 044610 (2012) .

[7] P. Belli et al., Phys. Rev. C.93 045502 (2016).

[8] Present study

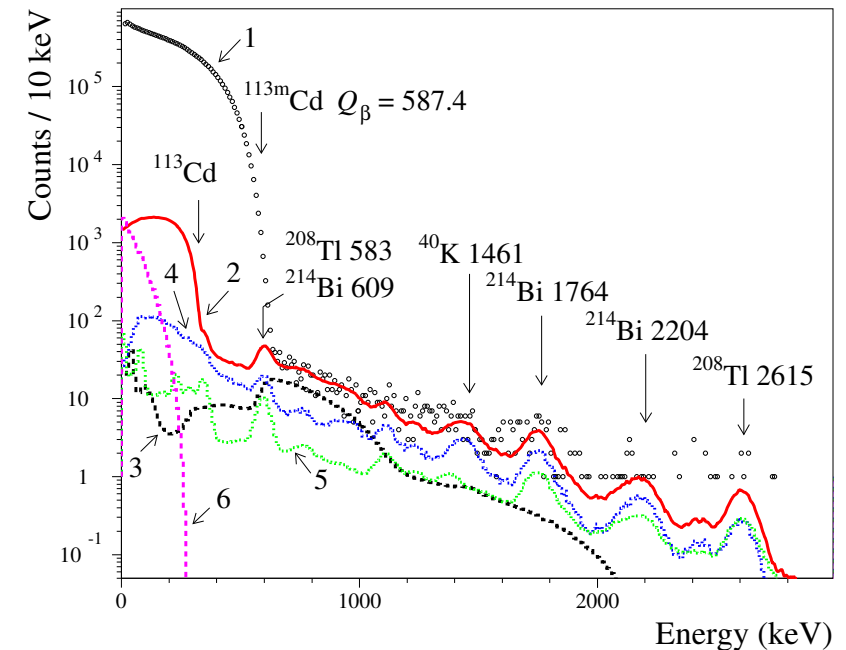
# PSD for event selection

- Mean-time parameter  $\langle t \rangle$  separates single  $\beta/\gamma$  events from  $\alpha$ , noise, pile-up.
- Events selected within  $\pm 3\sigma$  from Gaussian  $\langle t \rangle$  distribution.
- Clearly identifies bands:
  - ✓  $\beta/\gamma$  events (selected)
  - ✓  $\alpha$ -events, pile-ups, electronic noise, Cherenkov flashes (rejected)

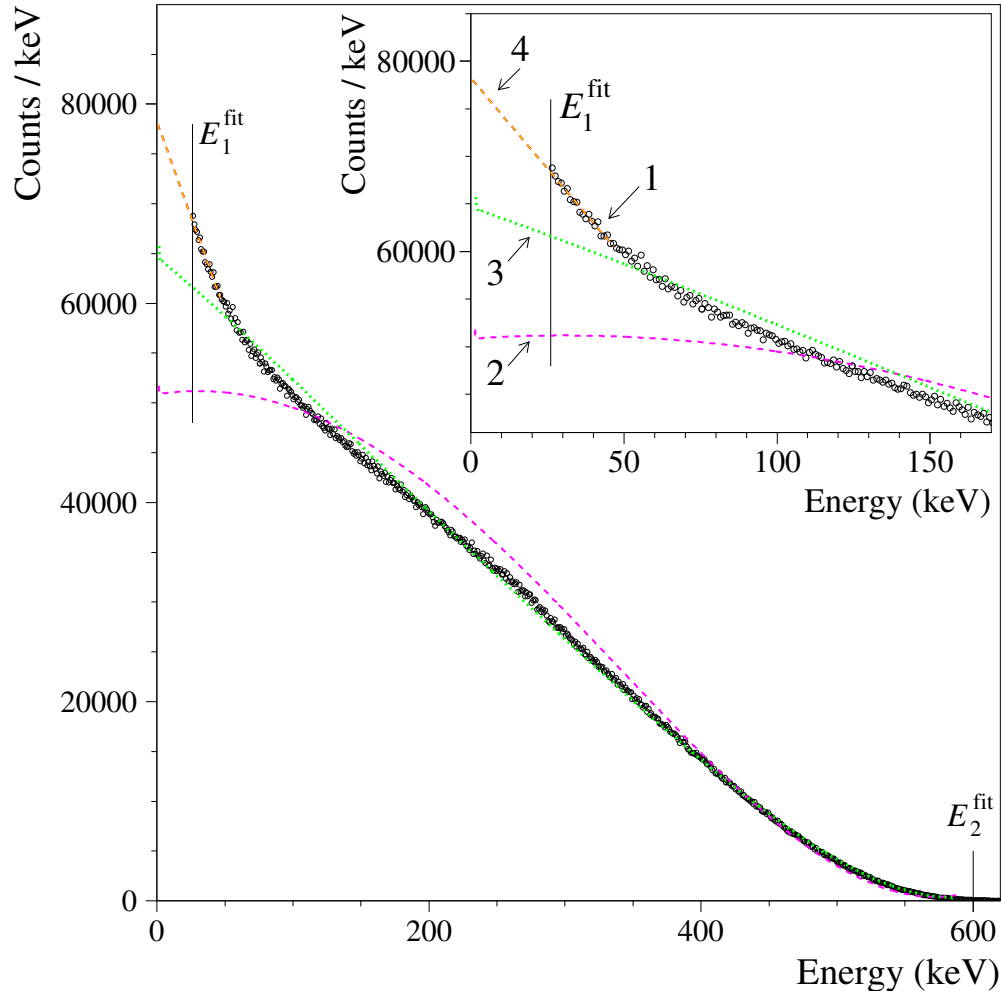


# Background Modeling of the 2023 data

1.  $\beta$  spectrum of  $^{113}\text{Cd}$ ;
2. model of the background;
3. radioactive contamination of the  $^{106}\text{CdWO}_4$  crystal scintillator (without the  $\beta$  spectrum of  $^{113}\text{Cd}$ );
4. radioactive contamination of the copper shield, PMTs, PTFE details and the plastic light guide;
5. background due to the radioactive contamination of the silicone oil;
6.  $\beta$  spectrum of  $^{87}\text{Rb}$  corresponding to the concentration 70 ppb in the  $^{106}\text{CdWO}_4$  crystal (limit of the ICP-MS analysis).



# First experimental determination of the $^{113m}\text{Cd}$ $\beta$ spectral shape



The **shape of  $\beta$  spectrum** in general is described as:

$$\rho(E) = \rho_{\text{allowed}}(E) \times C(w)$$

Correction factor  
 $C(w) = 1 + \frac{\epsilon_1}{w} + \epsilon_2 \cdot w + \epsilon_3 \cdot w^2$

Where:

$$\rho_{\text{allowed}}(E) = F(Z, E) \cdot w p (Q_\beta - E)^2$$

Fermi function

$w = E/m_e c^2 + 1$ ; E is the kinetic energy; p is the  $\beta$  particle momentum.

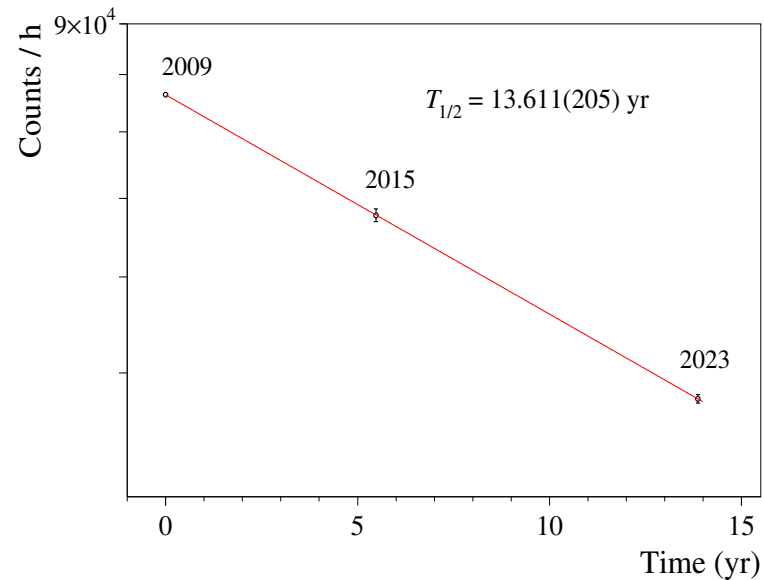
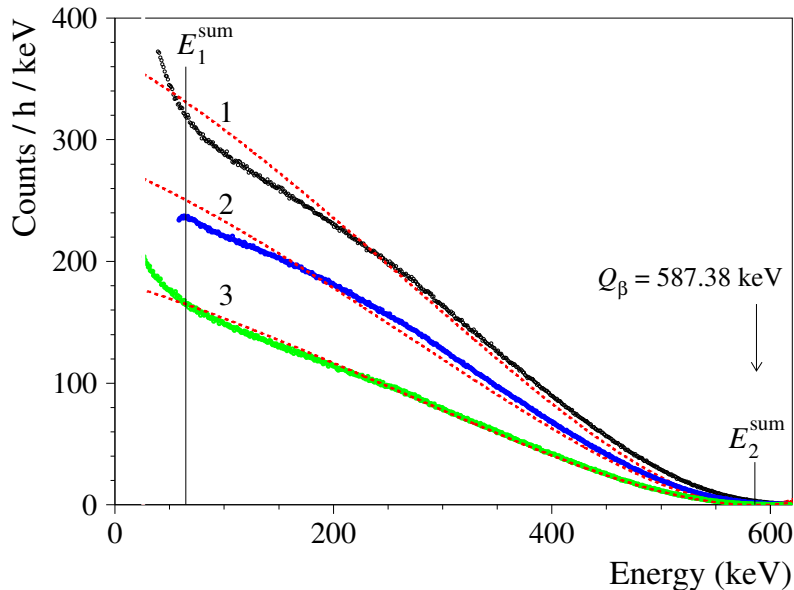
Fit of the energy spectrum of  $\beta/\gamma$  events measured by the low-background  $^{106}\text{CdWO}_4$  scintillation detector in 2023 for 340.9 h (black circles, 1) in the energy interval  $E_1^{\text{fit}} - E_2^{\text{fit}}$  (26 – 600 keV) by two functions:

- by the **allowed shape** (dashed purple line, 2),
- by **allowed shape with a correction factor  $C(w)$**  (dotted green line, 3).
- Dashed red line (4) is a result of the experimental data **fit by a linear function** in the energy interval (26 – 46) keV.

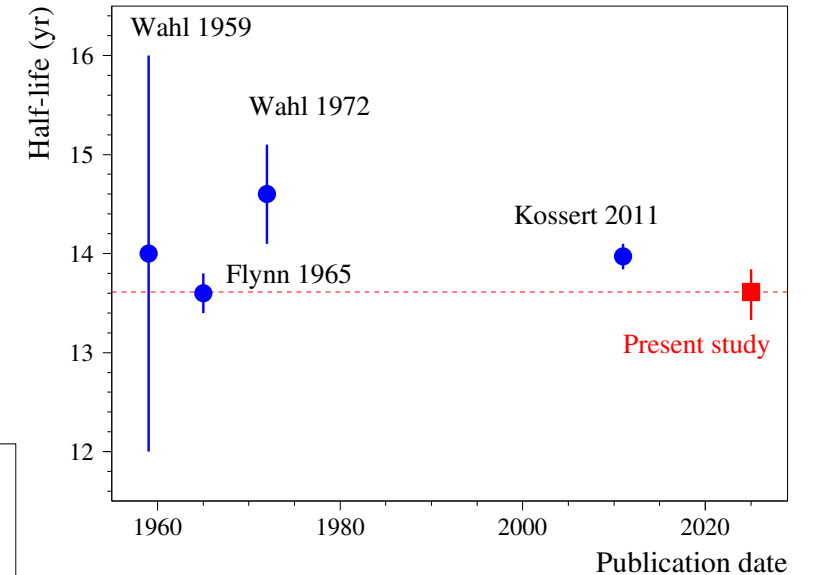
Comparison with the considered models indicates that the data are best described assuming a quenched axial-vector coupling constant of  $g_A \approx 0.8$  (or lower).

# The half-life of $^{113\text{m}}\text{Cd}$ relative to $\beta$ decay to the ground state of $^{113}\text{In}$

- Energy spectra of  $\beta(\gamma)$  events measured by low-background  $^{106}\text{CdWO}_4$  scintillation detectors in **2009** (black points, 1), **2015** (blue points, 2) and **2023** (green points, 3).
- The corresponding energy spectra after deconvolution and transformation to the same energy scale are shown by red dashed lines.
- To determine the half-life of  $^{113\text{m}}\text{Cd}$ , the counting rates in the deconvoluted spectra were calculated in the energy interval  $E_1^{\text{sum}} - E_2^{\text{sum}}$  [(64 – 587) keV]



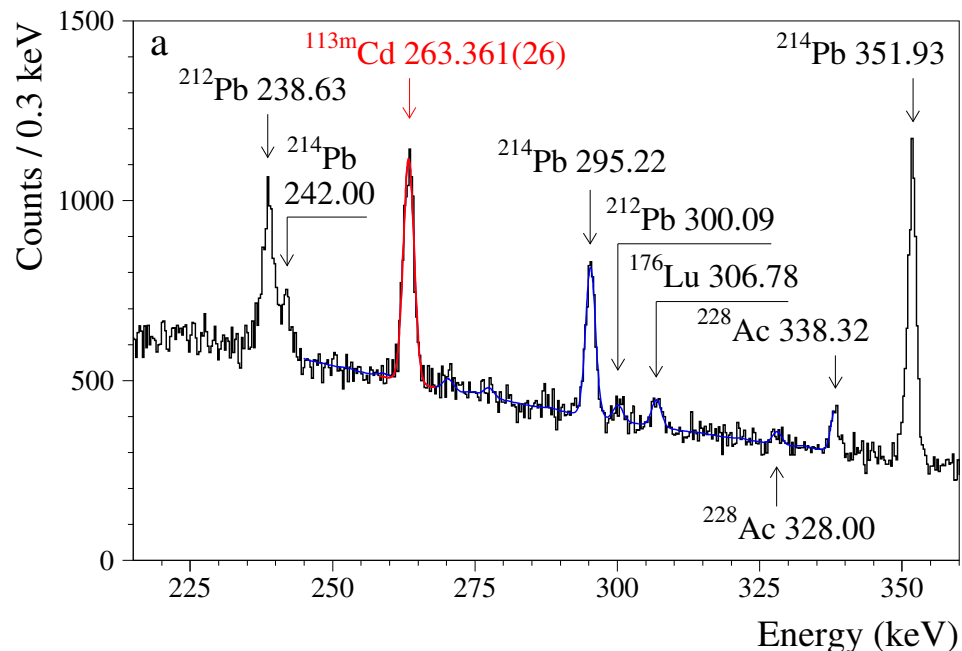
Historical perspective of the  $^{113\text{m}}\text{Cd}$  half-life



$$T_{1/2} = 13.61^{+0.22}_{-0.29} \text{ yr}$$

# Study of the isomeric transition $^{113m}\text{Cd} \rightarrow ^{113}\text{Cd}$

- **Objective:** characterize the isomeric transition (IT) of  $^{113m}\text{Cd}$  via  $\gamma$  detection.
- **Setup:**  $^{106}\text{CdWO}_4$  crystal placed in HPGe detector array at LNGS (STELLA facility) [1].
- Crystal acts as  **$\gamma$  source**; shielded with Cu, Pb, and PMMA flushed with  $\text{N}_2$ .
- Full absorption peak efficiency:  $(3.077 \pm 0.005)\%$ .



- ✓ 12843 h
- ✓ 4 HPGe detector system with the  $^{106}\text{CdWO}_4$  scintillation detector in [1].

## Results and comparisons:

- Accurate measurement of the IT  $\gamma$  energy:  
 $E_{\gamma}^{IT} = 263.36(4) \text{ keV}$ .
- Measured branching ratio:  
 $P_{\gamma+CE} = (0.0790 \pm 0.0021)\%$
- Value smaller than:
  - Tabulated value ( $\sim 0.14\%$ ) [9];
  - Kossert et al. (2011) result:  $0.104(8)\%$  [5].
- Higher precision than previous measurements.
- Confirms that  $\beta$  decay dominates over IT decay for  $^{113m}\text{Cd}$ .

[1] Phys. Rev. C.93 045502 (2016).

[5] K. Kossert et al. Appl. Radiat. Isot. 69, 500 (2011).  
[9] E. Der Mateosian, Phys. Rev. C 186, 1285 (1969).

# Summary and Conclusions

- A detailed experimental study of the  **$\beta$  decay of the  $^{113\text{m}}\text{Cd}$  isomeric state** was performed using a low-background  $^{106}\text{CdWO}_4$  **scintillation detector** over three separate data-taking periods: 2009, 2015, and 2023.
- For the **first time**, the  **$\beta$  energy spectrum of  $^{113\text{m}}\text{Cd}$**  was measured.
- The spectral shape shows sensitivity to the **effective axial-vector coupling constant  $g_A$ ; small relativistic nuclear matrix elements (sNMEs)**
- **Comparison** with the considered **models** indicates that the **data** are best described assuming a quenched axial-vector coupling constant of  **$g_A \approx 0.8$** .
- An accurate measurement of the  $^{113\text{m}}\text{Cd}$   **$\beta$ -spectral shape** and its dependence on  $g_A$  will be the subject of a separate study in progress.
- The **half-life** of the  $\beta$  decay to the ground state of  $^{113}\text{In}$  was determined as:  
$$T_{1/2} = 13.61^{+0.22}_{-0.29} \text{ yr}$$
(systematic uncertainties were not estimated in the previous experiments).
- The **IT branching ratio** to the first excited state  $\rightarrow$  ground state of  $^{113}\text{Cd}$  was measured using HPGe detectors, yielding:  
$$P_{\gamma+CE} = (0.0790 \pm 0.0021)\%$$
- These results provide **critical inputs for nuclear theory**, particularly in the modeling of **forbidden non-unique  $\beta$  decays** and are relevant for **background modeling** in rare-event searches using cadmium-based detectors.

**BACKUP**

# Spectral shape of $\beta$ decays

The energy distribution of the electrons emitted in the  $\beta$  decay can be described by:

$$\rho(E) = \rho_{allowed}(E) \times C(w)$$

where

$$\rho_{allowed}(E) = F(Z, E) wp(Q_\beta - E)^2$$

is the distribution for the allowed spectrum;  $w$  is the total energy of the  $\beta$  particle (in units of electron mass);  $p$  is the  $\beta$  particle momentum;  $Z$  is the charge number of the daughter nucleus and  $F(Z, E)$  is the Fermi function which accounts for the distortion of the spectrum due to the electric field of the nucleus and of the atomic shell.  $C(w)$  is a correction factor:

$$C(w) = 1 + \frac{\epsilon_1}{w} + \epsilon_2 \cdot w + \epsilon_3 \cdot w^2$$

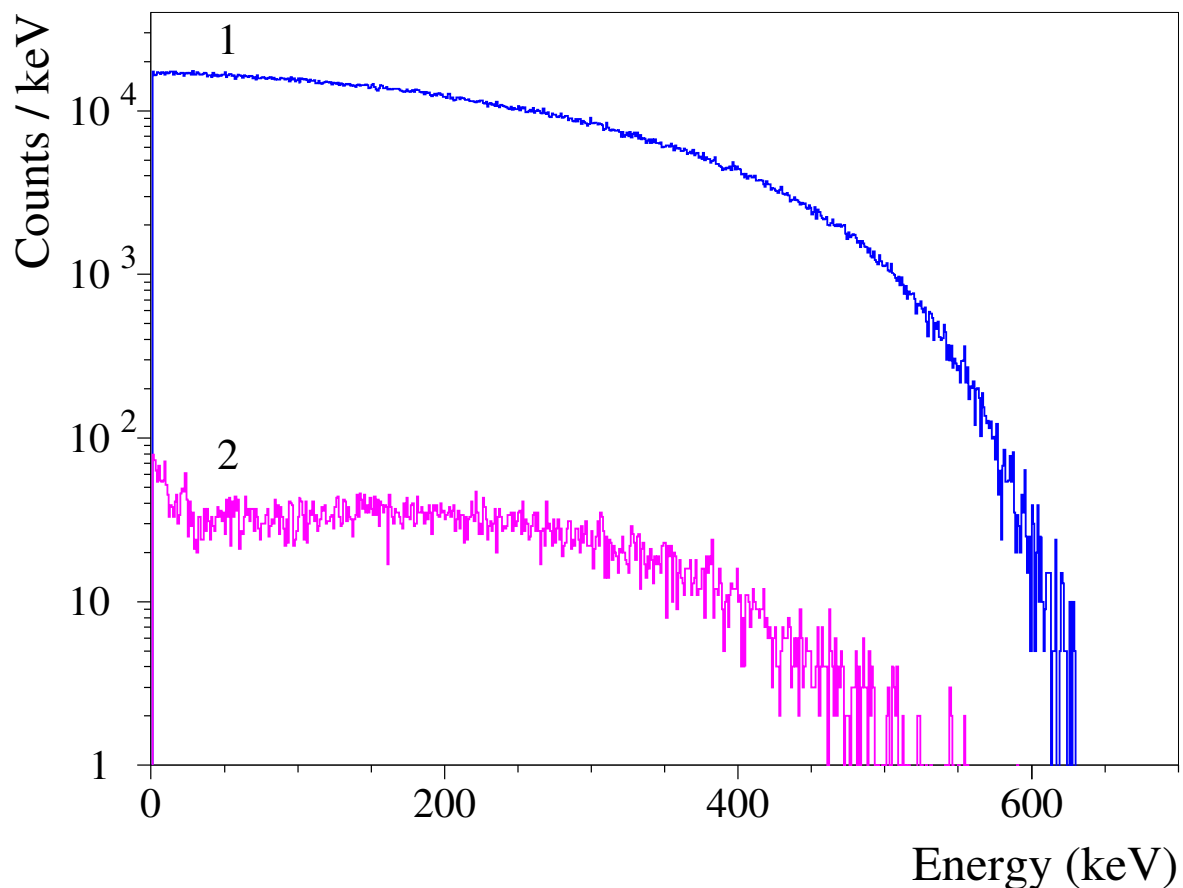
where  $\epsilon_i$  are fitting parameters.

A convolution of the  $\beta$  shape with the response function of the detector  $R(E, E')$  was employed to account for the detector energy resolution:

$$f(E) = \int_0^{Q_\beta} \rho(E') \cdot R(E, E') dE'$$

The response of the detector was described by a Gaussian function.

# Energy spectrum of electrons and bremsstrahlung $\gamma$ quanta

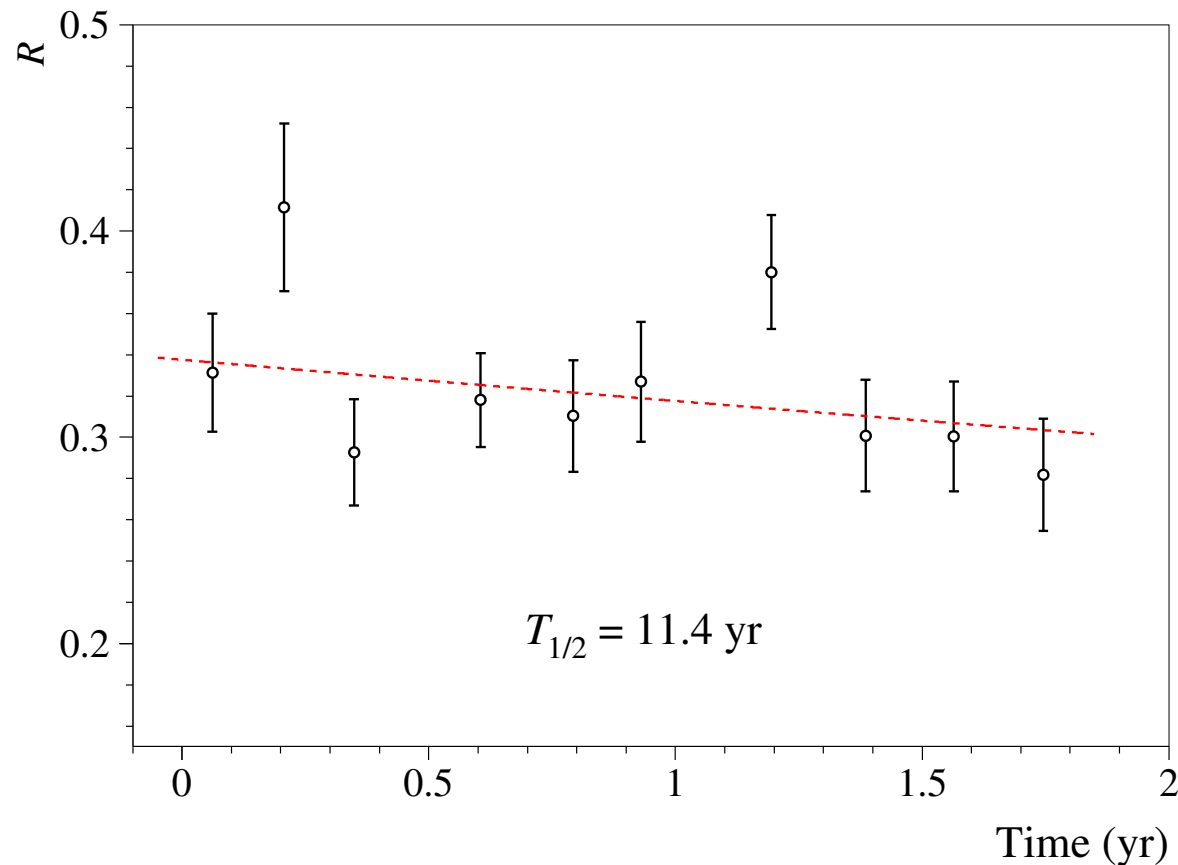


(1) in  $^{106}\text{CdWO}_4$ ;  
(2) in the silicon oil and the plastic light guide surrounding the crystal

assuming the allowed shape with a correction factor  $C(w)$  for electrons emitted in the  $\beta$  decays of  $^{113\text{m}}\text{Cd}$  in the  $^{106}\text{CdWO}_4$  crystal.

- Both spectra are blurred, considering the detector's energy resolution. One can see that escape of electrons and  $\gamma$  quanta changes the area and the spectral shape insignificantly.
- The area of the distribution (2) is only 0.25% of the spectrum (1).

# Decrease of the isomeric transition $\gamma$ -quanta counting rate in time

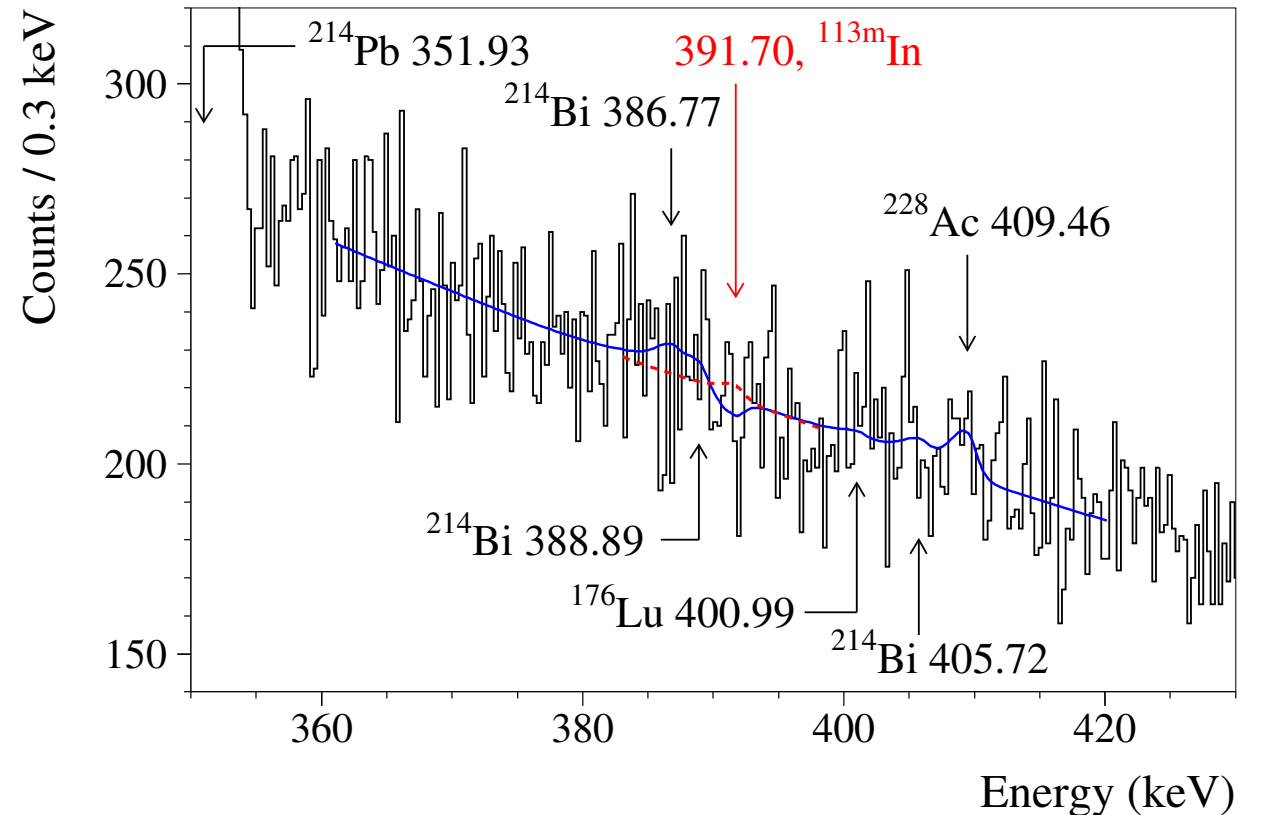


- The counting rate of the 263.4-keV peak should decrease in time due to the decay of  $^{113\text{m}}\text{Cd}$ .
- R is a ratio of the 263.4-keV peak area to the whole area of the  $\gamma$  peaks of  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$  in the energy spectra measured by the HPGe detector system in the energy interval (225 – 365) keV.
- Fit of the data by exponential function with  $T_{1/2} = (11.4 \pm 8.2) \text{ yr}$  is shown by red solid line.
- The result of the analysis of the IT-  $\gamma$  peak confirms the assumption about the decay of  $^{113\text{m}}\text{Cd}$  with  $T_{1/2} = 13.61 \text{ yr}$ .

# Search for $\beta$ decay of $^{113\text{m}}\text{Cd}$ to the $1/2^-$ 391.699 keV metastable level of $^{113}\text{In}$

- The sum energy spectrum measured for 12843 h by the HPGe detector system with the  $^{106}\text{CdWO}_4$  scintillator in work *P. Belli et al., Phys. Rev. C.93 045502 (2016)*, in the vicinity of a  $\gamma$  peak with energy 391.70 keV expected in the  $\beta$  decay of  $^{113\text{m}}\text{Cd}$  to the  $1/2^-$  391.699 keV metastable level of  $^{113}\text{In}$ .
- The model of background is shown by **blue solid line**, while the excluded peak with an area 41 count is presented by red dashed line.
- **The first experimental limit on the decay was obtained:**

$$T_{1/2}(^{113\text{m}}\text{Cd} \rightarrow ^{113\text{m}}\text{In}) \geq 8.6 \times 10^6 \text{ yr.}$$



# Sources of systematic uncertainties

Of the  $T_{1/2}$  of  $^{113m}\text{Cd}$  relative to the  $\beta$  decay to the ground state of  $^{113}\text{In}$ :

| Source of systematic uncertainty, range of the input quantity variation                                | Uncertainty (yr)     |
|--|----------------------|
| Live time of the measurements (see Table II)   | $\pm 0.205$          |
| Starting point ( $E_1^{\text{sum}}$ ) to calculate the number of events in the spectra, (26 – 430) keV | $+0.031$<br>$-0.177$ |
| End point ( $E_2^{\text{sum}}$ ) to calculate the number of events in the spectra, (530 – 587) keV     | $\pm 0.001$          |
| Instability of detectors   | $\pm 0.050$          |
| Energy scale, $\pm 1\sigma$  | $\pm 0.049$          |
| Energy resolution, free parameters   | $\pm 0.010$          |
| Choice of function to fit the $\beta$ spectrum   | $\pm 0.033$          |
| Starting point ( $E_1^{\text{fit}}$ ) to fit the spectral shape, (36 – 65) keV for 2009 and 2023 data  | $\pm 0.007$          |
| Difference of the experimental set-ups   | $+0.032$<br>$-0.043$ |
| Total systematic uncertainty   | $+0.224$<br>$-0.285$ |

Of the  $\gamma$  quanta energy in the isomeric transition of  $^{113m}\text{Cd}$  to the ground state of  $^{113}\text{Cd}$ :

| Source of systematic uncertainty and range of variation         | Uncertainty (keV) |
|---|-------------------|
| Energy interval of fit, from (221 – 254) keV to (283 – 345) keV | $\pm 0.0320$      |
| Energy scale  | $\pm 0.0136$      |
| Bin of energy spectrum, (0.2 – 0.5) keV with a 0.05 keV step    | $\pm 0.0053$      |
| Total systematic uncertainty                                    | $\pm 0.0352$      |

The uncertainties are assumed to be independent and added in quadrature.