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

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Understanding the β Decay of ^{113m}Cd: Motivation and Context

Beta electrons are crucial in modern nuclear and particle physics:

- The electrons in the β^- decay are associated with the antineutrino flux from nuclear reactors and the related anomalies
- they represent background in rare-event experiments (e.g., dark matter, double-β decay)

Forbidden non-unique β decays are especially informative:

- Spectral shapes depend on multiple nuclear matrix elements (NMEs)
- Sensitive to the effective axial-vector coupling constant, g_A

The effective value of g_a in finite nuclei is uncertain

- Key parameter in modeling β and double-β decays
- Directly impacts predictions for neutrinoless double-β decay sensitivity
- The quenching of g_A can depend on the process type and momentum transfer

Why Study ^{113m}Cd Decay?

^{113m}Cd (metastable state of ^{113}Cd):

- Decays via first-forbidden non-unique β transition ($\Delta J = 1^-$) to ^{113}In
- Offers complementary information to the ground-state decay of ^{113}Cd ($\Delta J = 4^-$)

The β spectrum of ^{113m}Cd was never studied before

- It can help constrain g_a and small relativistic NMEs (sNMEs)
- Allows comparison of theory and experiment using shell-model calculations

Additional motivations:

- ^{113m}Cd presence in $CdWO_4$ crystals contributes to the background for low-background experiments
- Understanding its decay is essential to suppress backgrounds in 0ν2β searches with cadmium-based detectors

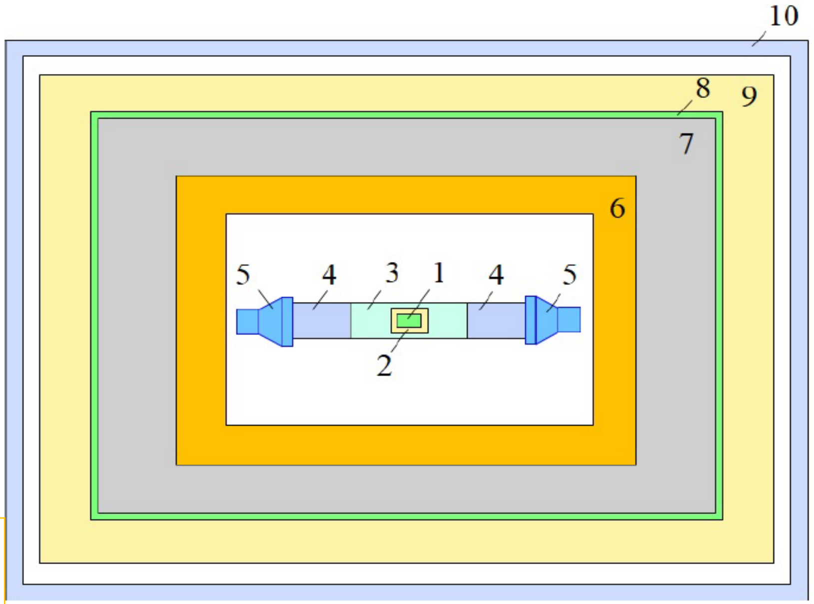
Three Data Sets Used

- The β-decay of ^{113m}Cd was studied using experimental data collected in three distinct measurement campaigns (2009, 2015, and 2023):

- **2009, 2015 and 2023 data sets**:
Employed to evaluate the decay **half-life** of ^{113m}Cd by comparing counting rates from spectra measured several years apart. Differences between these measurements allowed precise extraction and validation of the half-life value.
- **2023 data set**:
Featured the lowest energy threshold, improved energy resolution, and optimized event selection. These characteristics made it ideal for performing a detailed first-time analysis of the β-spectrum shape of ^{113m}Cd, enabling exploration of the sensitivity of the β-spectrum shape to the axial-vector coupling constant (g_A) and relativistic nuclear matrix elements (sNMEs).

Experimental Setup: Scintillation Measurements

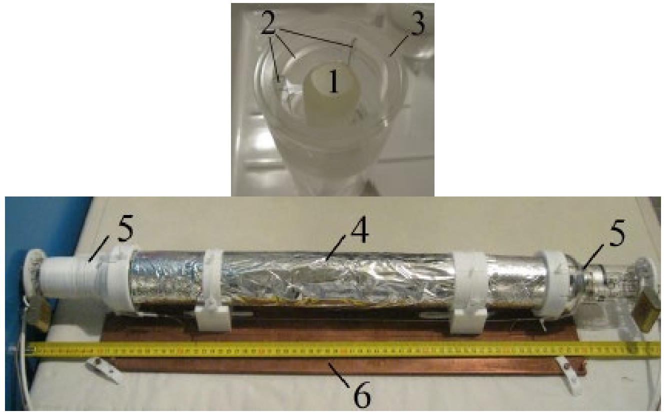
- Experiments performed underground at LNGS (3.8 km w.e. shielding)
- Scintillator: ^{106}CdWO$_4$ crystal (enriched ^{106}Cd) contaminated with ^{113m}Cd
- Measurements in 2009, 2015, 2023:
  - Crystal acts both as source and detector
  - Surrounded by passive shielding (Cu, Pb, Cd, PE)
  - Event-by-event acquisition with waveform digitizers



Schematic cross-sectional view of the experimental set-up used to measure ^{113m}Cd β spectrum in 2009. The ^{106}CdWO4 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), lowradioactive lead (7), cadmium (8), polyethylene/paraffin (9), and a poly(methyl methacrylate) box flushed with N_2 gas (10).

Year	Specific Modifications	Live Time (h)	σ at 587 keV (kev)	Energy Threshold (keV)	Signal-to-background ratio in (100–580 keV)
2009	Reference setup with quartz light guides and original electronics [1]	248.0 ± 1.0	31.1 ± 0.2	39	549
2015	Crystal etched to remove ^{207}Bi surface contamination [2,3]	392 ± 6	31.8 ± 0.4	64	398
2023	Quartz light guides removed; new low-background Hamamatsu PMTs; improved light collection efficiency [3]	340.9 ± 3.4	23.2 ± 0.3	26	294

[1] Phys. Rev. C 85 044610
[2] Phys. Rev. C.93 045502
[3] Present study



Photograph of the ^{106}CdWO4 crystal scintillator (1) fixed by using poly(methyl methacrylate) support details (2) in polystyrene plastic light guide (3). Lower: quartz and plastic light guide (with the 106CdWO4 crystal scintillator inside), covered by aluminized foil (4), viewed by PMTs (5), assembled on a copper plate (6).

Pulse-Shape Analysis and Event Selection

Event Selection by Pulse-Shape Discrimination (PSD)

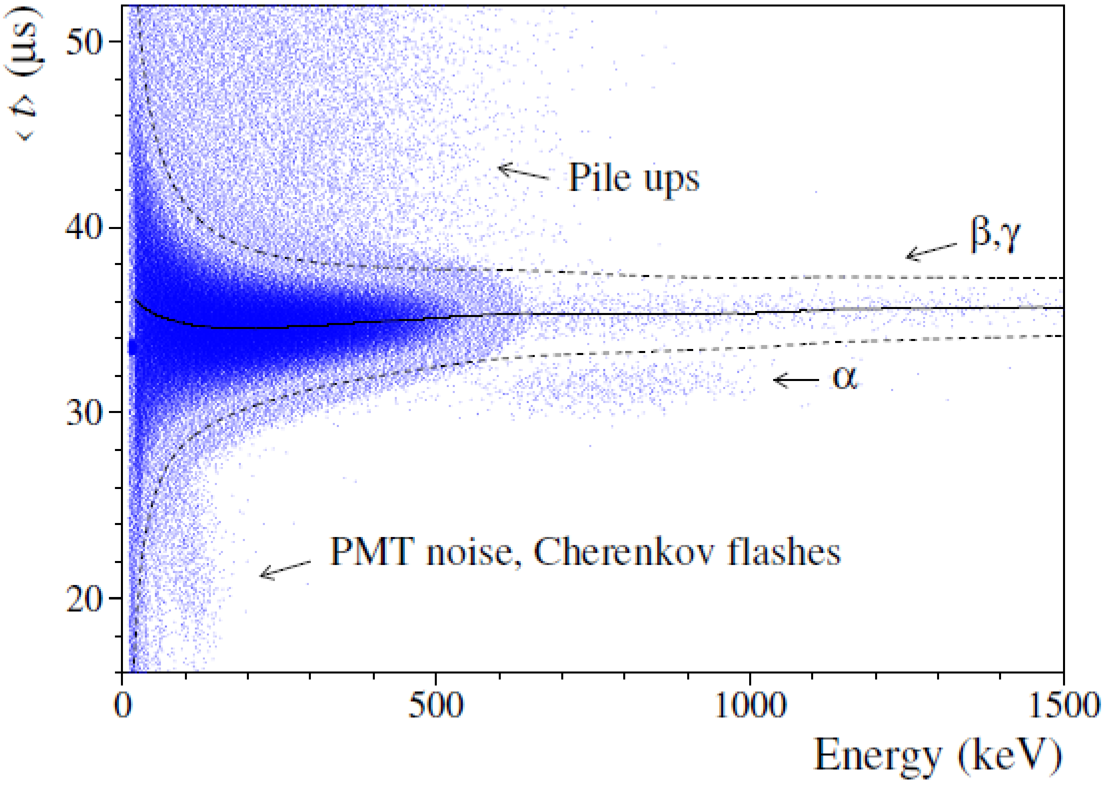
- Mean-time parameter ⟨t⟩ separates genuine β/γ events from α, noise, pile-up.
- Events selected within ± 3σ from Gaussian ⟨t⟩ distribution.
- Clearly identifies bands:
  - ✓ β/γ events (selected)
  - ✓ α-events, pile-ups, electronic noise (rejected)

Energy Range	**NSSBG contribution**
20–30 keV	<2.6 %
290–300 keV	0.008 %
700–1000 keV	~1.2 % (pile-ups)

Outcome: Very clean β/γ dataset with minimal residual contamination.

NSSBG = non-single-CdWO4-scintillation β(γ) events

Scatter plot: ⟨t⟩ vs Energy (2023 run, 340.9 h)



Mean time versus energy measured for 340.9 h with the ^{106}CdWO4 scintillation detector in **2023**. Three σ⟨t⟩ intervals for mean-time values corresponding to β(γ) events are shown. The events beyond the region are due to pile-ups of β(γ) events, α particles from U/Th contamination of the $^{106}CdWO_4$ scintillator, PMT and electronic noise, and Cherenkov flashes in the silicon oil, light guide, and PMTs windows.

Background Modeling of the 2023 data

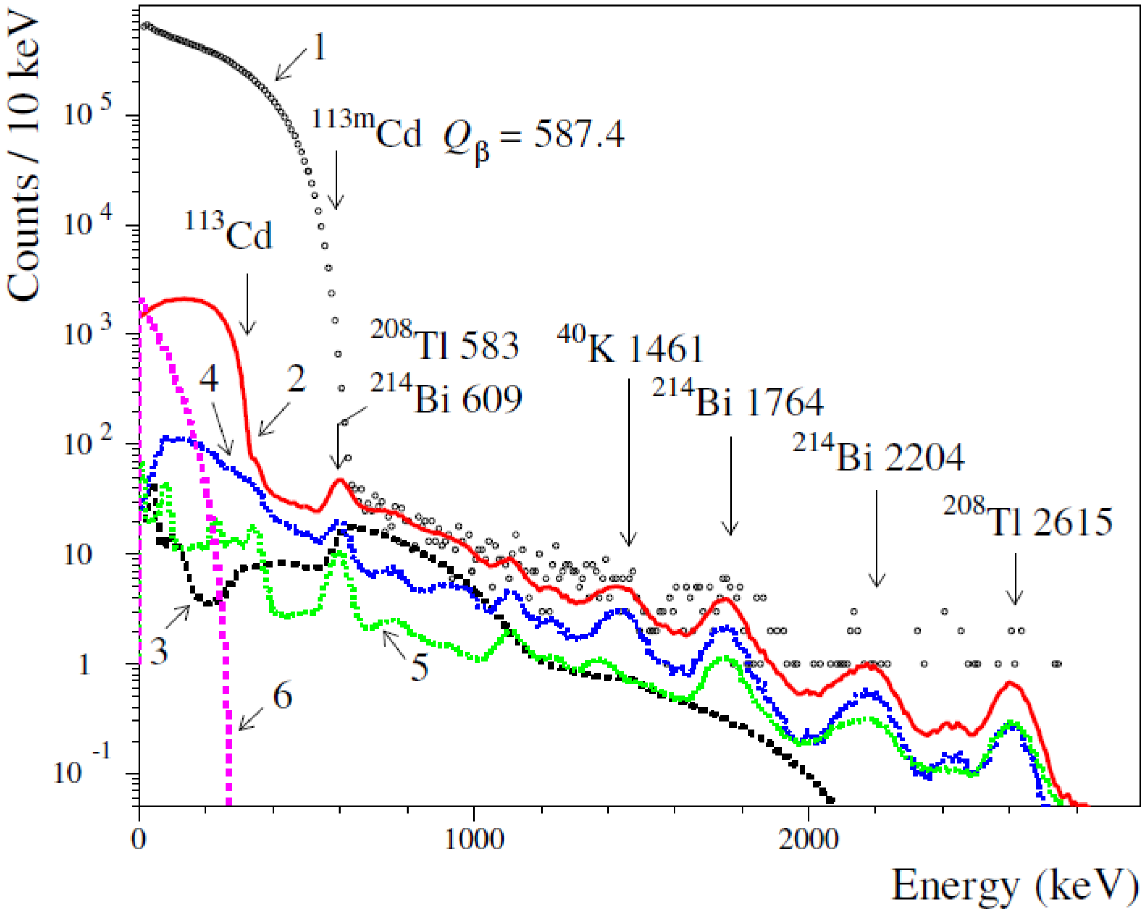
The energy spectrum of **β and γ events** measured by the low-background ^{106}CdWO$_4$ scintillation detector in 2023 for 340.9 h after rejection and correction for **NSSBG** events (**black circles, 1**).

The **model** of the radioactive background is shown by **red histogram** (2). The **main components** of the **background** model are:

- β spectrum of ^{113}Cd,
- radioactive contamination of the ^{106}CdWO$_4$ crystal scintillator (without the β spectrum of Cd, 3);
- radioactive contamination of the copper shield, PMTs, PTFE details and the plastic light guide (4),
- background due to the radioactive contamination of the silicone oil (5).

A β spectrum of ^{87}Rb corresponding to the concentration 70 ppb in the ^{106}CdWO$_4$ crystal (limit of the ICP-MS analysis) is shown (6).

The β spectrum of ^{113m}Cd dominates in the data with a signal-to-background ratio equal to 294 in the energy interval (100 – 580) keV.



First Experimental Determination of the ^{113m}Cd β Spectral Shape

Energy distribution of the electrons emitted in the β decay of ^{113m}Cd:

$$\rho(E) = \underbrace{w \cdot p \cdot F(E,Z) \cdot (Q_\beta - E)^2}_{\text{Allowed β decay shape}} \cdot C(w),$$

Fermi function

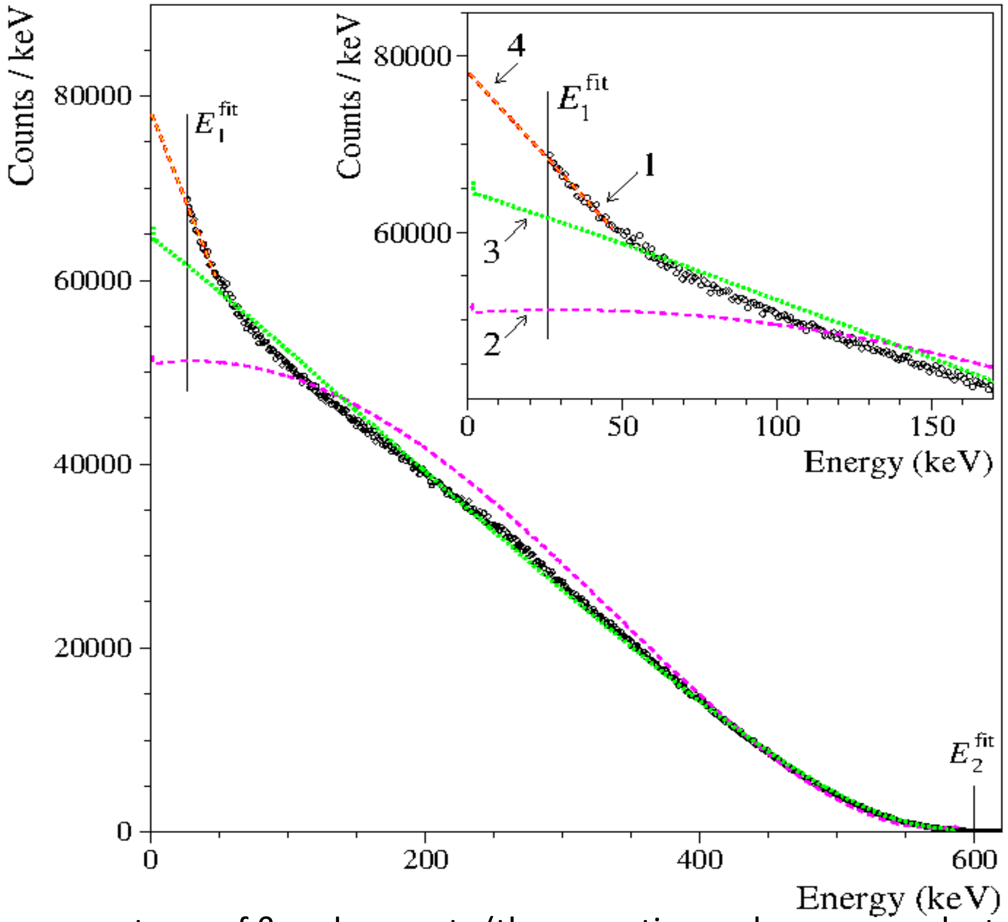
Correction factor

$$C(w) = 1 + \epsilon_1/w + \epsilon_2 \cdot w + \epsilon_3 \cdot w^2,$$

$w = E/m_ec^2+1$; E = kinetic Energy, $p = \text{sqrt}(w^2-1)$
ϵ_i are fitting parameters.

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

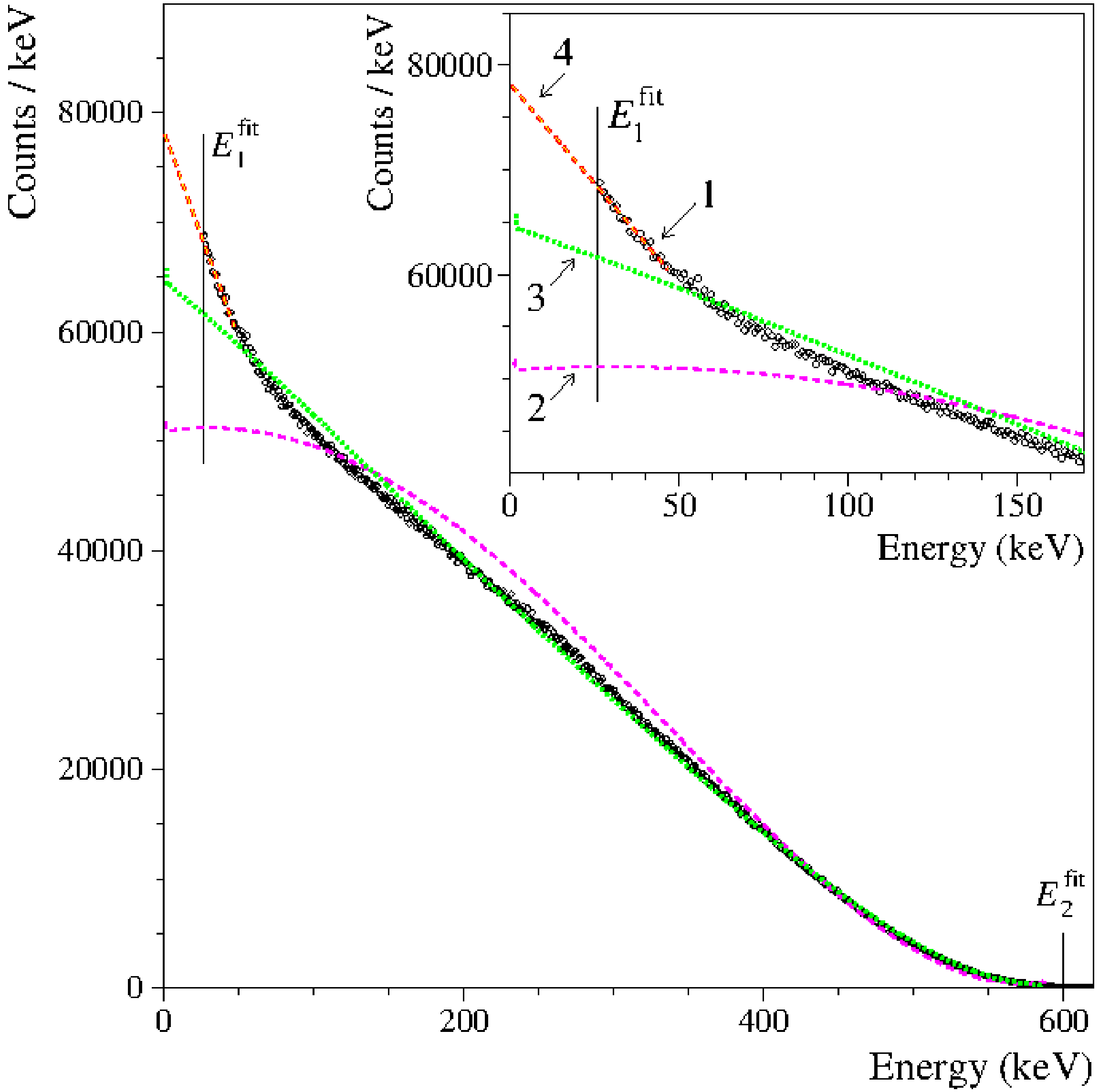
$$f(E) = \int_0^{Q_\beta} \rho(E') \cdot R(E,E')dE'$$



Energy spectrum of β and γ events (the meantime values were selected within ⟨t⟩ ± 3σ⟨t⟩) measured by the low-background ^{106}CdWO$_4$ scintillation detector in 2023 for 340.9 h, after correction on presence of NSSBG events and subtraction of radioactive background (black circles, the spectrum is labelled as 1 in Inset, where a low energy part of the data is shown). Fit of the data in the energy interval $E^{fit}_1 - E^{fit}_2$ (26 – 600 keV) by two functions are shown: 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.

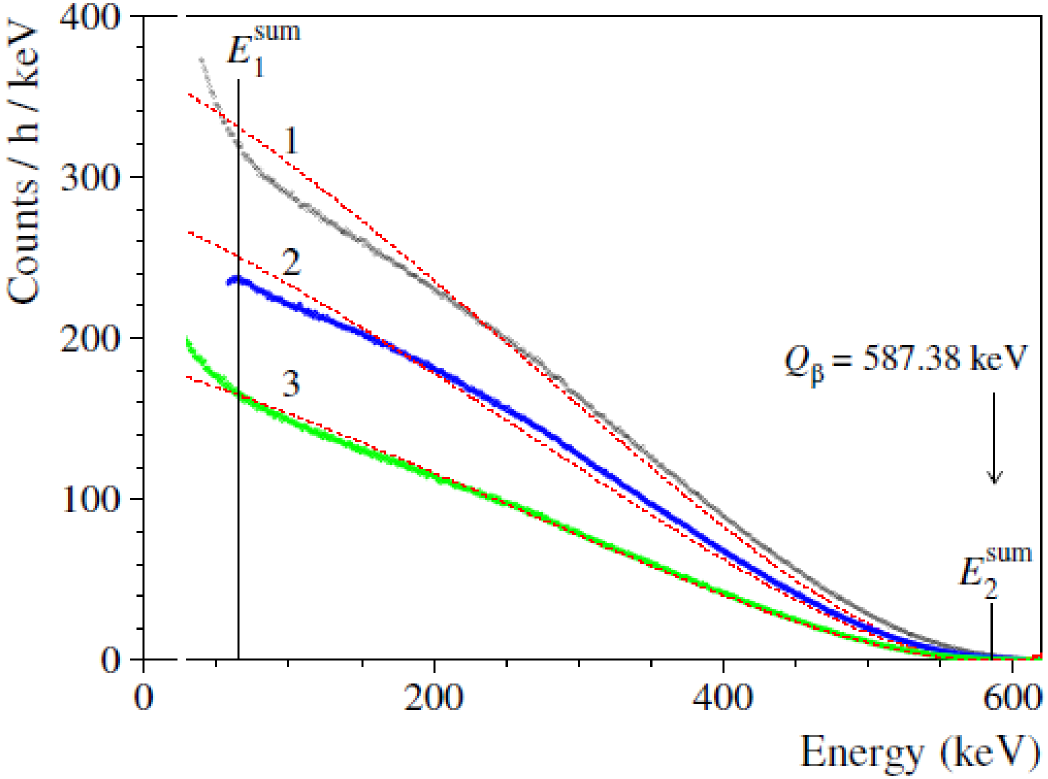
Theoretical Interpretation and Axial Coupling g_A

- Comparison with the considered models indicates that the data are best described assuming a quenched axial-vector coupling constant of $\mathbf{g_A \approx 0.8}$ **(or lover)**
- Supports quenching of g_A and provides new nuclear structure constraints.
- **Further theoretical** calculations of β-spectral shape **are in progress**
- **Further studies** with improved experimental setup **are in progress**



The half-life of ^{113m}Cd relative to β decay to the ground state of ^{113}In

Run Year	Live Time (h)	Count Rate (counts/s)
2009	248.0 ± 1.0	0.1627 ± 0.0008
2015	392 ± 6	0.1513 ± 0.0006
2023	340.9 ± 3.4	0.1436 ± 0.0007



Energy spectra of β(γ) events measured by low-background ^{106}CdWO$_4$ scintillation detectors in **2009** (**black** points, **1**), **2015** (blue points, 2) and **2023** (green points, 3), after rejection and correction for NSSBG events, subtraction of radioactive background, and normalization on the time of measurements. 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 ^{113m}Cd the counting rates in the deconvoluted spectra were calculated in the energy interval E^{sum}_1–E^{sum}_2 [(64 – 587) keV].

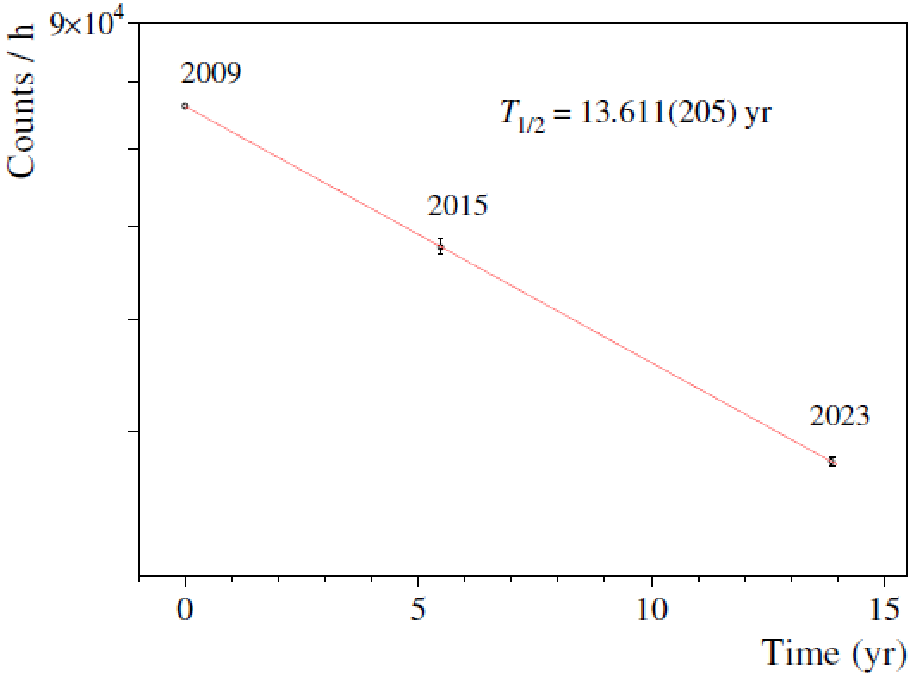
Result: Half-life of ^{113m}Cd β Decay

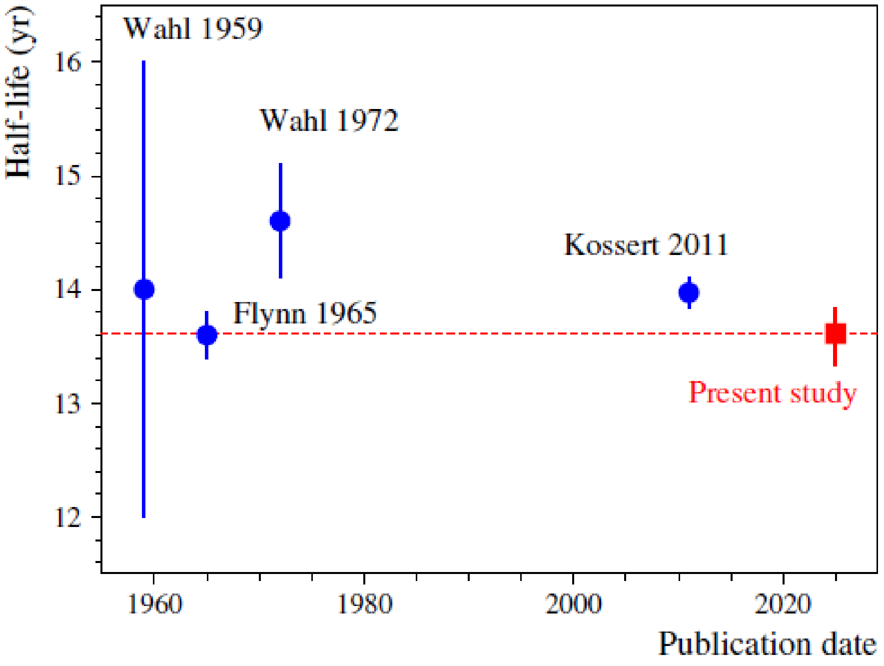
Exponential decay fit over 3 points (2009, 2015, 2023):

$R(t) = R_0\, e^{-t/\tau} \;\Rightarrow\; T_{1/2} = \tau \ln(2)$

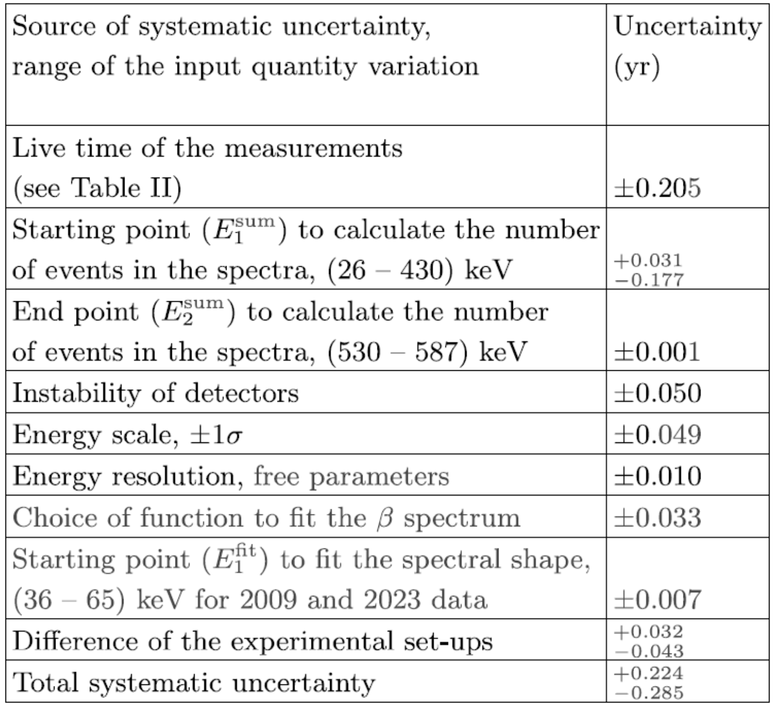
result:

$$T_{\frac{1}{2}} = 13.61^{+0,22}_{-0,29}\ \text{yr}$$





Historical perspective of the ^{113m}Cd half-life as a function of the publication date Red square and red dashed line show the half-life obtained in the present study. It should be noted that **systematic uncertainties** were **not estimated** in the **previous** experiments, unlike the present one.

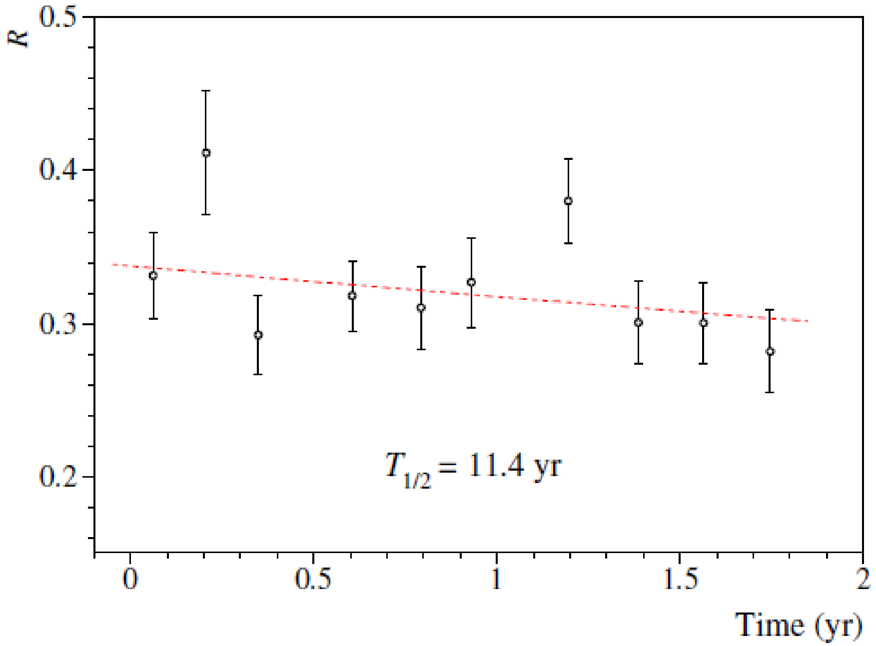


Source of systematic uncertainty, range of the input quantity variation	Uncertainty (yr)
Live time of the measurements (see Table II)	±0.205
Starting point (E_1^{sum}) to calculate the number of events in the spectra, (26 – 430) keV	$^{+0.031}_{-0.177}$
End point (E_2^{sum}) to calculate the number of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

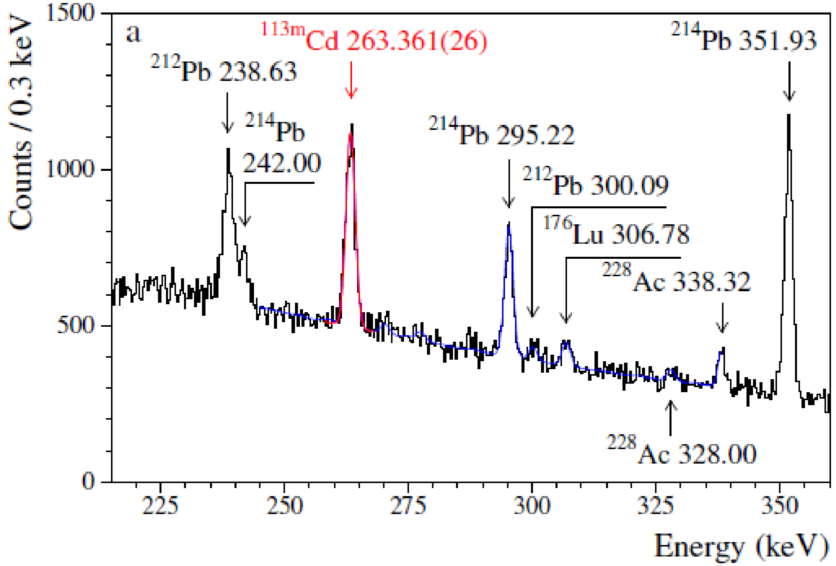
HPGe Study of the ^{113m}Cd → ^{113}Cd IT Decay

By product

- Objective: characterize the isomeric transition (IT) of ^{113m}Cd via γ detection.
- Setup: ^{106}CdWO4 crystal placed in HPGe detector array at LNGS (STELLA facility) [2].
- Crystal acts as γ source; shielded with Cu, Pb, and PMMA flushed with N_2.
- Detected γ energy: (263.24 ± 0.03) keV.
- Corrected detection efficiency: (3.077 ± 0.005)%.



Decrease of the isomeric transition γ-quanta counting rate in time. R is a ratio of the 263.4-keV peak area to the whole area of the γ peaks of **^{214}Pb** and **^{214}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 the half-life 11.4 yr is shown by red solid line.



Sum energy spectrum measured for 12843 h by four-crystal HPGe detector system with the ^{106}CdWO$_4$ scintillation detector in [2]. The γ peak with energy 263.361(26) keV emitted in the isomeric transition of ^{113m}Cd to the ground state of ^{113}Cd, and the most intense background γ peaks are shown. The energy of the γ peaks is in keV.

[2] Phys. Rev. C.93 045502

IT Branching Ratio of ^{113m}Cd Decay: Result and Comparison

By product

- Measured branching ratio: $BR_{IT} = (0.0790 \pm 0.0021)\%$

- Higher precision than previous measurements.

- Confirms that β decay dominates over IT decay for ^{113m}Cd.

Value significantly lower than:
Tabulated value (~0.14%) [4]
Kossert et al. (2011) result: 0.104(8)% [5]

- Relevant for background modeling in rare-event searches with Cd-based detectors.

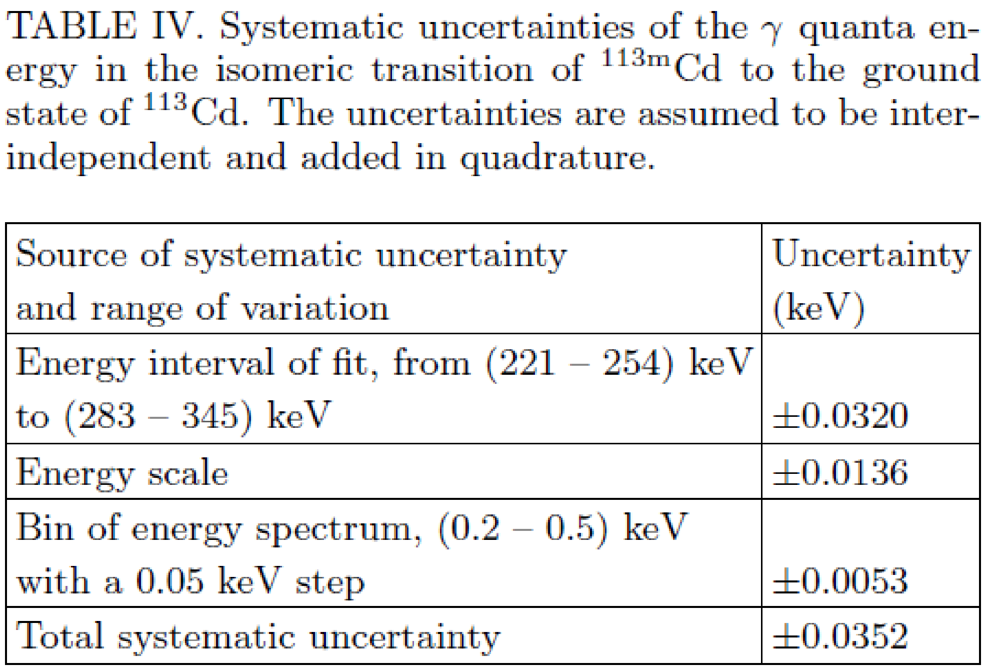


TABLE IV. Systematic uncertainties of the γ quanta energy in the isomeric transition of ^{113m}Cd to the ground state of ^{113}Cd. The uncertainties are assumed to be inter-independent and added in quadrature.

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

[4] Phys. Rev. C 186, 1285 (1969).
[5] Radiat. Isot. 69, 5001195 (2011).

Summary and Conclusions

A detailed experimental study of the **β decay of the ^{113m}Cd isomeric state** was performed using a low-background **^{106}CdWO$_4$ scintillation detector** over three separate data-taking periods: 2009, 2015, and 2023.

For the **first time**, the **β energy spectrum of ^{113m}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 $\mathbf{g_A \approx 0.8}$.

The **half-life** of the β decay to the ground state of ^{113}In was determined as:
$\boldsymbol{T_{\frac{1}{2}} = 13.61^{+0{,}22}_{-0{,}29}}$ **yr** (systematic uncertainties were not estimated in the previous experiments).

The **IT branching ratio** to the first excited state of ^{113}Cd was measured using HPGe detectors, yielding:
BR_{IT}=(0.0792 ± 0.0021)% (tabulated value (~0.14%); Kossert et al. (2011) result: 0.104(8)%)

These results provide **critical inputs for nuclear theory**, particularly in the modeling of **forbidden non-unique β decays**, and are relevant for **background modeling** in rare-event searches using cadmium-based detectors.

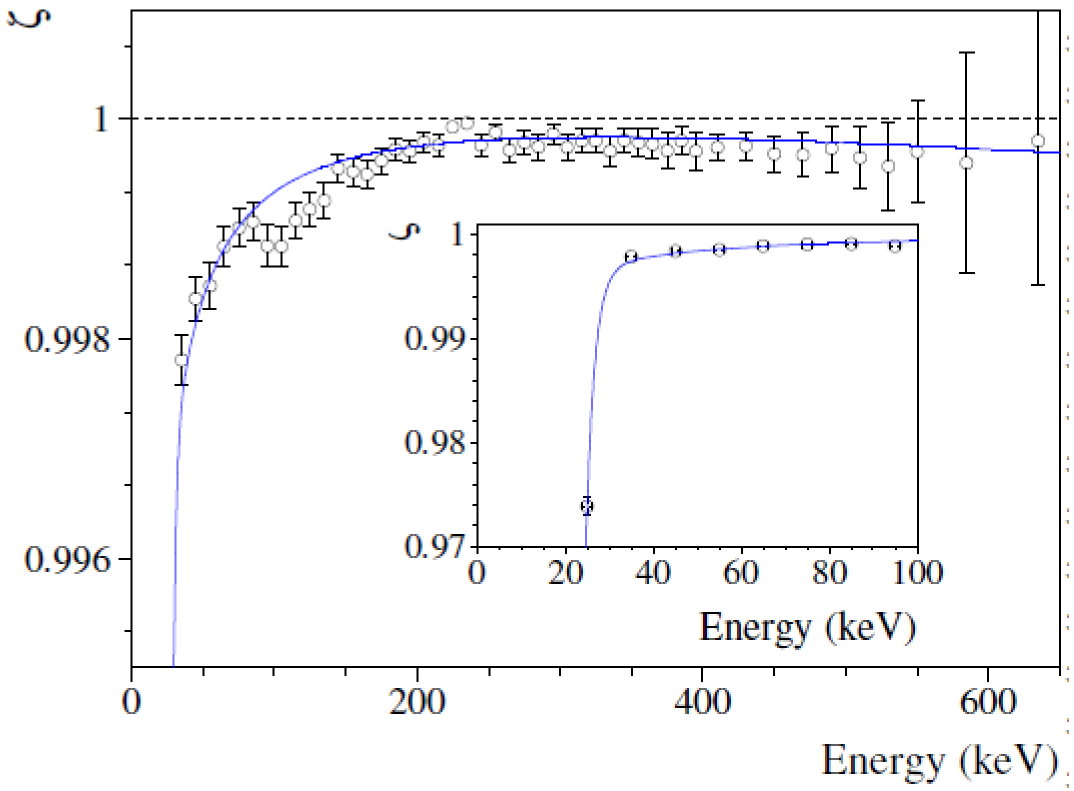


FIG. 7. Energy dependence of the parameter ζ that takes into account contribution of NSSBG events to the spectrum of β and γ events in the mean-time interval $\langle t\rangle \pm 3\sigma_{\langle t\rangle}$ for the data measured in 2023 for 340.9 h (see text for explanation of the parameter ζ). The approximation of the variable ζ by the function Eq. 5 is shown by solid blue line. Inset: the low energy part of the dependence.

ζ is a ratio $(S_{\beta+\gamma} - S_i)/S_{\beta+\gamma}$, where $S_{\beta+\gamma}$ is the number of events in the distribution of β and γ events, and S_i is the number of NSSBG events (both are in the mean-time interval ⟨t⟩

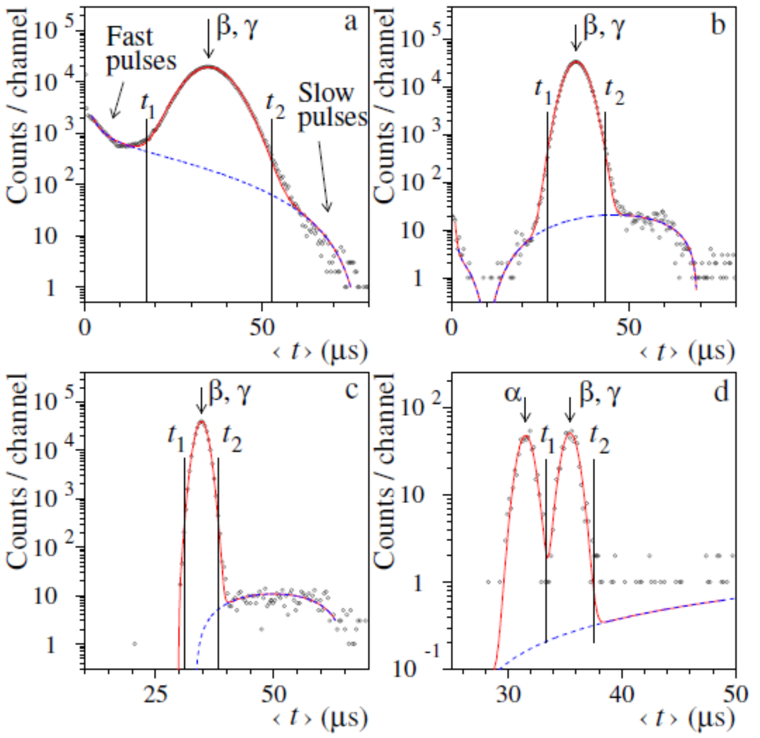


FIG. 5. Distributions of the mean-time parameter $\langle t\rangle$ for the data taken with the ^{106}CdWO$_4$ scintillation detector for 340.9 h in 2023 in the energy intervals (20 – 30) keV (a), (60 – 70) keV (b), (290 – 300) keV (c), and (700 – 1000) keV (d). The distributions are fitted by Gaussian function plus functions (exponent plus polynomial for the distributions a and b, and polynomial ones for the data c and d) to describe the contributions of the fast and slow interfering NSSBG events. The contribution of the NSSBG events to the region of β and γ events within $\langle t\rangle \pm 3\sigma_{\langle t\rangle}$ (shown by vertical lines labelled t_1 and t_2) does not exceed 2.62%, 0.116%, 0.008%, and 1.2% for the data presented in panels a, b, c, and d, respectively.