Exploring the Isomeric Decay of ^{180m}Ta with the MAJORANA DEMONSTRATOR:

New Insights from the Second Year of Data

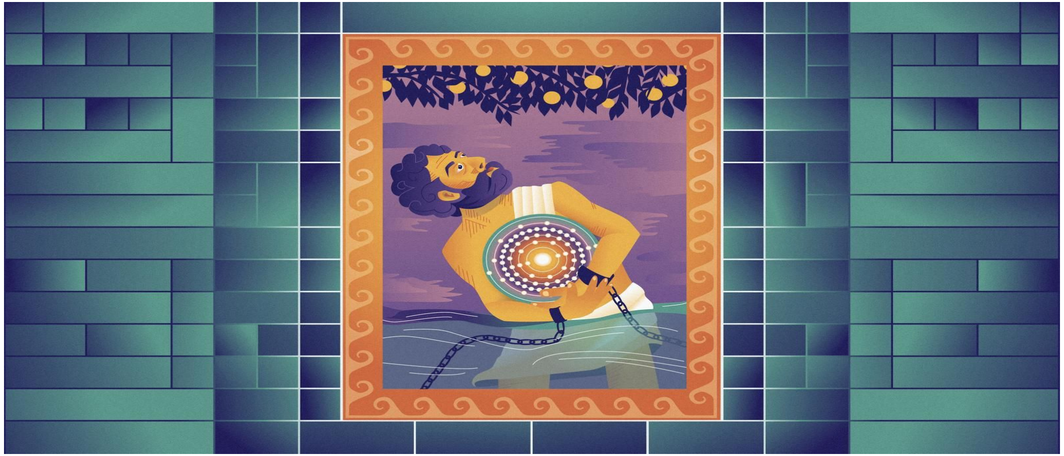
Ralph Massarczyk (LANL)

LA-UR-24-31756

Los Alamos NATIONAL LABORATORY EST.1943

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

A bit of (ancient) history…



Tantalus trapped as punishment.

Illustration from www.symmetrymagazine.org/article/majorana-demonstrator-finds-tantalizing-new-purpose

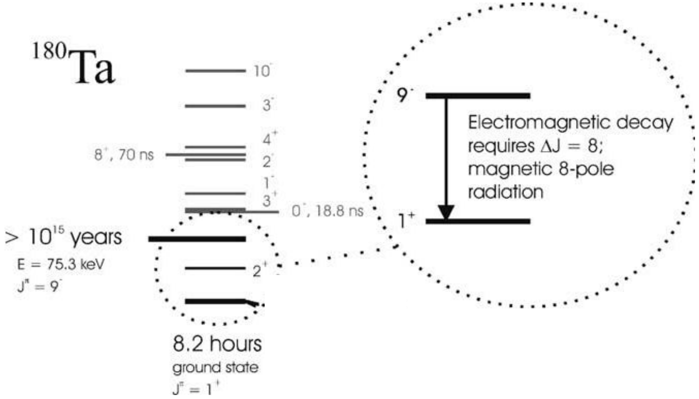
In greek mythology **Tantalus** offended the gods…

… so he was punished to be **trapped** in a pond under a fruit tree.

He could **not** reach **up** to eat.

He could **not** lean **down** to drink.

A bit of (modern) history…



Level scheme of ^{180m}Ta

Ta used in the experiment

For nuclear physics **Tantalum** *(named 1802)* is one of the rarest elements and has two isotopes…

… one of them (^{180m}Ta) is **trapped** in an isomeric state while the ground state decays.

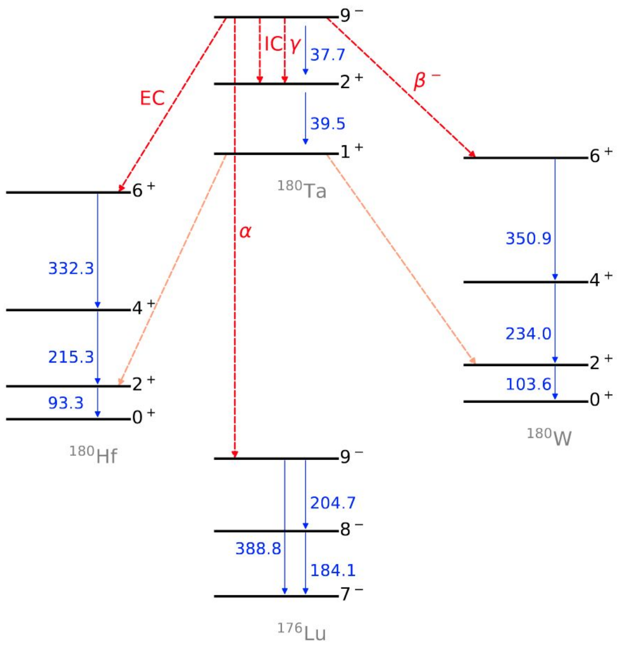
It can **not** go to a **higher** state due to energy.

It can **not** go down to a **lower** state due to spins

Variety of physics studies in the Tantalum system

- The origin of Tantalum in the universe :
  - Study helps to understand the observed abundance of ^{180m}Ta within a wider nucleosynthesis framework
  - Understand which candidate processes are strong enough to produce Ta (ν*-interactions, thermal excitation in early universe*)

- Longest lived metastable state never observed to decay
  - **Most extreme case to study nuclear structure spin traps**
  - Theory varies on predictions for half-life
  - Variety of transitions possible:
    β-decay , electron capture (EC), internal conversion, γ-transition, α-decay
  - **Ground-state ^{180}Ta is unstable ($T_{1/2}$ ~ 8 hours)**



Decay scheme of ^{180m}Ta with possible decay channels (red) and detection signatures (blue)

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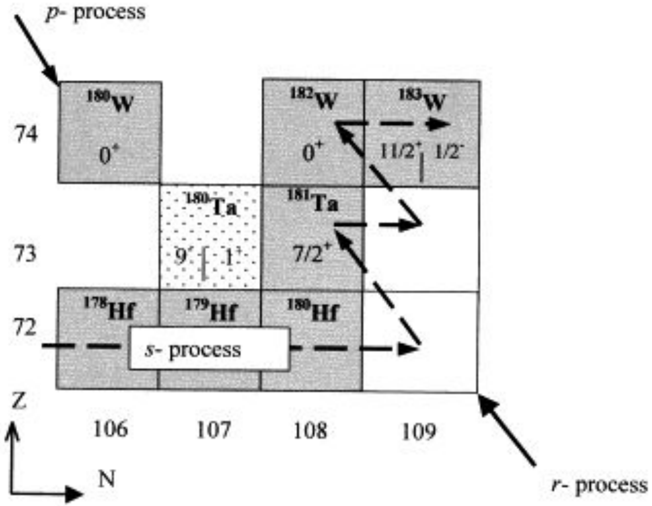

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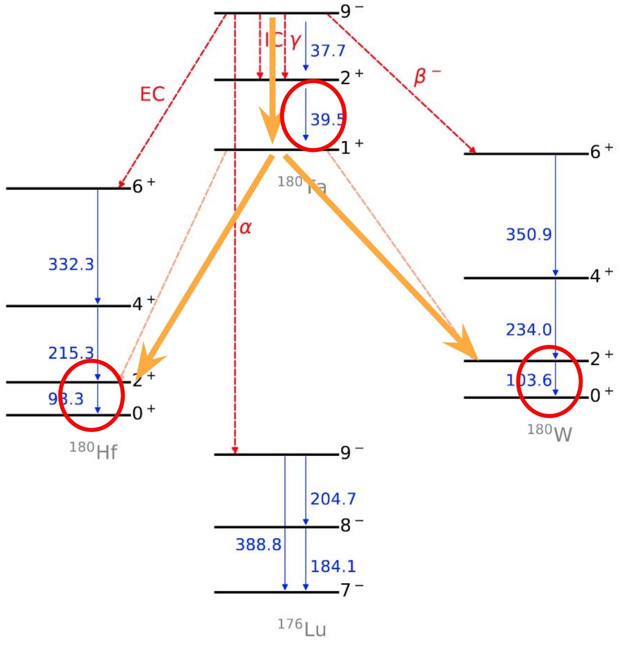

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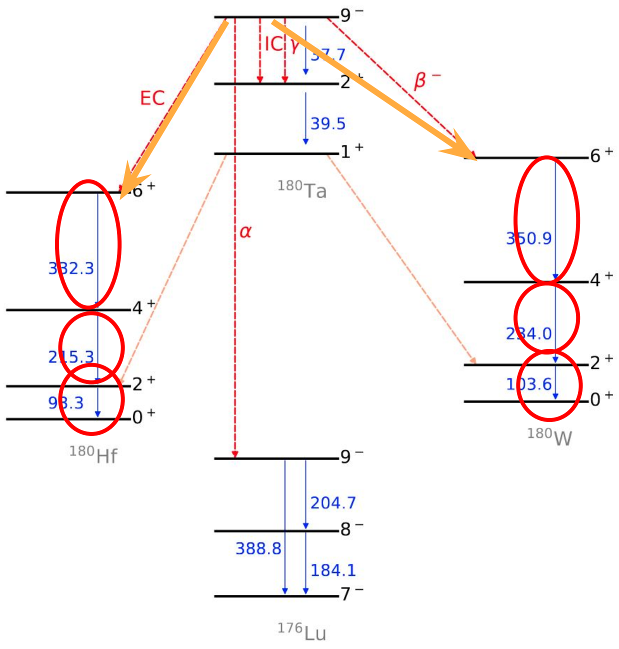

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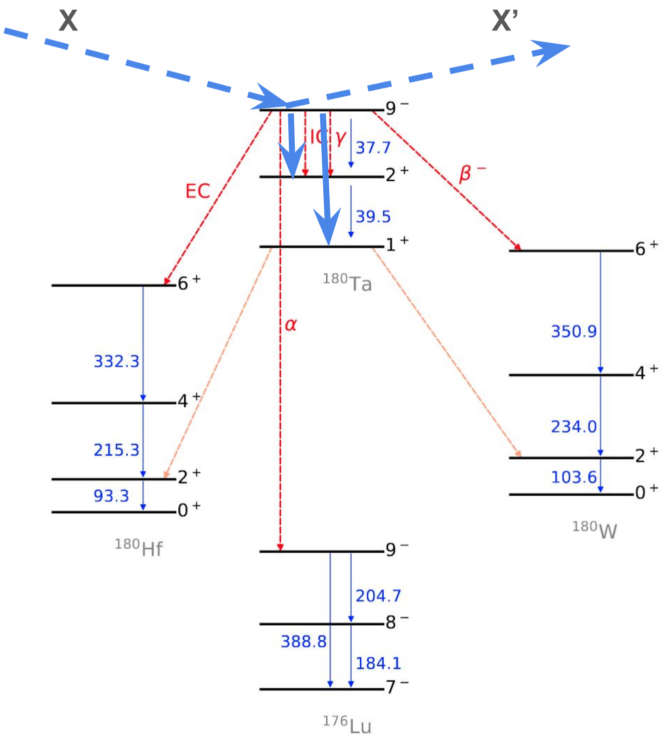
- Search for Dark Matter interaction
  - Additional energy from the isomer allows reaction with particles that would not interact otherwise
  - Candidates: **Strongly Interacting DM, Inelastic DM**



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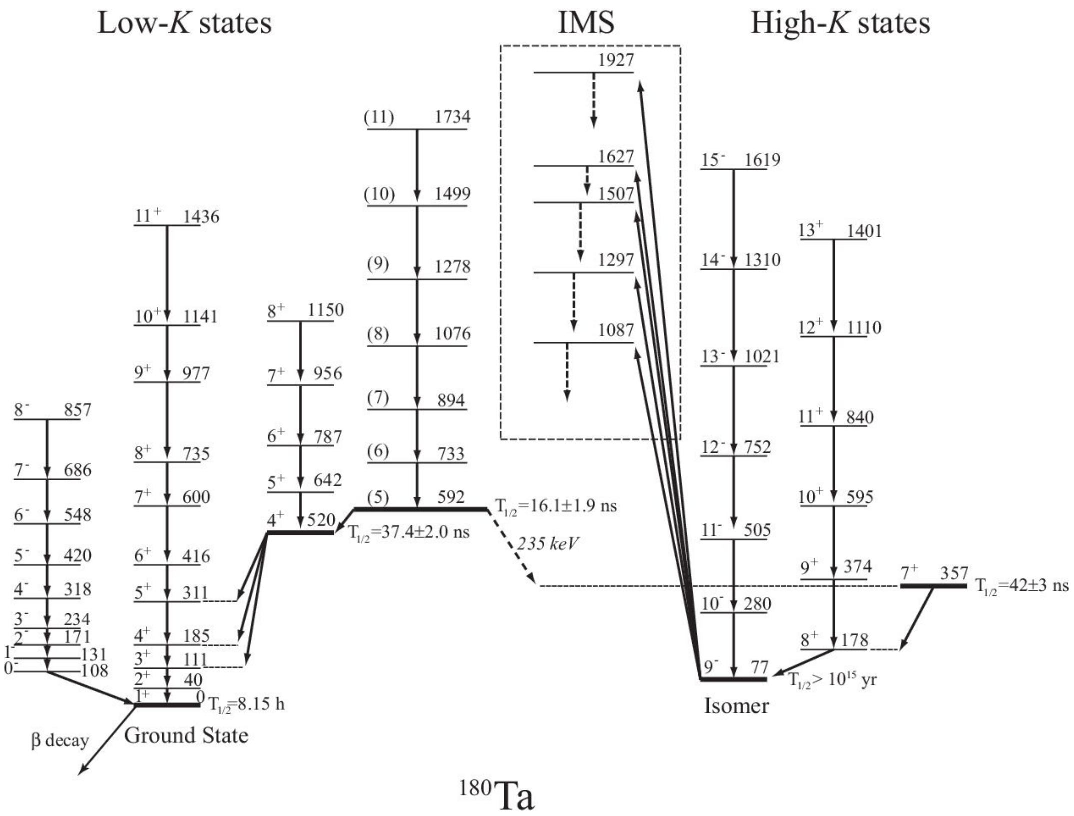
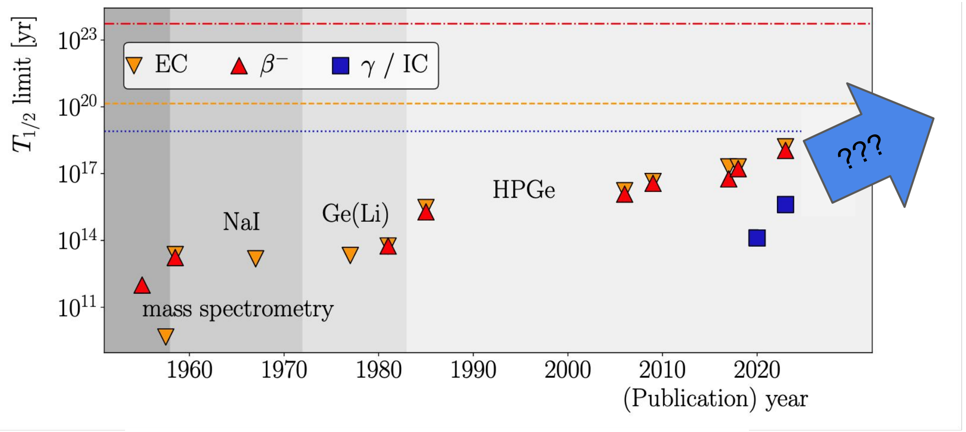


What is needed for a measurement…

Previous limits:

PRC 95, 044306 (2017)
2305.17238 (2023)



History of Tantalum decay measurements with predictions (dashed lines), from arxiv 2305.17238

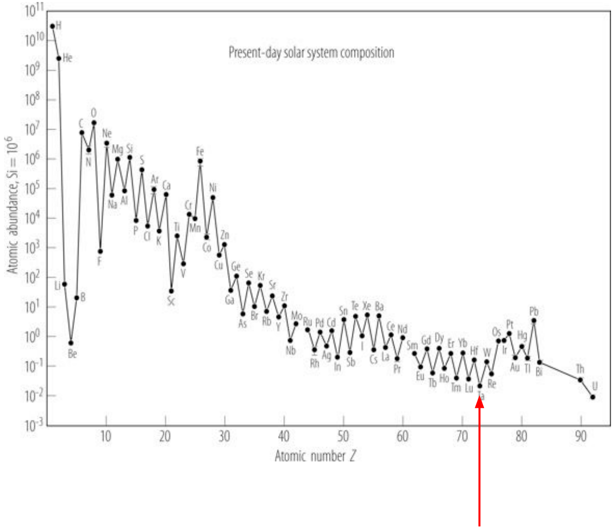
- Large exposure (material and time)
- Detector with excellent energy resolution
- If possible multiple detectors, that can detect coincidences
- A clean, ultra low-background system and environment

Perfect use of MJD facility after enriched detector removal

Tantalum – a rare element (isotope)

- 1 - 2 ppm of earth's crust is Ta
- 99.98% is ^{181}Ta
- Best previous measurement used ~1kg of ^{nat}Ta (~0.2 g of ^{180m}Ta)
- All the ^{180}Ta is metastable:

the only naturally occurring long-lived isomer

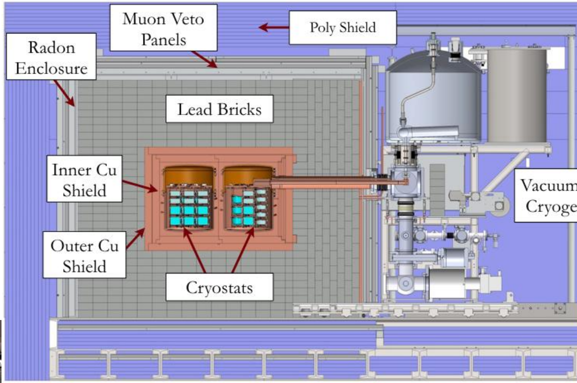


MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

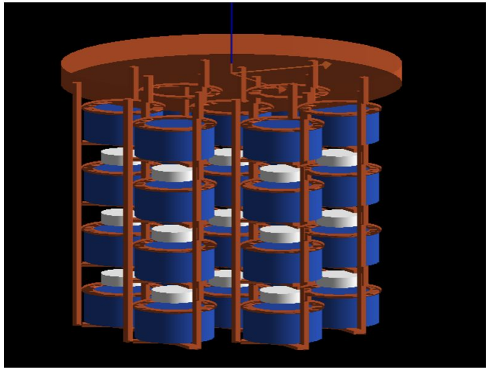
- Source & Detector:
  - Array of p-type, point contact detectors 30 kg of 88% enriched ^{76}Ge crystals
  - Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run
  - Enriched detectors removed in 2021 for LEGEND
  - **14 kg of natural Ge crystals**
- **Excellent Energy Resolution**: 2.5 keV FWHM @ 2039 keV
- Low **Analysis Threshold:** 1 keV
- **Low Background:** 2 modules within a compact graded shield and active muon veto using ultra-clean materials

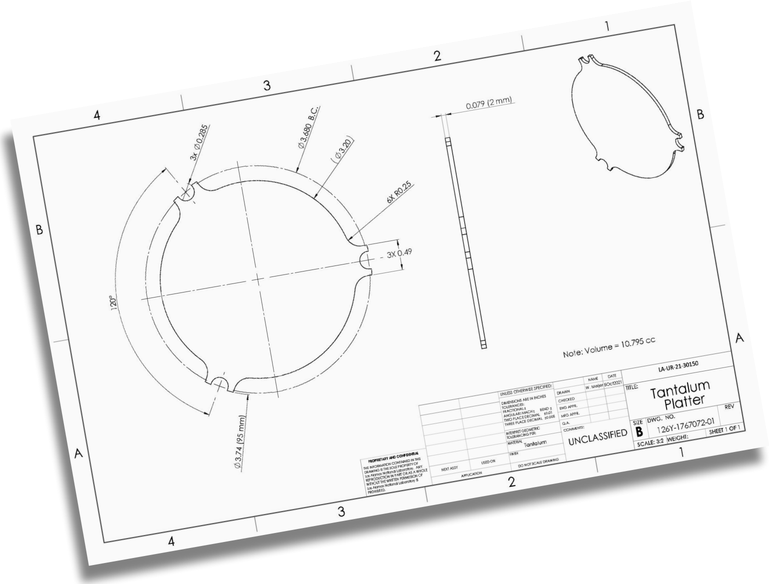
- **Final Result,** *(PRL 130, 062501, 2023)*
  - **65 kg-yr exposure**
  - Median $T_{1/2}$ Sensitivity: 8.1×10^{25} yr (90% C.I.)
  - Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I)

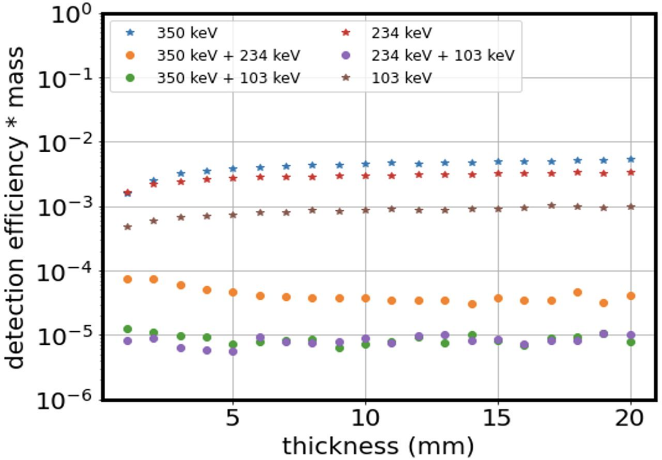


Reconfiguring of the DEMONSTRATOR

- Detectors and Ta arranged to maximize efficiency

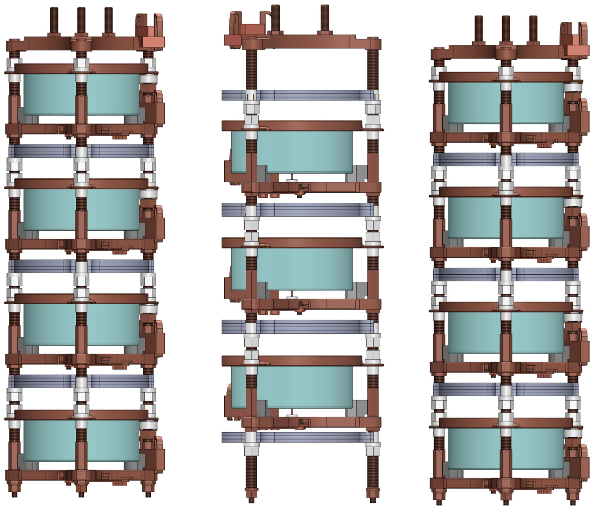


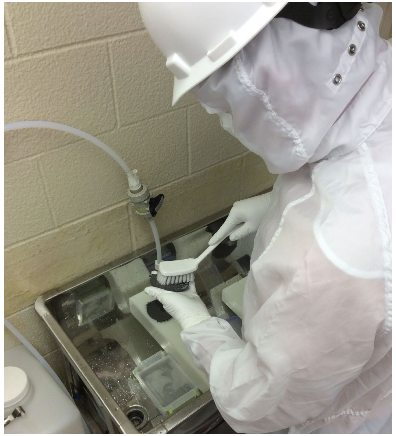




Reconfiguring of the DEMONSTRATOR

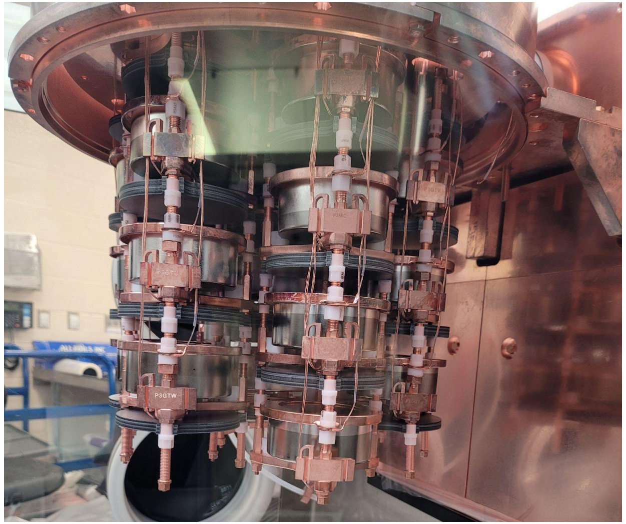
- Detectors and Ta arranged to maximize efficiency
- **17.4 kg installed** ~ 2 g ^{180m}Ta,
  (x10 more than best previous measurement)
- 23 active detectors
  (before only one or two HpGe setups)
- Operating since May 2022



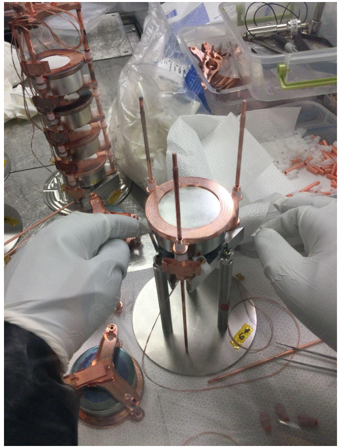


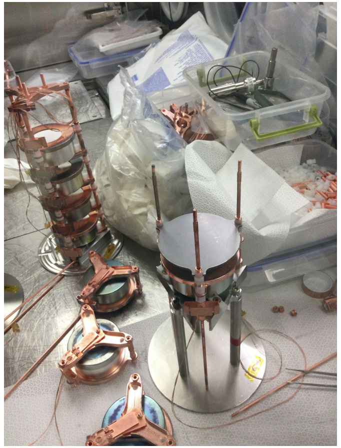
(left) cleaning and installation in the MJD strings

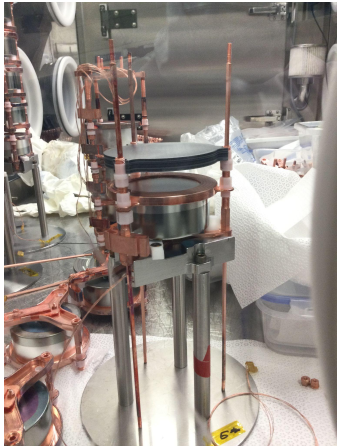
(right) schematic arrangement of detectors, green, and Ta, grey, and photograph of the full detector array

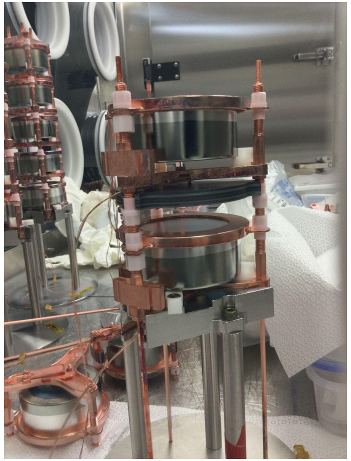


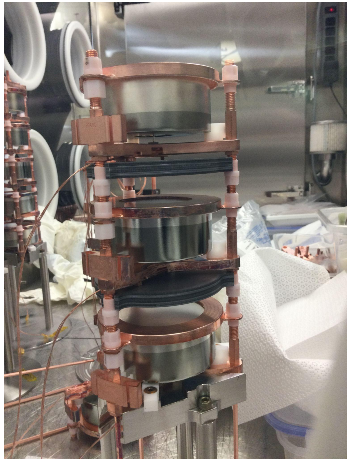
Installation





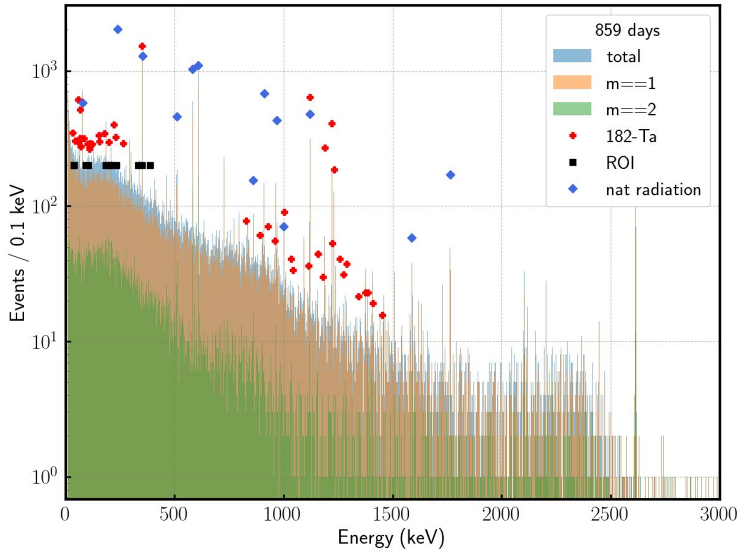


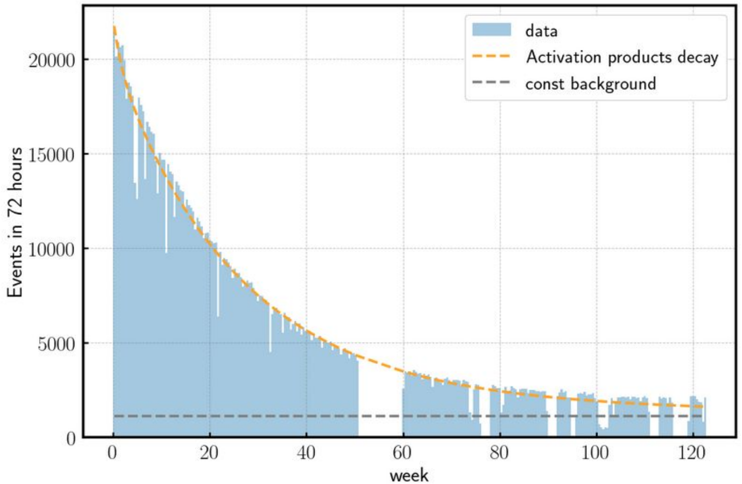




Data Overview and Analysis

- Data Set of 859 days (84.0% live)
- Background contributions from:
  - natural radioactivity within the Tantalum disks (< 0.5 mBq/kg_{Ta})
  - **surface activation in Ta**
    - ^{182}Ta ($T_{1/2}$ = 114 days)
    - ^{175}Hf ($T_{1/2}$ = 70 days)
- Background improving over time





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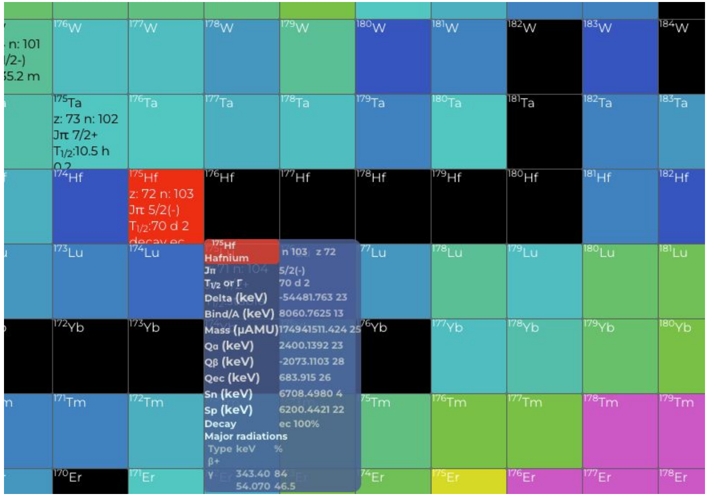
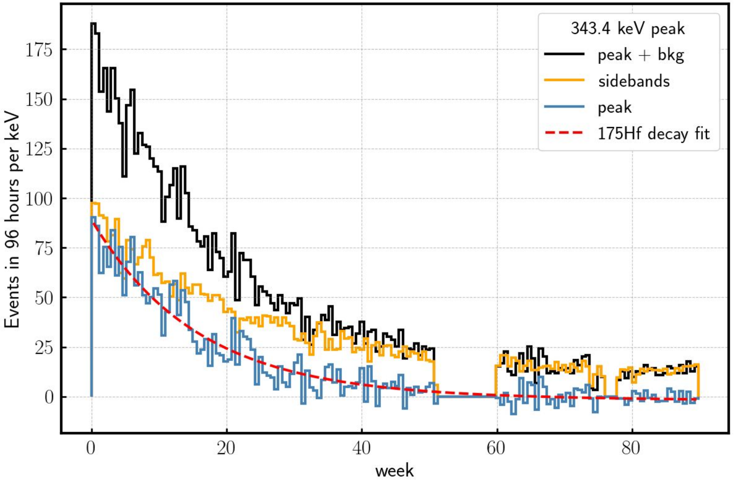
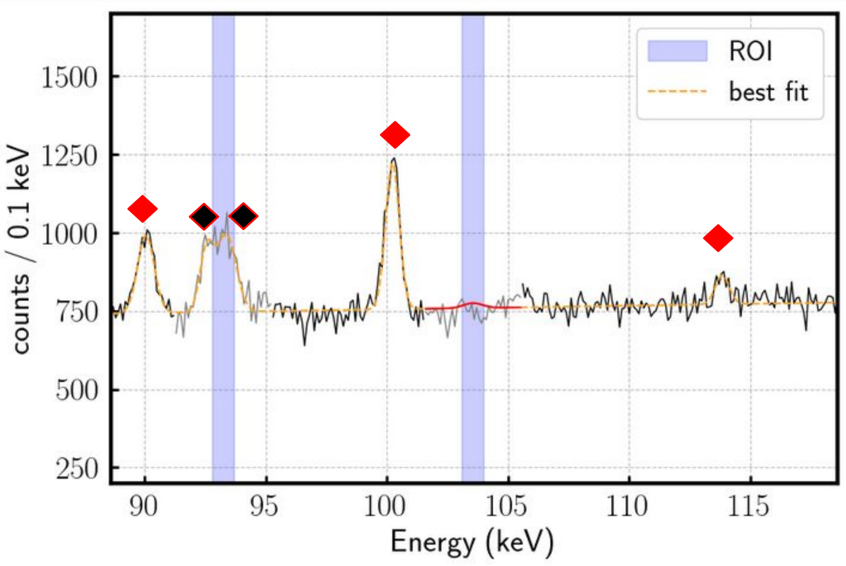
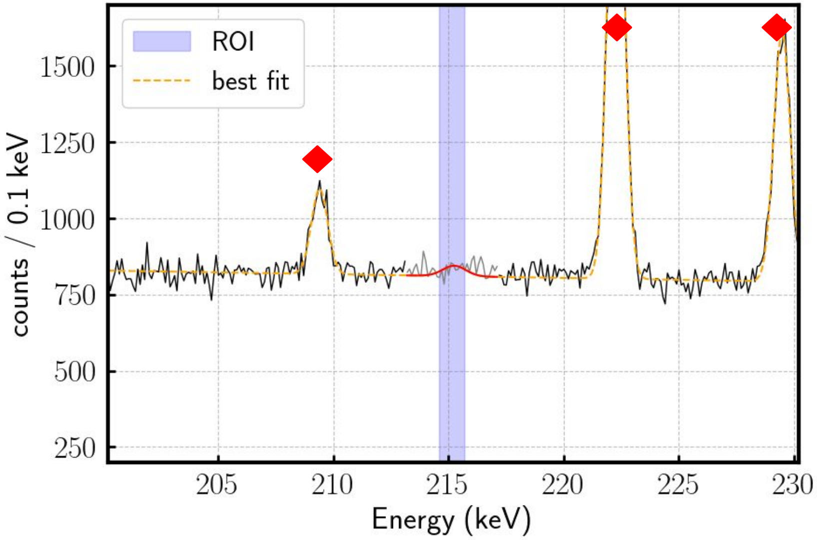




A look in a few region of interests – full data



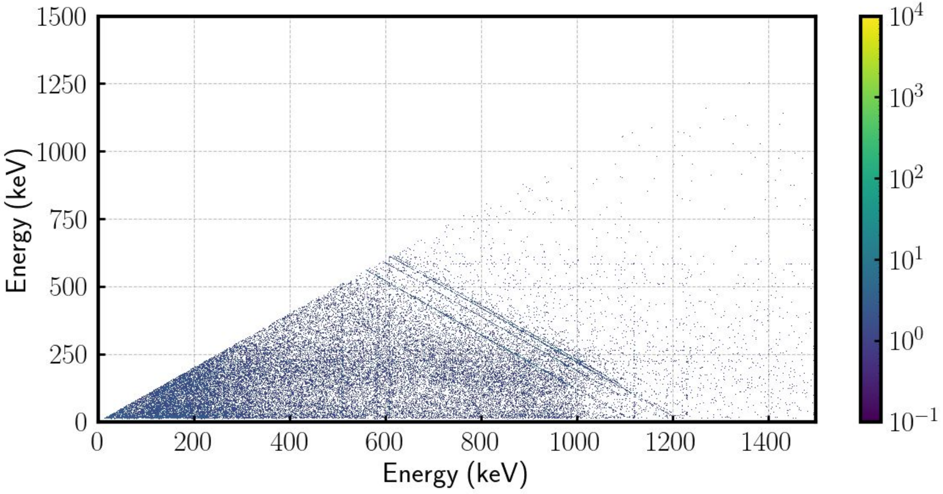
Signal region for deexcitations after β-decay

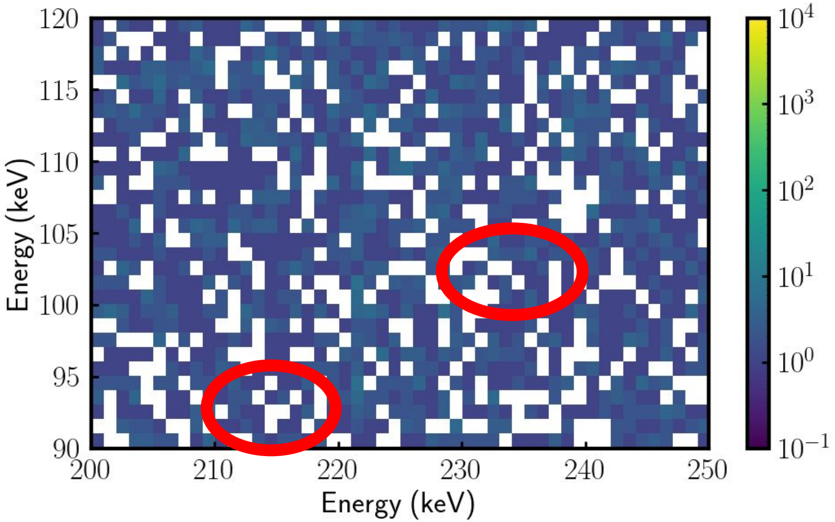


Signal region for deexcitations after electron capture

◆ ^{182}Ta
◆ U/Th decay chain

Multiplicity analysis





- Replaces search of individual signatures
- Efficiency lower
- Background much lower !

Updated results

- Current improvements
  - Efficiency (x 2-3)
  - Mass (x 12)
  - Background
- multiplicity analysis allows high sensitivity search

Previous limits:

PRC 95, 044306 (2017)
2305.17238 (2023)

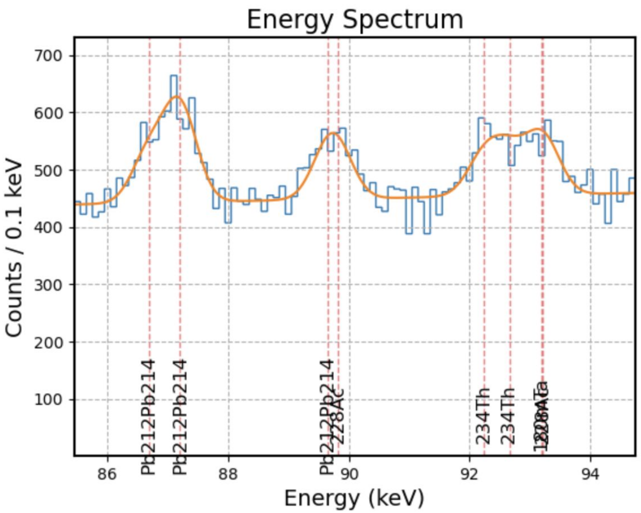
MAJORANA
PRL 131, 152501 (2023)

$$\lambda_{total} = \lambda_{EC} + \lambda_{\beta-} + \lambda_{\gamma} + \lambda_{IC} + \lambda_{\alpha} + \lambda_{DM}$$

	EC	β^-	γ	IC	α
Previous Limits	> 1.6 x 10^{18}	> 1.1 x 10^{18}	> 4.5 x 10^{14}	> 4.5 x 10^{14}	–
MJD - 2023	**> 1.3 x 10^{19} ****	**> 1.5 x 10^{19} ****	**> 6.0 x 10^{17}**	**> 2.9 x 10^{17}**	**> 1.1 x 10^{19} ****
Full data (preliminary)	***3.7 x 10^{19}***	***4.3 x 10^{19}***	***1.3 x 10^{18}***	***5.9 x 10^{17}***	***3.0 x 10^{19}***
Theory	10^{23}	10^{20}	10^{31}	10^{18}	10^{25}

Recent updates

- Before 1D spectral analysis
- Inclusion of correlated peak fits



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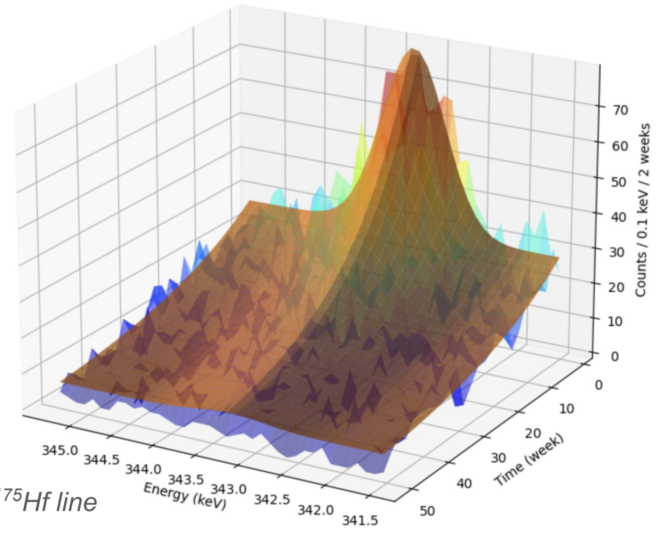
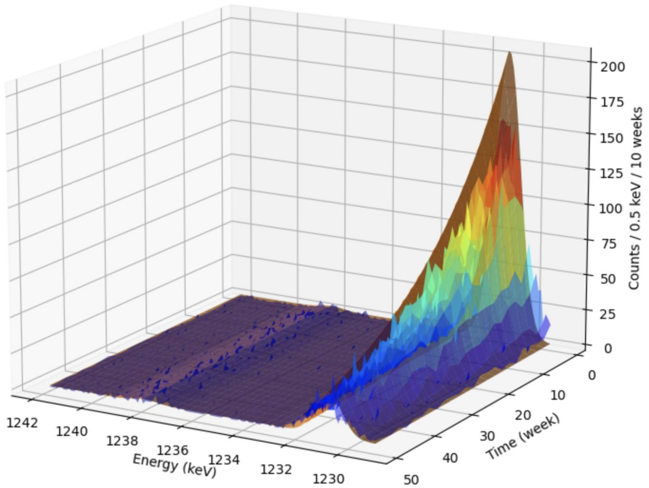
- Before 1D spectral analysis
- Inclusion of correlated peak fits
- Investigation in ^{175}Hf and other short lived
- Optimize sensitivity by using 2D fits in energy and time
  - Background – decaying component
  - Background – constant component
  - Signal – constant in time for Ta, or decaying for ^{175}Hf



Fit of the ^{175}Hf line



2D fit of constant signal on background in presence of other peaks

Recent updates

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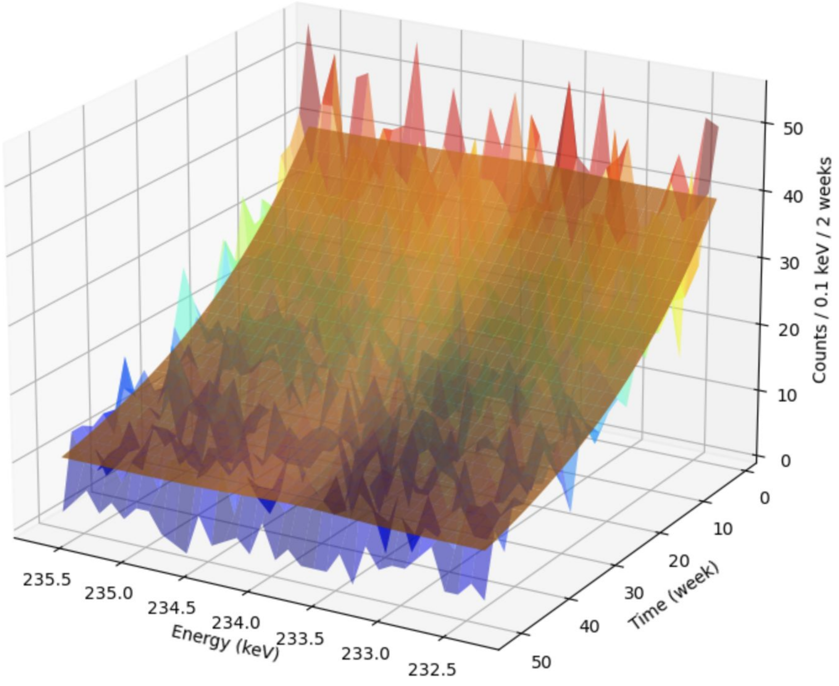
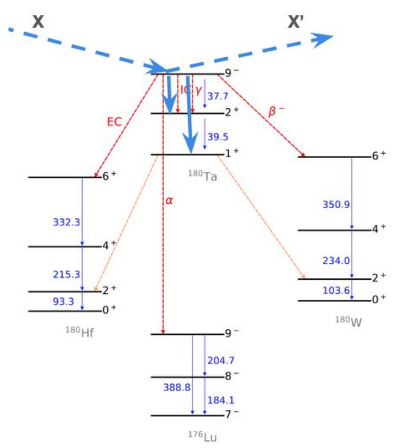
- Inclusion of correlated peak fits
- Investigation in ^{175}Hf and other short lived
- Optimize sensitivity by using 2D fits in energy and time
  - Background – decaying component
  - Background – constant component
  - Signal – constant in time for Ta, or decaying for ^{175}Hf
- 20-30 % improvement over 1D fits



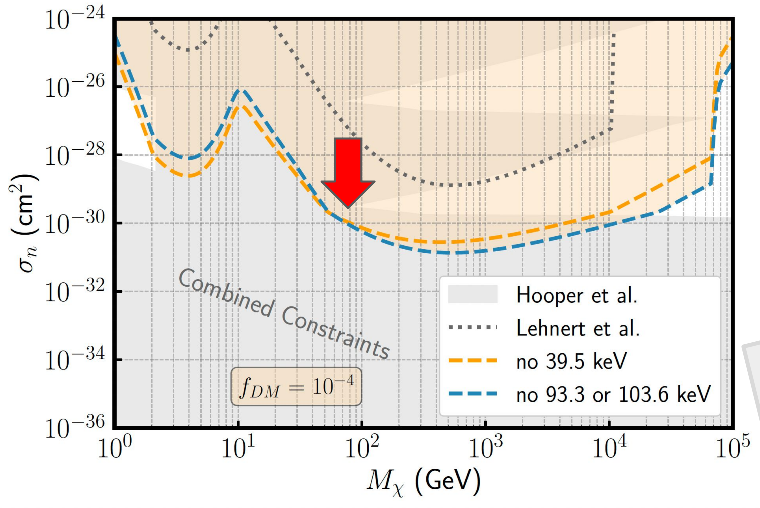
Makes use of all data

- Early data good background determination and statistics
- Later data: better signal to background ratio

Dark matter induced deexcitation

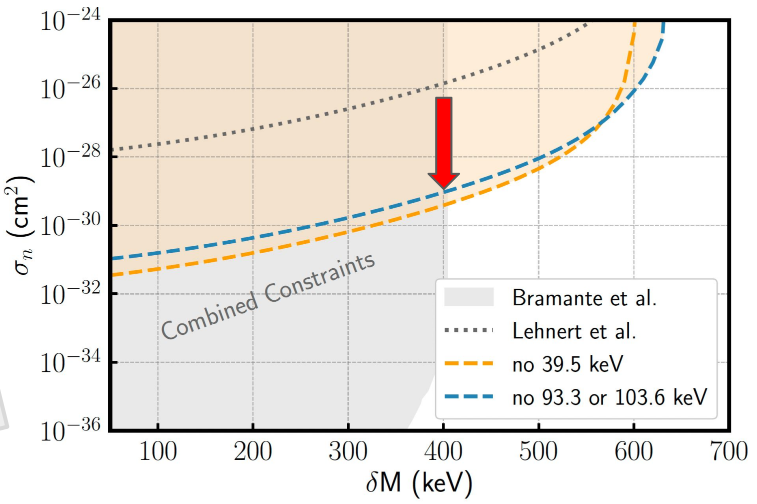


- No observation of ^{180m}Ta decay → no DM-induced decay
- Improved sensitivities to strongly interacting DM (siDM)
- Additional sensitivities to more complex DM with multiple states
- and/or particles via inelastic scattering



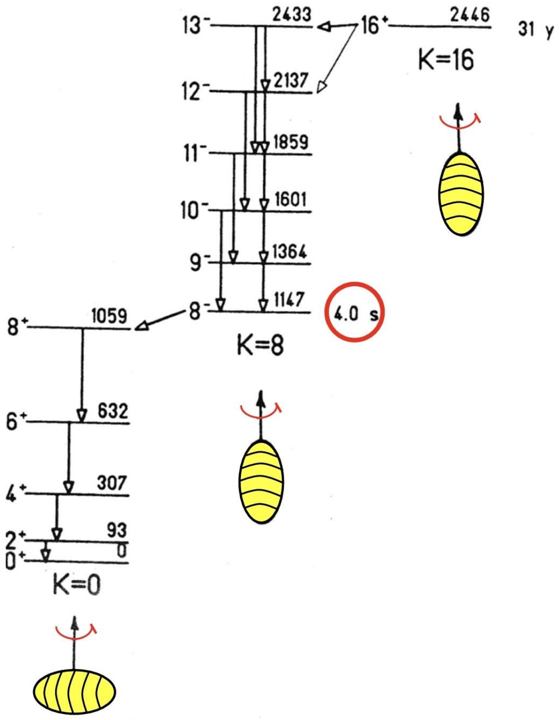
Limits on siDM (left) and inelastic scattering (right)

Previous limits:
PRL 124, 181802
PRD 94, 115026
PRD 97, 115006



Similar studies in other isomers

- Different approach
  - Short half life
  - High activity using a LANL in-house source
- Portable Ge detector, short measurement time (15m)
- Search for new transitions next to known transitions



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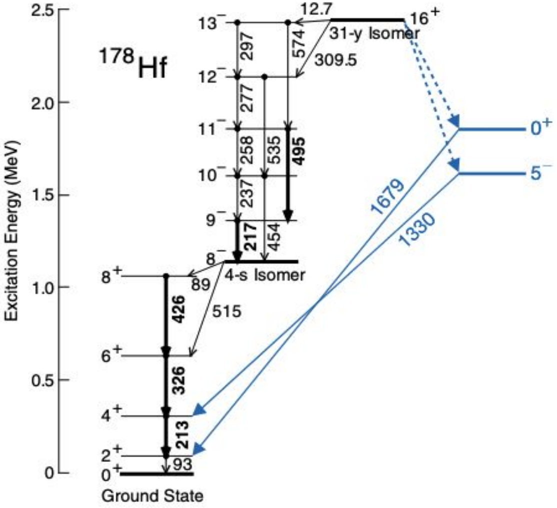

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$$\chi + {}^{178m}\mathrm{Hf} \rightarrow \chi^* + {}^{178}\mathrm{Hf}_j$$

PHYSICAL REVIEW LETTERS **131,** 141801 (2023)

Editors' Suggestion

Dark Matter Constraints from Isomeric ^{178m}Hf

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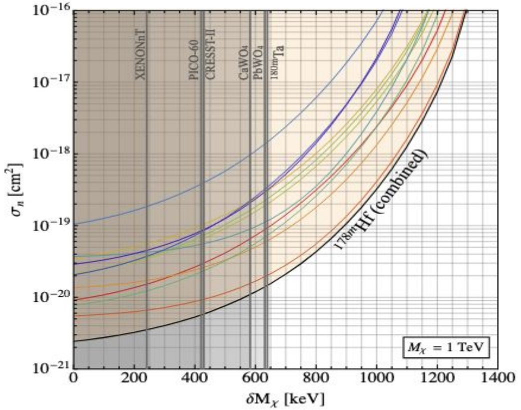
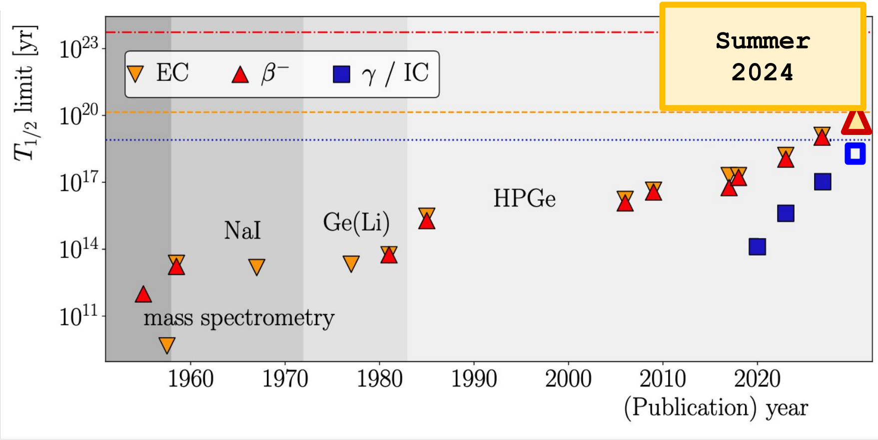
(Received 7 June 2023; revised 10 August 2023; accepted 11 September 2023; published 5 October 2023)

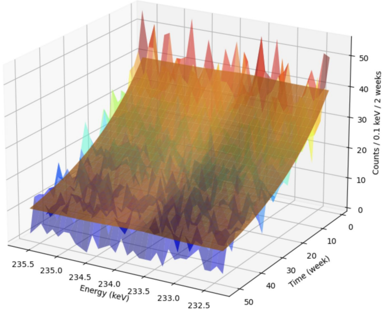
We describe a first measurement of the radiation from a ^{178m}Hf sample to search for dark matter. The γ flux from this sample, possessed by Los Alamos National Laboratory nuclear chemistry, was measured



Summary

- Most sensitive search for half-life measurements in isomers world-wide
- Data improved previous measurements by 1-2 orders of magnitude
- Background continues to improve
- Expect final results at the end of project Spring 2025





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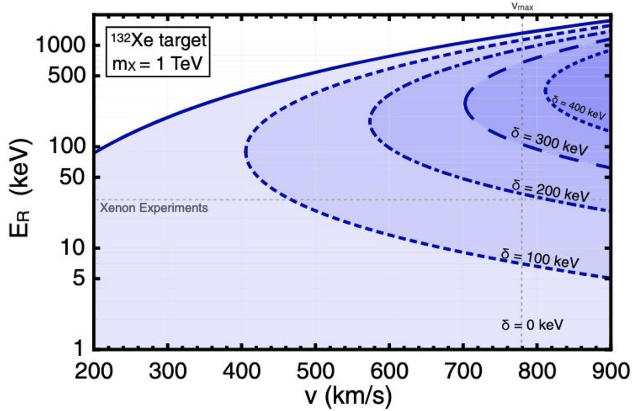
Inelastic dark matter motivation

- What if the DM species evade direct detection ?
- Production in colliders possible, but very low
- No reason that there is no a whole DM zoo of particles or composite DM
- Based on Tucker-Smith & Weiner (2001) or Alves et al (2010)
- Requires additional “energy” in the system
  - Sufficiently fast DM interacts with standard detectors measuring nuclear recoils
    OR



Recoil energy as a function of incoming DM velocity for non-isomers

Detect recoil E_r