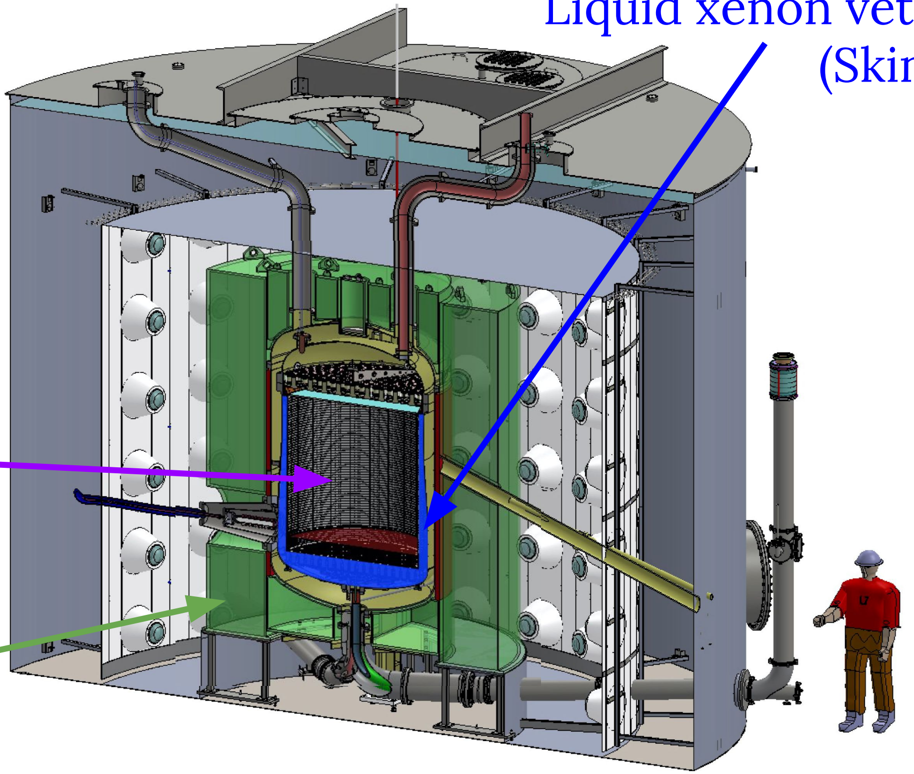
Measurement of ^{125}Xe positron emission branching fraction

2025/08/28

Miguel Hernandez on behalf of the LZ Collaboration
University of Zurich
TAUP 2025 - Xichang, Sichuan

LZ Detector

- Located ~1500 m underground at Sanford Underground Research Facility (SURF), South Dakota, USA
- Three nested detectors
- Primary focus of measuring WIMP dark matter



LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

https://lz.lbl.gov/

250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King’s College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Texas at Austin
- University of Wisconsin, Madison
- University of Zürich

US Europe Asia Oceania

LZ Collaboration Meeting at UCLA, March 2025

Department of Energy – United States of America

UKRI Science and Technology Facilities Council

fct Fundação para a Ciência e a Tecnologia

Sanford Underground Research Facility

Swiss National Science Foundation

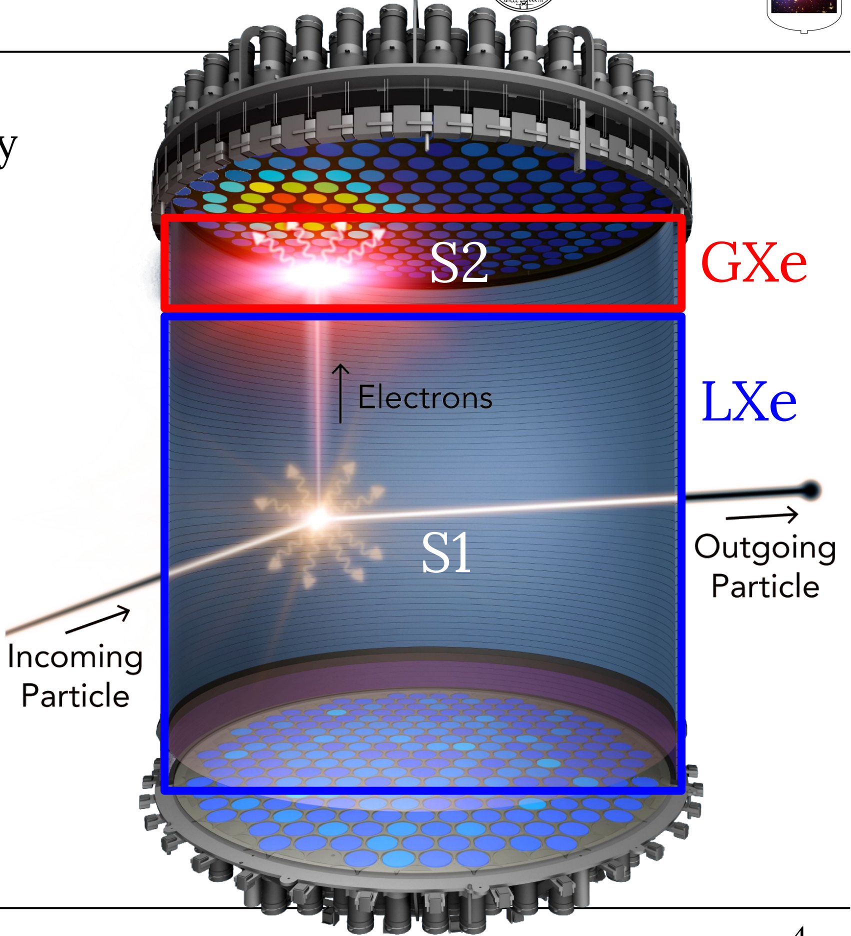
ibs Institute for Basic Science

ARC Centre of Excellence for Dark Matter Particle Physics

Thanks to our sponsors and participating institutions!

Xenon Dual-Phase TPC

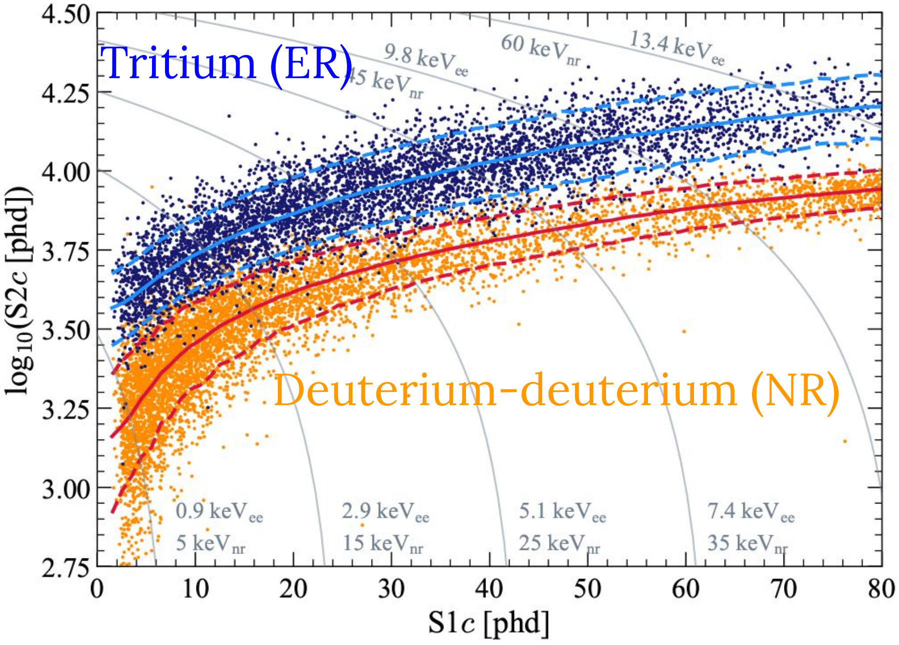
- Scatters occur in LXe target, inducing primary scintillation (S1), ionization, heat
- Electrons are drifted to GXe, extracted creating secondary electroluminescence (S2)
- Good energy and 3D position reconstruction
- Natural Xe stable and purifiable
  - ^{124}Xe ($\tau_{1/2} \sim 10^{22}$ yr) , ^{136}Xe ($\tau_{1/2} \sim 10^{21}$ yr)
- High density
  - Self-shielding provides low background inner fiducial volume
  - Larger mass in smaller detector



LZ Calibrations

- Nuclear recoils (NR) have higher quenching and produce less prompt scintillation (S1) and ionization (S2) than electronic recoils (ER)
- NRs have distinct S2/S1 ratio providing interaction type discrimination
- Fluctuations in recombination occur, but total produced quanta is conserved
- Calibrations inform of scintillation and ionization extraction efficiencies (g_1, g_2) and detector response
- Analysis will be looking into ^{125}Xe, one of the by-products of the NR calibrations

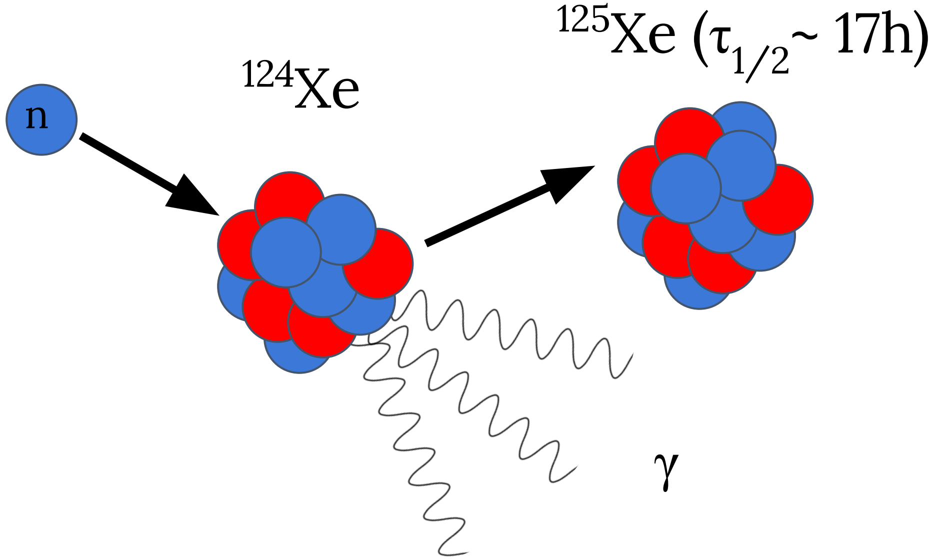
Example calibrations w/ NEST simulated bands



Phys. Rev. Lett. 131, 041002, 2023

Neutron Activation

Neutron captures on xenon,
^{124}Xe -> ^{125}Xe + γ-ray



Electron Capture Decay

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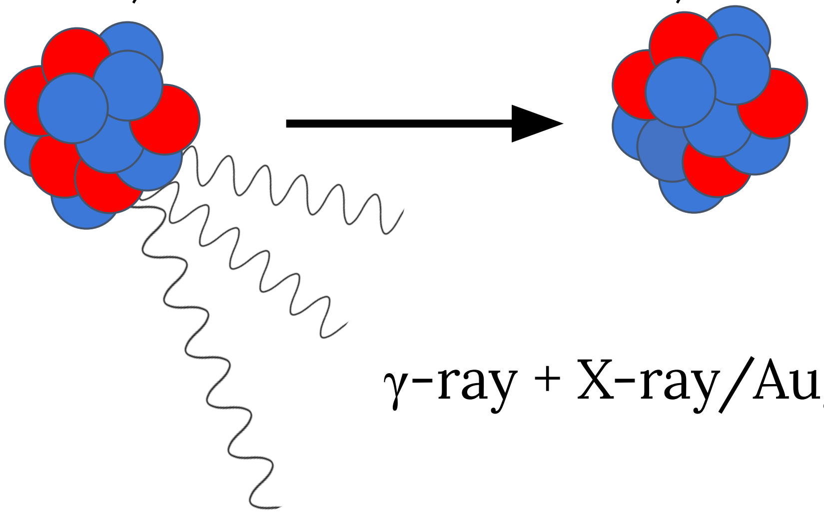
^{125}Xe decays by electron capture
(γ-ray + X-ray/Auger)

^{125}Xe ($\tau_{1/2}$~ 17h)

^{125}I ($\tau_{1/2}$~ 59 days)



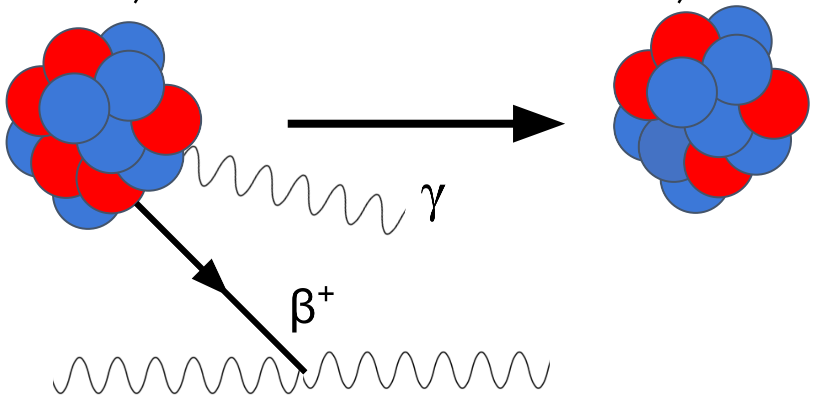
(Decays or removed through circulation)

γ-ray + X-ray/Auger

Looking for Positron Emission

or ^{125}Xe decays by positron emission (γ-ray + positron), target of analysis

^{125}Xe ($\tau_{1/2}$~ 17h) ^{125}I ($\tau_{1/2}$~ 59 days)



(Decays or removed through circulation)

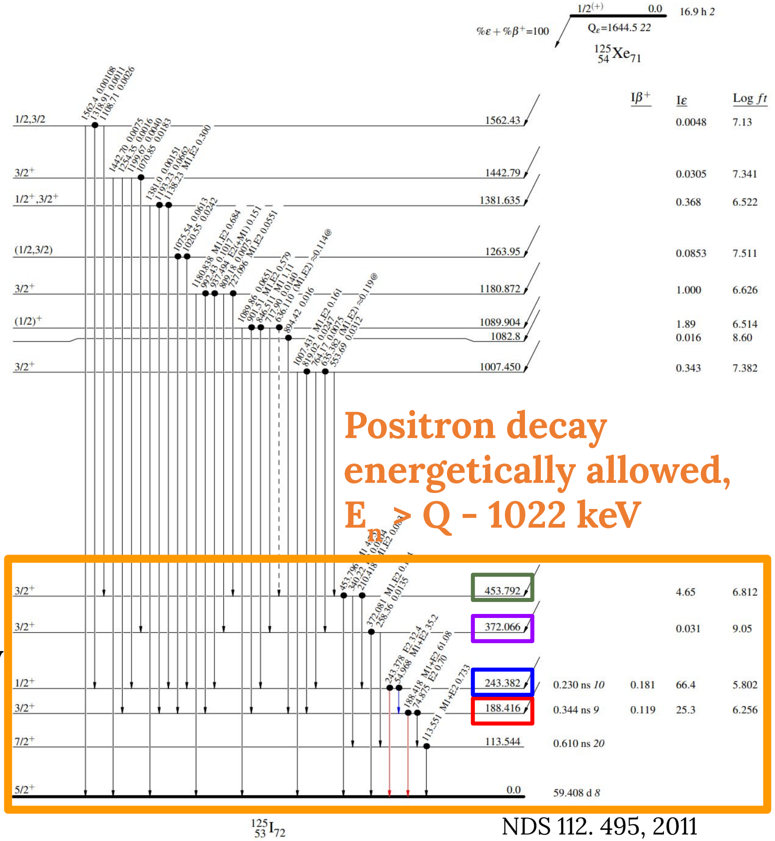
2×511 keV annihilation γ

Miguel Hernandez, miguel.hernandez@physik.uzh.ch

Existing Measurements

- ^{125}Xe primarily decays by electron capture, 99.7±0.1 %
- One measured, (one suspected), [two possible] positron decay modes
  - (188 keV), 243 keV, [372 keV], [454 keV] levels of ^{125}I
- Triple coincident confirmation of annihilation gammas and 188 keV, 243 keV de-excitation gammas [1]
- Direct measurement of ***only*** 243 keV positron spectrum [2]
- 243 keV level will de-excite to 188 keV ~52% of the time, not a direct indication of decay to 188 keV level
- Total positron emission rate constrained by 511 keV rate measurement, 0.3±0.1 %[2]
- Possibility for first direct measurement of unconfirmed positron decay modes and increased precision of total rate
- Measuring this process with LZ demonstrates the capability for multiple scatter analysis

[1] Phys Rev. 158, 1094, 1967
[2] Phys. Polon. 36, 939, 1969



NDS 112. 495, 2011

Expected Signal Characteristic

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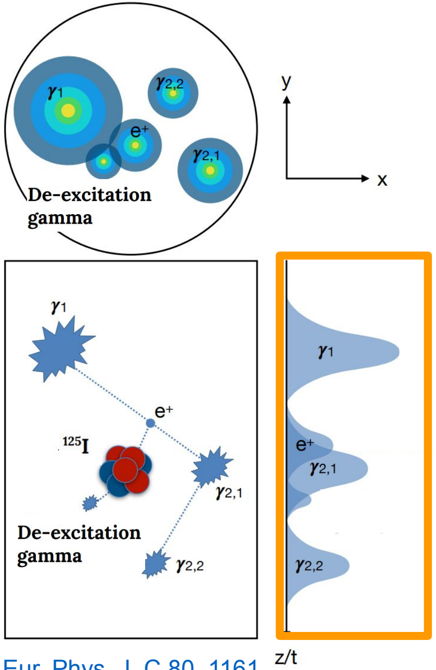
- Positron will be emitted with energy corresponding to ^{125}I final state level
- 511 keV pair annihilation gamma-rays created upon annihilation
- Additional accompanying de-excitation gamma / internal conversion electron
- Total expected quanta can be characterized as

Source	**Energy [keV]**
Annihilation gamma	2 × 511
De-excitation gamma / ICE	188 [or 243]
Positron kinetic energy endpoint	434 [or 379]
Total deposited energy	**1210 - 1645**

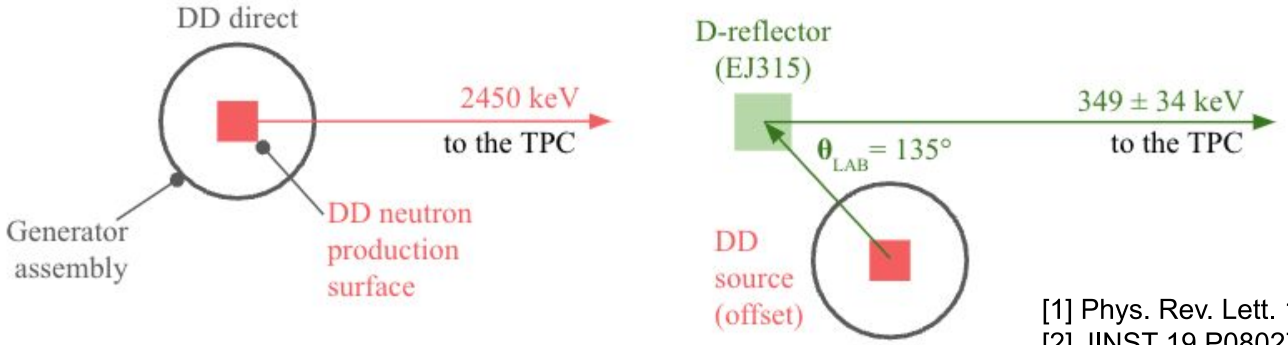


Eur. Phys. J. C 80, 1161, 2020

Multiple S2 but only single S1

Analysis Datasets

- Pre-activation dataset taken as background model
- Consists of 85.2 live-day exposure in WS 2024 detector conditions [1]
- Neutron irradiation via reflected DD-neutrons
- D-reflector mode, 349 ± 34 keV [2]
- Several days of calibration sufficient time to reach secular equilibrium
- Activated dataset consists of 1.5 live-day exposure, small gap for LED gain calibrations



[1] Phys. Rev. Lett. 135, 011802, 2025
[2] JINST 19 P08027, 2024

Prominent Backgrounds

- Most dominant backgrounds are primary ^{125}Xe electron capture modes
  - Same spatial distribution as signal
- Intrinsic radioactivity of detector materials (^{40}K, ^{60}Co, ^{238}U, etc...)
  - Externally located
  - Significantly reduced by fiducialization of detector volume

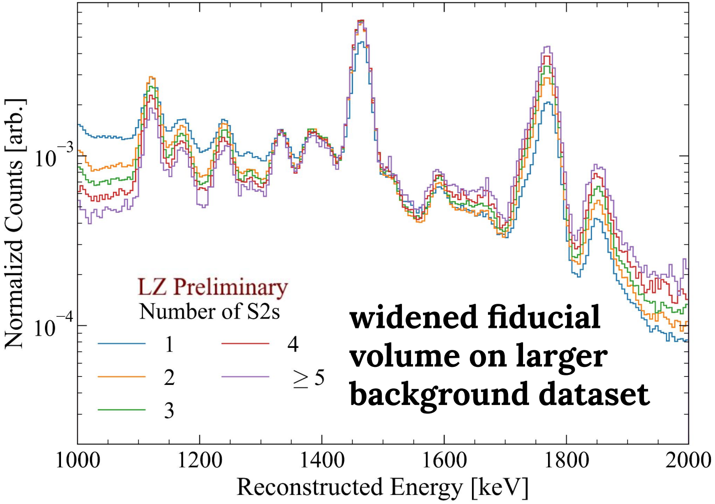
Source	**Energy [MeV]**	**Particle Type**
^{125}Xe EC	1007, 1090, 1181, 1264, 1382	Gammas and X-rays / Auger
^{40}K	1461	Gamma
^{60}Co	1173, 1333	Gamma

Multiple Scatter Analysis

- Provided sufficient depth separation interactions may resolve with multiple S2s and combined S1
- Single and multiple scatters up to 16 S2s are used for event reconstruction and identification
- To avoid saturation, only bottom array is used ($S2_{bi}$) for energy reconstruction
- Spatial and temporal corrections are applied ($cS1$, $cS2_{bi}$)
- Total energy calculated as sum of all pulses

$$E = W\left(\frac{cS1}{g_1} + \frac{\sum_i cS2_{bi}}{g_{2b}}\right)$$

- Consistency in energy across number of scatters!



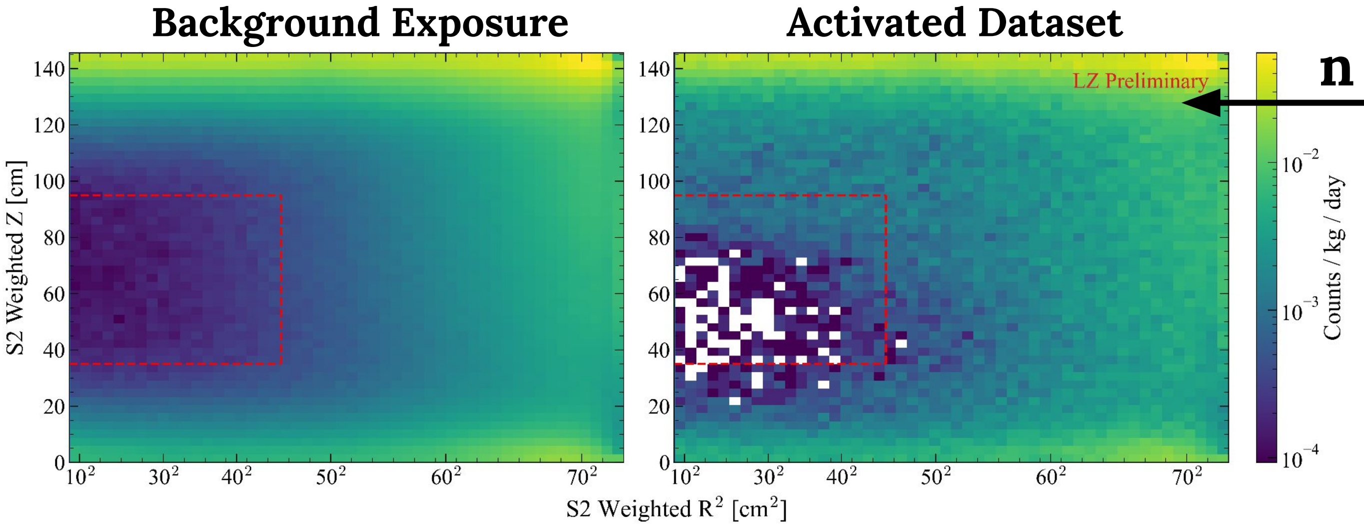
widened fiducial volume on larger background dataset

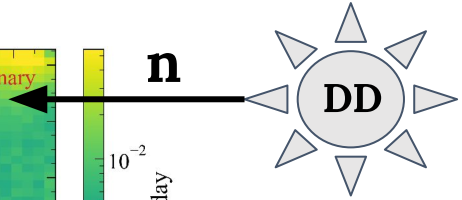
Analysis Selections

- 1.5 day exposure allows circulation of activated xenon into inner volume*
- Center one tonne volume selected for high signal purity
- Fiducial cuts applied on S2 weighted center of mass

Radius < 45 cm
35 cm < Z < 95 cm

*DD activation in upper volume





Additional Analysis Selections

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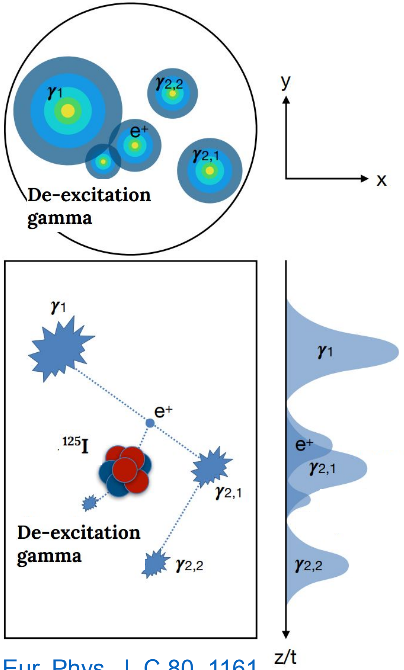
- Minimal additional analysis selections applied to keep high signal acceptance

Number of S2s	0 < number of S2s < 17
Physical Drift Time (all S2s)	0 μs < drift-time < 1049.5 μs
Physical Radius (all S2s)	0 cm < radius < 72.6 cm
Fiducial Z (S2 Weighted)	35 cm < Weighted Z < 95 cm
Fiducial Radius (S2 Weighted)	Weighted Radius < 45 cm
S1-S2 Region of Interest	3500 phd < cS1 < 16000 10^5 phd < Total $cS2_b$ < 10^6 phd
Energy Region of Interest	1000 keV < Energy < 1650 keV
Total Events Post Cuts	**1774**

Model and Analysis

- Signal model uses LZ standard simulation with high energy tuned NEST parameters [1]
  - Each clustered energy deposition treated separately for light and charge yields
  - Overlapping S2s will have modified light and charge yields which will require more complex modeling to use individual S2 information, work in progress!
- Data is analyzed using a combined binned likelihood in total energy with both pre-activation and post-activation data terms
- Pre-activation background expectation is optimized for each bin

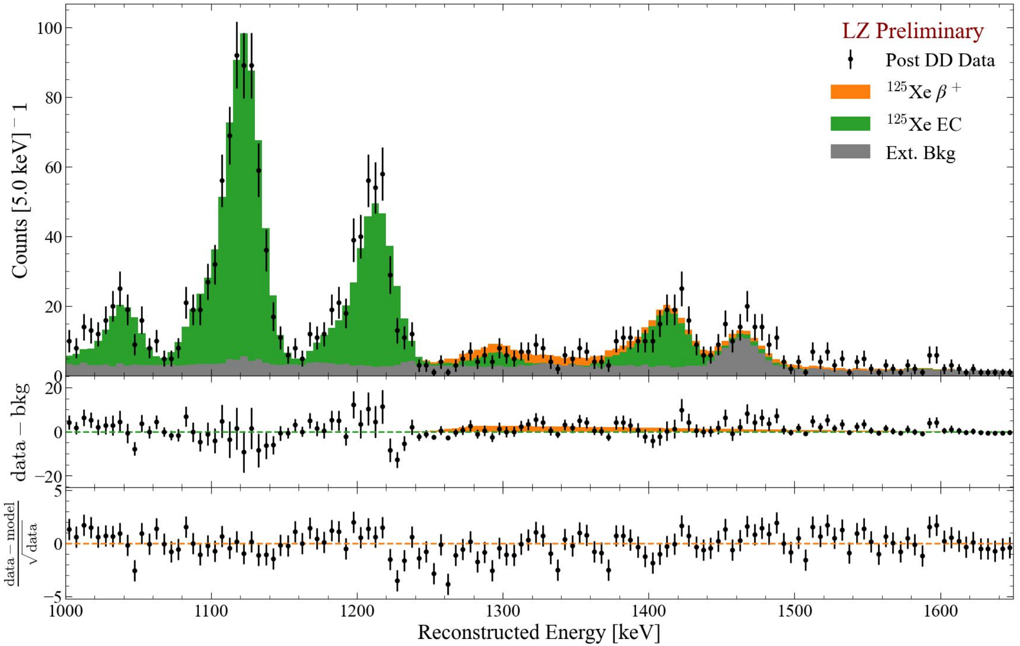
[1] J Astro. Phys 125, 102480, 2021



Eur. Phys. J. C 80, 1161, 2020

Results

- Positron signal constrained against EC background with improved precision
  - BR(β^+): **0.29 ± 0.08** %
  - Data and model agreement, p(χ^2) = **0.057**
  - High significance against background only hypothesis, σ = 5.47
- Consistent with existing measurement of **0.3 ± 0.1** % [1]
- First measurement of this decay process in a noble liquid detector



[1] Phys. Polon. 36, 939, 1969

Fitted Results

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Source	Fitted Results [counts]
Ext. Bkg	406^{+30}_{-30}
^{125}Xe EC	1229^{+55}_{-54}
^{125}Xe β^+ 188 keV	0^{+17}_{-0}
^{125}Xe β^+ 243 keV	96^{+29}_{-27}
Total	1731^{+71}_{-67}
BR(β^+)	$0.29^{+0.08}_{-0.08}\%$
σ_{sig}	5.47
$p(\chi^2)$	0.057

LZ Preliminary

} Consistent with existing measurements (for the ^{125}Xe β^+ 188 keV and 243 keV rows)

Summary

- LZ provides new measurement on ^{125}Xe positron emission relative branching fraction with improved precision, consistent with existing literature and demonstrates LZ's ability to model multiple scatter events
- First measurement of this decay process in a noble liquid detector
- Improvement in composite yields modeling will allow for increased measurement precision
- A uniformly distributed positron source can prove to be useful for future rare positron emission analysis searches (^{124}Xe $2\nu\beta^{+}$EC)
- As LZ continues to take data, many exciting new physics prospects in the works
    - ^{214}Pb flow tagging paper on arxiv as of Wednesday (arxiv:2508.19117)!
    - Neutrino physics ($0\nu\beta^{-}\beta^{-}$, ^{8}B CEνNS, Supernova)
    - Muon flux and muon-induced background measurements
    - Additional low and high energy ER searches

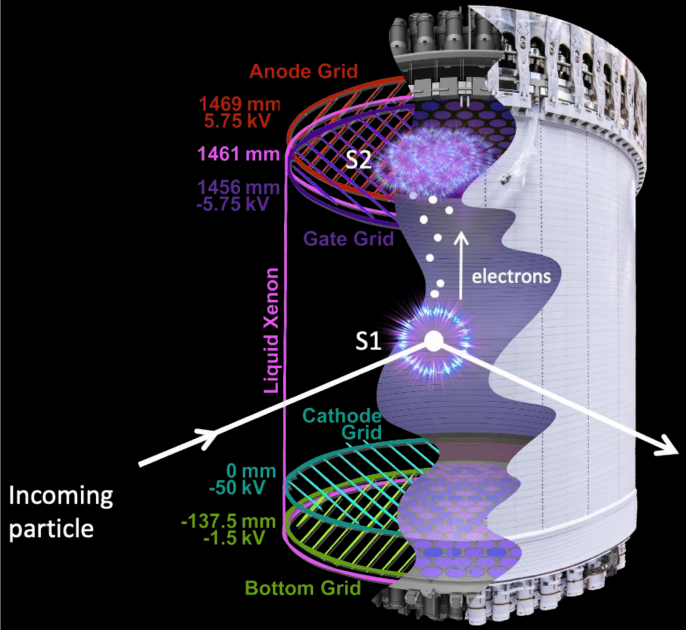

Image by Nicolas A. (UZH)

Thank you!

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Office of Science

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Backup Slides

Energy Binned Likelihood

- Maximum estimator for μ_{bi} found analytically, computed at each step of maximization based on N_i^{Pre}, N_i^{Post}
- Discovery significance and confidence intervals assume asymptotic likelihood test statistic

$$\mathcal{L}_{\rm tot}(\mu_{\beta+}, \mu_{\rm EC}, \vec{\mu_{\rm b}}) = \mathcal{L}_{\rm post}(\mu_{\beta+}, \mu_{\rm EC}, \vec{\mu_{\rm b}}) \times \mathcal{L}_{\rm pre}(\vec{\mu_{\rm b}})$$

Exposure Ratio

$$\mathcal{L}_{\rm pre}(\vec{\mu_{\rm b}}) = \prod_i {\rm Pois}(N_i^{\rm pre} | \alpha \, \mu_{\rm b,i})$$

$$\mathcal{L}_{\rm post}(\mu_{\beta+}, \mu_{\rm EC}, \delta, \vec{\mu_{\rm b}}) = \prod_i {\rm Pois}(N_i^{\rm post} | \mu_{\beta+} \cdot f_{\beta+,i} + \mu_{\rm EC} \cdot f_{EC,i} + \mu_{\rm b,i})$$

total counts

Weighted Analysis Variables

To incorporate spatial corrections, weighted S1 variable is defined as:

$$wS1c = \frac{\sum_i cS1_i \cdot cS2b_i}{\sum_i cS2b_i}$$

Weighted versions of position variables used for analysis selections

$$wR = \frac{\sqrt{(\sum_i x_i \cdot cS2_{bi})^2 + (\sum_i y_i \cdot cS2_{bi})^2}}{\sum_i cS2_{bi}}.$$

$$wdt = \frac{\sum_i dt_i \cdot cS2_{bi}}{\sum_i cS2_{bi}}$$