

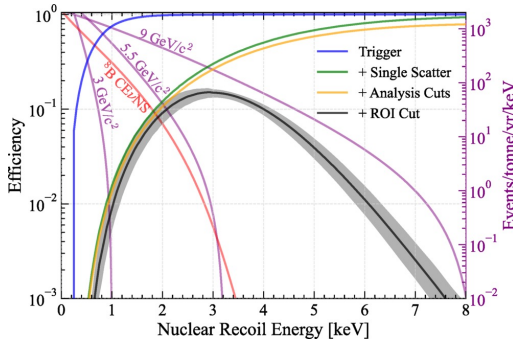
Towards Low-Level Tritium Background Quantification

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INTRODUCTION

Tritium is a radioactive isotope of hydrogen with a half-life of 12.3 years. It undergoes beta decay (b-) emitting an electron and an antineutrino. It is generated naturally in the environment via cosmogenic activation as well as anthropogenically from the modern nuclear fuel cycle. While atmospheric testing injected a large quantity of tritium into the atmosphere, it has since decayed and we have returned to modern background levels.

Tritium is a problematic background contribution for next-generation dark matter searches (LUX-ZEPLIN (LZ), XENONnT) and neutrino mass experiments (KATRIN) which require background environments devoid of low-energy radioactive noise.



Detection efficiency as a function of nuclear recoil energy for LZ after applying the S2 trigger (blue), ≥ 3 -fold single scatter reconstruction (green), analysis cuts (orange), and region-of-interest (black) in sequence with uncertainty band. (From Akerib et al. 2026)

Liquid noble gas time projection chambers like XENONnT, LUX-ZEPLIN, and PandaX-4T look for faint dark matter recoils but face severe background risks from tritium. Cosmic rays constantly breed trace tritium within target materials stored on Earth's surface, while lingering tritiated methane calibration gases require complex, extreme purification engineering to completely remove.

Traditional assay tools lack the sensitivity to screen for materials clean enough to meet these rigorous requirements. A small contamination level—undetectable by standard liquid scintillation counters—can cause fake electronic recoil anomalies or mask neutrino endpoints. **To improve the tritium detection threshold for environmental and rare-event measurements, an electrolytic enrichment capability is being created that can be used to enable ultra-low level tritium quantification.**

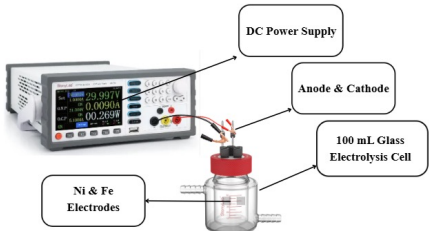
CURRENT CAPABILITIES

Tritium metrology requires balancing analytical sensitivity against operational throughput, as traditional counters face strict minimum detectable activity floors from environmental radiation and quenching. While emerging machine-learning CCDs and precise ³He in-growth mass spectrometry overcome these radiological backgrounds, they are limited by early-stage technology and lengthy multi-month storage bottlenecks.

Method	Phase / Matrix	Detection Limit	Advantage	Limitation
Low Background LSC	Liquid / Aqueous Soluble	~0.3 Bq/L	High throughput; standard baseline interface for enriched water assaying.	Vulnerable to chemical quenching; cannot visually separate background radiation.
Gas Proportional Counting	Gas (H ₂ , CH ₄)	~0.1 Bq/L	Zero chemical quenching; excellent spectral stability.	Labor-intensive chemical synthesis lines required to generate counting gases.
CCDs + AI	Direct Solid-State Surface	Experimental (Ultra-low)	Visual track-reconstruction; direct rejection of background radiation through ML.	Emerging technology; requires specialized ultra-thin dead layers on silicon.
³ He In-Growth Mass Spec	Liquid/Gas to Noble Gas Phase	~0.05 Bq/L	Absolute best ultimate sensitivity; completely bypasses radiological backgrounds.	Requires a 1 to 3-month storage bottleneck for daughter isotope accumulation.

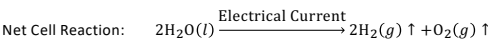
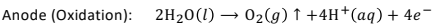
ELECTROLYTIC ENRICHMENT SYSTEM

Electrolytic enrichment acts as an upstream physical amplifier for trace tritium analysis. Because direct radiometric detection of ultra-low-level tritium is fundamentally limited by detector background noise, increasing the physical concentration of the radioisotope within a sample prior to measurement is required. By driving a controlled direct current through an aqueous sample, the system preferentially breaks apart light water molecules while keeping heavier isotopologues concentrated in the liquid residue.

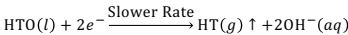


Primary Electrolysis Reactions

At the cell electrodes, light water undergoes standard reduction and oxidation:



While light hydrogen gas escapes rapidly, the corresponding reduction of tritiated water at the cathode occurs at a much slower rate due to the higher zero-point energy of the T – O bond:

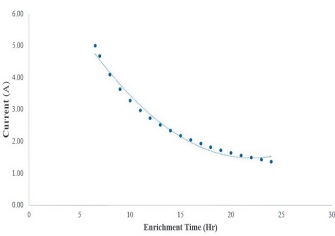


Tritium Enrichment Factor

The final Tritium Enrichment Factor (TEF) can be modeled as a function of the initial volume (V_0), final volume (V_f), recovery efficiency (η), and the separation factor, β , which compares the isotopic ratios of the escaping gas to the remaining liquid:

$$\text{TEF} = \eta \cdot \left(\frac{V_0}{V_f}\right) = \left(\frac{V_0}{V_f}\right)^{(1/\beta)-1} \text{ where } \beta = \frac{(H/T)_{\text{gas}}}{(H/T)_{\text{liquid}}}$$

Because $\beta > 1$ (typically ranging from 10 to 30 depending on electrode materials like nickel or iron, and cell temperature), the liquid sample systematically concentrates its tritium content as the total volume shrinks.



Preliminary planned experiments to be performed with both nickel and iron cathode/anode pairs for performance comparison. All experiments will be performed at 1% by weight NaOH.

Exp #	Total Volume (mL)	Time (Hrs.)	Current (A)	Final Volume (mL)
1	18	24	1.36	7
2	18	12	2.73	7
3	18	6.55	5	7
4	100	51	4.96	15

ENHANCING DETECTION CAPABILITIES

Integrating an upfront electrolytic enrichment loop fundamentally redefines tritium metrology by serving as a universal physical signal amplifier across all major detection platforms. By dramatically concentrating trace isotopes prior to analysis, this approach breaks past traditional minimum detectable activity limits for LSC, minimizes required sample volumes and noise for gas proportional counting, and slashes the multi-month storage bottlenecks of ³He in-growth mass spectrometry to enable rapid, ultra-sensitive material screening for rare-event physics.

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