

# Experimental and Monte Carlo Evaluation of a CLLBC-Based Gamma–Neutron Spectroscopy System for Planetary Hydrogen Detection

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Gamma–neutron spectroscopy (GNS) is a well-established technique for detecting near-surface hydrogen in planetary regolith, where hydrogen most strongly manifests as a suppression of epithermal neutrons [1]. Accurate separation of thermal and epithermal neutron components is therefore essential for robust hydrogen interpretation across planetary environments relevant to in-situ resource utilization (ISRU) [2]. Cs<sub>2</sub>LiLaBr<sub>6</sub>:Ce (CLLBC) is a recently developed elpasolite scintillator that combines high gamma-ray stopping power with intrinsic thermal neutron sensitivity via the <sup>6</sup>Li(n,α)t reaction and pulse-shape discrimination (PSD) capability [3], enabling flexible gamma–neutron measurements under both passive galactic cosmic ray–induced neutron fields and active neutron source conditions [4].

In this study, we evaluate a CLLBC-based GNS system through controlled laboratory experiments and Monte Carlo simulations, with emphasis on cadmium-assisted separation of epithermal neutron components. Measurements are performed using lunar regolith simulants with low intrinsic hydrogen content under a moderated <sup>252</sup>Cf fission neutron field. Hydrogen is introduced through homogeneous mixing of water or ice and through layered configurations consisting of dry overburden above hydrogen-bearing layers at controlled depths. Cadmium shielding is used to selectively absorb thermal neutrons, enabling differential measurements with and without thermal neutron contributions.

Detector responses are analyzed using PSD to separate neutron- and gamma-induced events. Comparisons between cadmium-covered and uncovered configurations show systematic hydrogen-dependent reductions in epithermal neutron contributions, while thermal neutron capture-related features, including the <sup>6</sup>Li capture peak, provide complementary information on neutron moderation. A GEANT4-based Monte Carlo model is developed to reproduce the experimental geometry, materials, and neutron transport, validated against experimental data, and extended to explore hydrogen concentrations and burial depths beyond laboratory limitations.

The combined experimental and simulation results demonstrate that cadmium-assisted epithermal neutron discrimination significantly enhances the sensitivity and interpretability of CLLBC-based GNS measurements for hydrogen detection, establishing a physically grounded experimental–simulation framework applicable to future lunar and Martian surface missions.

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