PROCEEDINGS OF SCIENCE

Design and Simulation of the Assessing Lunar Ion-Generated Neutrons (ALIGN) Payload for Observing Cosmic Ray-Generated Epithermal Neutrons in the Lunar South Polar Region

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The "Assessing Lunar Ion-Generated Neutrons" (ALIGN) payload is designed to monitor the particle radiation environment, in the lunar south polar region, for the Chang'E-8 lunar lander. The detector will monitor the rate of high energy cosmic rays-generated albedo neutrons created by their interactions in near-surface rocks. These albedo neutrons are sensitive to the local topography and composition of subsurface rocks; therefore, their detection is important for accurate assessment of the radiation environment and its variability, as well as for validation of simulation models of the radiation environment. The instrument will be mounted on the lander and will have three detector modules sensitive to thermal and epithermal neutrons, which will provide information on the directional distribution of this radiation component. This fixed system on the lander will provide a stable platform for the measurement of time variations of hazardous radiation. We will present the scientific objectives and technical design of the payload and GEANT4 simulations of geometrical acceptance and angular resolution, as well as the expected detection range and count rate. The effect of the environmental thermal neutrons, e.g., from the radioisotope heater unit (RHU), will also be discussed.

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1. Introduction

The Assessing Lunar Ion-Generated Neutrons (ALIGN) is a particle detector payload Sino-Thai International Cooperation project which is selected for Scientific and Engineering Collaboration Research in Chang'E-8 Mission under the International Lunar Research Station Program. The payload will be attached to the outside wall of the Chang'E-8 lunar lander. The lander has a main mission on lunar exploration to better understand the lunar environment and prepare the groundwork for future lunar bases. The ALIGN payload is specifically designed for the precise and continuous measurement of these cosmic ray-generated albedo neutrons directly from the lunar south polar region. By providing a stable, fixed platform, ALIGN will enable critical, time-resolved measurements that will be invaluable for characterizing the dynamic radiation environment, space weather, and particle transport models, and ensuring the safety and success of long-duration human presence on the Moon. This proceeding will detail the scientific motivations, technical design, and GEANT4 simulations that underlie the ALIGN payload.

Since the Moon is lack of the substantial atmosphere and intrinsic magnetic field to shield it from the continuous bombardment of high-energy particles originating from galactic and solar sources. It is a challenging environment for long-duration human missions. This motivated us to study the radiation environment, especially cosmic rays impact, of the ground surface for the upcoming International Lunar Research Station (ILRS). When the high-energy cosmic rays, Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs), bombard the lunar surface, it undergoes complex interactions with the lunar regolith [1]. These interactions lead to spallation, fragmentation, and nuclear reactions, generating a cascade of secondary particles, including gamma rays, electrons, positrons, and, notably, a significant flux of albedo neutrons. These secondary neutrons carry crucial information about the composition and structure of the near-surface and subsurface materials, particularly the presence of hydrogen (water ice), and contribute significantly to the total radiation dose.

A key aspect of the presence of water on the lunar surface and within the regolith is that it is primarily driven by the continuous bombardment of the lunar surface by solar wind. Specifically, the H ions in the solar wind, bombard the lunar surface, and then are injected into the surface. There, they can chemically react with the abundant oxygen atoms present in lunar minerals to form hydroxyl (OH) and molecular water (H_2O) [2].

From the stated motivations, the ALIGN payload is planned to monitor the particle radiation environment that will be experienced by future taikonauts exploring the lunar south polar region. In particular, this detector suite will monitor the rate of high energy cosmic particles as well as the albedo neutrons [3] created by their interactions in near-surface rocks. These albedo neutrons are sensitive to the local topography and composition of subsurface rocks; therefore, for accurate assessment of the radiation environment and its variability, as well as for validation of simulation models of the radiation environment, it is important to measure the "ground truth" with instruments on the rover and the lander.

The ALIGN payload consists of three detector modules on the lander sensitive to epithermal neutrons, which will provide information on the directional distribution of this radiation component, which is crucial to estimating the safety of taikonauts at the ILRS. This fixed system on the lander will provide a stable platform for the measurement of time variations of hazardous radiation.

2. Scientific Objectives

The scientific objectives of the ALIGN can be listed as follows, ordered not by importance, but rather by causality, from studies of the parent cosmic ray flux that varies with space weather effects and the solar activity cycle, to studies of the neutrons that arise from cosmic ray interactions in the lunar subsurface:

- **Monitoring solar energetic particle (SEP) events:** This data will directly support real-time radiation warnings, enhancing taikonaut safety during future lunar missions. Additionally, by comparing these measurements with orbital data, we can differentiate between temporal variations and spatial anisotropies in SEP distributions.
- **Tracking Galactic cosmic ray (GCR) ion flux variations:** This aims to investigate the complex modulation effects influenced by solar activity cycles, solar wind conditions, and transient space weather events such as Forbush decreases [4], which significantly impact the GCR variation.
- **Studying Earth's magnetotail effects on GCR transport:** This will be achieved as the Moon periodically passes through this region during its orbit, offering a unique opportunity to understand how Earth's magnetosphere influences the deep space radiation environment.
- **Monitoring lunar albedo neutron flux at the ILRS site:** This will allow for a precise assessment of surface radiation exposure and an investigation into its energy dependence through the use of variable shielding. The data will also be used to validate simulation models of cosmic ray interactions with the lunar subsurface. This objective leverages synergy with the ALIGN payload on the Chang'e-7 orbiter (Moon-Aiming Thai-Chinese Hodoscope, MATCH, [K. Puprasit et.al., ICRC 2025, SH, 572]), which will provide complementary measurements of incoming cosmic ray spectrum, and will account for variations caused by local topography and subsurface composition.
- **Exploring radiation dosage and subsurface water ice:** To explore the effects of local geography and geology on radiation dosage throughout the ILRS region. This includes the potential to map radiation hazards for future missions and to probe for subsurface water ice by detecting neutron energy moderation in hydrogen-rich areas, which would indicate the presence of water.

These objectives collectively underscore the significance of the Chang'E-8 mission in advancing both fundamental space physics and practical applications for future lunar exploration.

3. Technical Design

The ALIGN payload is designed for compact integration onto the Chang'E-8 lunar lander. It will consist of three independent detector modules, strategically oriented to provide directional sensitivity. Figure 1 shows the conceptual design schematic of the detector.

From the conceptual design, each of the three independent detector modules will be constructed to discriminate between different neutron energy ranges and to reject charged particle backgrounds.

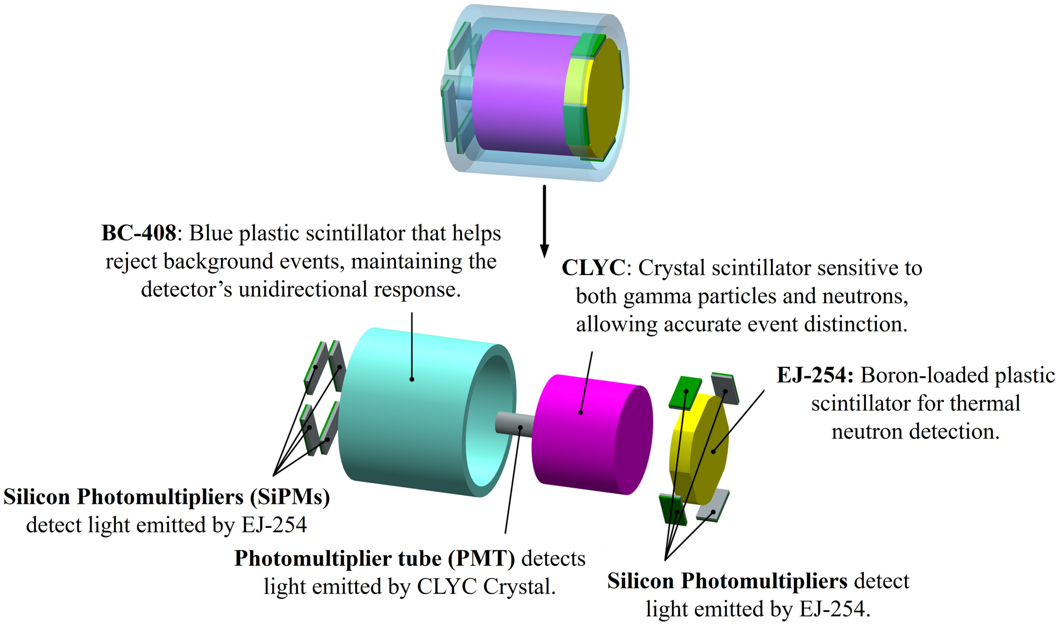

Figure 1: Conceptual diagram of the ALIGN payload, illustrating key detector components and their layered arrangement. The diagram displays only the detector's sensitive areas, excluding the shielding. The CLYC scintillator (purple) serves as the main detector element sensitive to both gamma particles and neutrons, with collected by an photomultiplier tube (green). EJ-254 plastic scintillator (yellow) positioned at the front for dedicate thermal neutron detection with it scintillation light by Silicon photomultiplier (green). The outermost surrounding layer, BC-408 (light blue), is primarily function as a Veto detector to reject charge particle background events and help maintain the detector directional sensitivity. This multi-layer design allows the ALIGN payload to achieve comprehensive monitoring and discrimination of various neutron energies within the lunar surface.

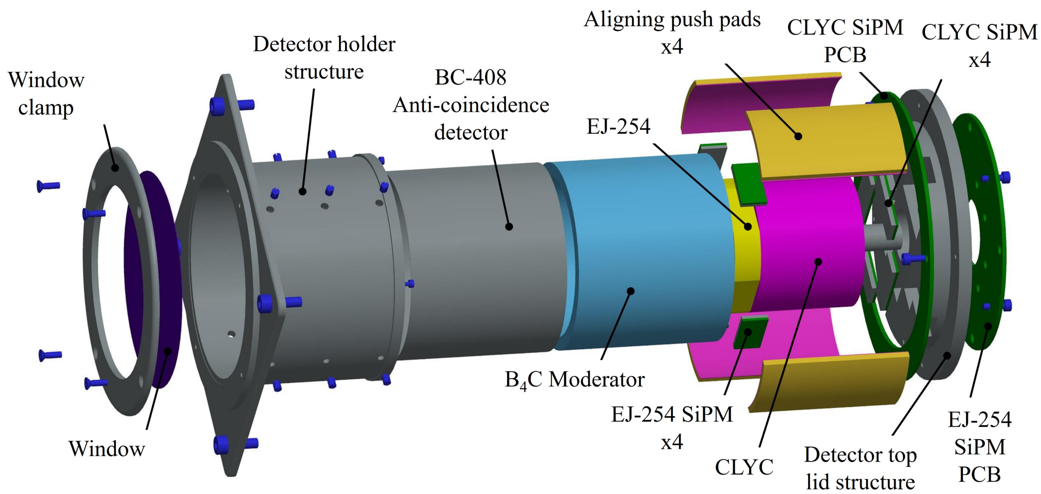

Figure 2: Exploded view of the ALIGN payload structure, showing the major detector components and support assemblies.

Table 1: ALIGN Detector Component Summary

Component/Layer	Position/Primary Function	Key Dimensions		Electronic Trigger Threshold
		Diameter (D)	Height/Thickness (H)	
Aluminum (Al) Shield	Outermost front layer; Light & dust shield, absorbs recoil p/e.	-	10 mm	N/A
EJ-254 Plastic Scintillator	Behind Al shield; Thermal neutron detection (0.01 eV - 0.4 eV).	50 mm	12 mm	300 keV
CLYC Scintillator	Behind EJ-254; Epithermal to fast neutron detection (0.4 eV - 1 MeV).	50 mm	50 mm	600 keV
B_4C Shield	Surrounds inner scintillators (sides & back); Neutron absorption/collimation.	-	10 mm (Thickness)	N/A
BC-408 Anti-Coincidence	Outermost layer, encloses entire stack; Charged particle discrimination.	-	5 mm	700 keV

The front layer detector was designed to be made of Boron-doped plastic scintillator (EJ-254) for thermal neutron detection. This detector scintillates the blue light (~425 nm) when the charged particles produced by thermal neutron capture interaction with the Boron atoms within the detector, as shown in the following interaction. This front layer acts as an initial indicator of the thermal neutron flux, $^{10}\mathrm{B} + n \rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He},\ Q = 2.31$ MeV.

The central main detector was designed to make of CLYC (Cs_2LiYCl_6:Ce) Scintillator for the epithermal to fast neutron detection. The base detection element within the scintillator is a Cerium-doped Cesium Lithium Yttrium Chloride (CLYC) scintillator. The thermal and epithermal neutron can be detected by the interaction of the incomming neutron with the enriched Lithium-6 (^{6}Li) atom, which has a high thermal neutron capture cross-section. The neutron interacts undergoes the following reaction: $^{6}\mathrm{Li}+n \rightarrow {}^{3}\mathrm{H}+{}^{4}\mathrm{He},\ Q = 4.78$ MeV. For the fast neutron detection, the CLYC is also can be detected by: $^{35}\mathrm{Cl}+n \rightarrow {}^{35}\mathrm{S}+p,\ Q = 0.615$ MeV. In addition, the CLYC has neutron and gamma-ray detection and identification capabilities using the pulse shape discrimination technique.

The outermost detector is a Plastic Scintillator (BC-408). This anti-coincidence detector locates surround to enclose both the front plastic scintillator and the CLYC scintillator. This detector was selected to moderate the sided-incomming neutrons and rejecting events caused by charged cosmic ray particles. The other significant detector parts shows in the following table 1.

4. Simulations and Detection Efficiency Estimation

4.1 Simulated Neutron Deposited Energy Distribution

From the design of the ALIGN payload was evaluated the material and thickness to meet the scientific objective and requirements using the Geant4 simulations. To confirm the simulation setup, the expected energy deposit distribution for both the CLYC and the boron-doped scintillators (EJ-254) were simulated. Figure 3 shows the simulated results of deposited energy distribution for the both scintillators. The depesited energy in CLYC (Figure 3 (a)) shows features of its sensitivity to neutron as expected nuclear interaction. The peak of Cl(n, p)S is observed at lower deposited energy. This corresponds to the neutron reaction with Cl-35 isotope present in the CLYC crystal. The peaks of Li(n,α)t are observed around 4.78 MeV due to the neutron capture. This peak is

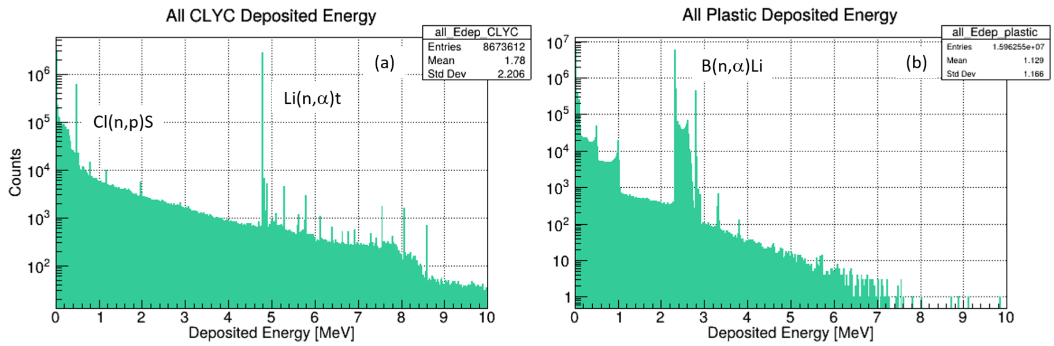

Figure 3: The simulated neutron detection spectrum illustrates the deposited energy spectra for (a) the CLYC detector and (b) the plastic scintillator (EJ-254).

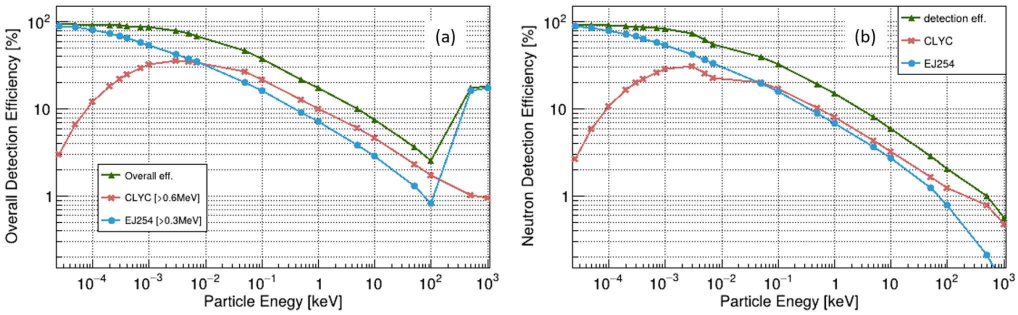

Figure 4: Simulated detection efficiency of the ALIGN Payload for the selected 10mm EJ-254 plastic (blue line) and the 50mm CLYC (red line) detectors, along with their combined overall efficiency (green line); (a) overall detection efficiency, and (b) neutron detection efficiency.

fundamental for identifying thermal and epithermal neutrons. The plastic scintillator distribution also shows feature related to neutron interaction . The B(n,α)Li peak is observed around 2.31 MeV. This confirms the EJ-254's main role in the detecting thermal neutron.

4.2 Detector and Shielding Thickness Optimization

To optimize the performance of the ALIGN detector, especially the detection range consistency between the EJ-254 plastic scintillator and the CLYC main detector have to be consider. The simulations were conducted to vary the thickness of the EJ-254 with the fixed sized of the CLYC of 5cm as a baseline. The simulated neutron beams were generated and directed onto the EJ-254. The neutron detection efficiency was calculated based on the deposited energy in the detector volume and the counts of fission events from the incoming neutrons.

Figure 4 shows the detection efficiencies for both the CLYC and EJ-254 detectors as a function of the generated incoming energy. The CLYC detector exhibits higher efficiency for epithermal and lower fast neutrons, while the EJ-254 is more efficient at detecting thermal neutrons. The intersection point of efficiency trend between the CLYC detector and the EJ-254 detector is particularly important. Given that 0.4 eV is considered the maximum energy for thermal neutrons and this value is close to the crossing point of the efficiency trends, it suggest an optimal thickness for the EJ-254.

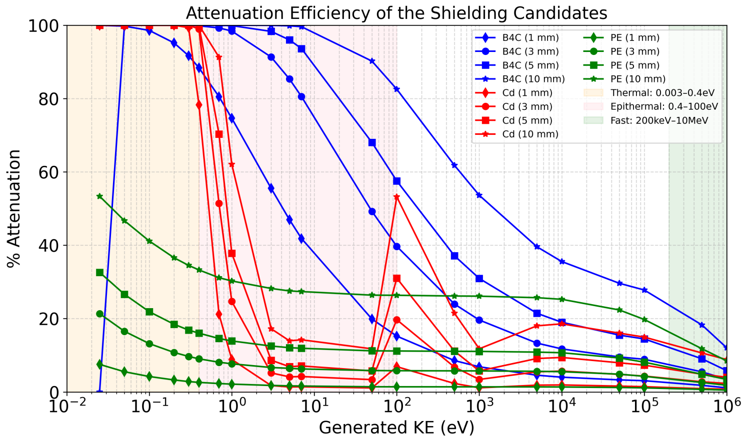

Figure 5: Attenuation efficiency of various shielding material candidates (Boron Carbide (B_4C, blue), Cadmium (Cd, red), and Polyethylene (PE, green)) as a function of incident neutron kinetic energy. Data are presented for thicknesses of 1, 3, 5, and 10 mm for each material. The shaded regions indicate typical energy ranges for thermal (0.01-0.4 eV), epithermal (0.4-100 eV), and fast (200 keV-10 MeV) neutrons.

From varying the EJ-254 thickness, the optimal range of 8-10 mm for the scintillator was selected. This specific thickness ensures that the majority of thermal neutrons will be effectively detected by the EJ-254 plastic detector. Epithermal and fast neutron will mostly penetrate this thin plastic layer and be detected by the CLYC, allowing for clear energy discrimination and accurate spectral measurements.

The effective shielding is important for any detector, especially in the complex environments like the lunar surface where various neutron energies are present and background sources need to be reduced. Material shielding is employed to selectively filter particles of specific energies, allowing desired particles to penetrate into the detector while attenuating unwanted components. To optimize the detector's performance and energy discrimination capabilities, varying materials and their thicknesses were investigated through simulations. Figure 5 illustrates the attenuation efficiency of three primary shielding candidates: boron carbide (B_4C), cadmium (Cd), and polyethylene (PE), across a broad range of neutron kinetic energies. These materials were considered based on their distinct inter action mechanisms with neutrons, and simulations were performed to evaluate their performance at varying thicknesses (1, 3, 5, and 10 mm). Both Cd and B_4C are excellent at blocking thermal neutrons, almost completely stopping them even at just 1 mm thick. Cd is especially good at this with a sharp drop-off in transmission for these low energies. Polyethylene, does not block thermal neutron but moderate the energy. For epithermal neutron, B_4C still blockings them well, through its effectiveness decrease as neutron energy increases. To ensure the detector's primary response is to neutrons directly incident through its unshielded front, it will be covered by 1 mm of Cd on all sides except the front. This is because Cd is exceptionally good at absorbing thermal neutrons, allowing for a clearer characterization of different neutron energy components and their directional distribution.

5. Conclusion and Future Work

The ALIGN payload represents a significant step towards a more compregensive under standing of the lunar radiation environment and its implications for future lunar exploration. It innovative design, sensitive to both thermal and epithermal neutron, will provide unprecedented understanding the distribution and temporal variations of albedo neutrons in the lunar polar region. Detailed Geant4 simulations confirm the instrument's performance and its ability to meet scientific objectives. Future work will focus on the optimizing the shielding design to precisely separate Radioisotope Heater Unit (RHU) flux from lunar surface albedo neutrons. This also includes the detailed engineering design, fabrication of flight models, calibration, and the development of data processing algorithms to maximize the ALIGN mission's scientific return.

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