^{3}He Prospecting Challenges

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Overview & Motivation

Existing knowledge of the lunar ^{3}He abundance distribution is limited, anchored solely by sparse mid-latitude Apollo samples.

^{3}He is a (potentially) valuable lunar resource. This isotope has been continuously deposited on the Moon for billions of years. Parts-per-billion (ppb) abundance levels were identified in returned Apollo samples [1] and found to be correlated with the TiO_2 and optical maturity (e.g., [2], and references therein).

We explored the viability of radiative neutron capture orbital geochemistry methods for ^{3}He prospecting from orbit. This effort was motivated by the goal to facilitate a global lunar survey agnostic to geologic (or other model-based) assumptions.

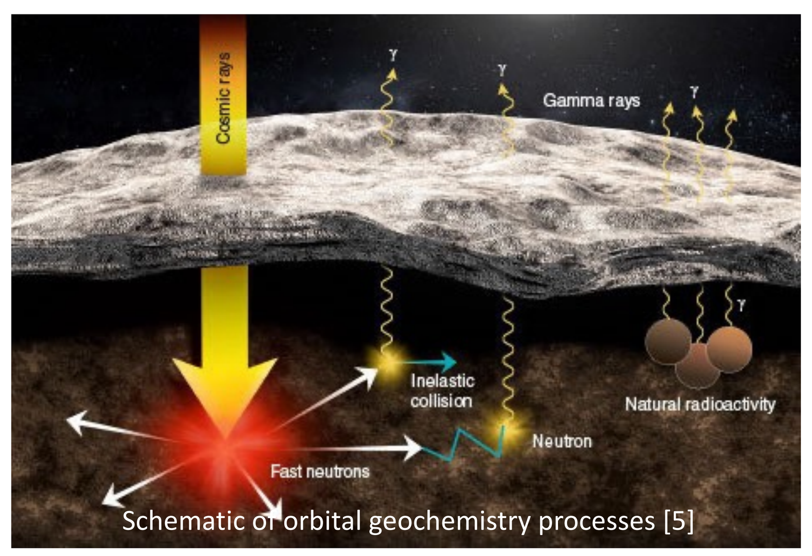
Orbital Geochemistry

Nuclear remote sensing techniques inform our understanding of the Moon.

Neutron and gamma-ray detection from orbit is a well-established remote sensing technique for airless planetary bodies [3. 4]. It is initiated by cosmic ray bombardment of the lunar regolith.

Fast neutrons produced cosmic-ray interactions in the lunar regolith may be moderated and ultimately captured by nuclei in the regolith.

Characteristic de-excitation and/or capture gamma-rays and/or neutrons that escape the lunar surface provide key remote sensing detection channels.



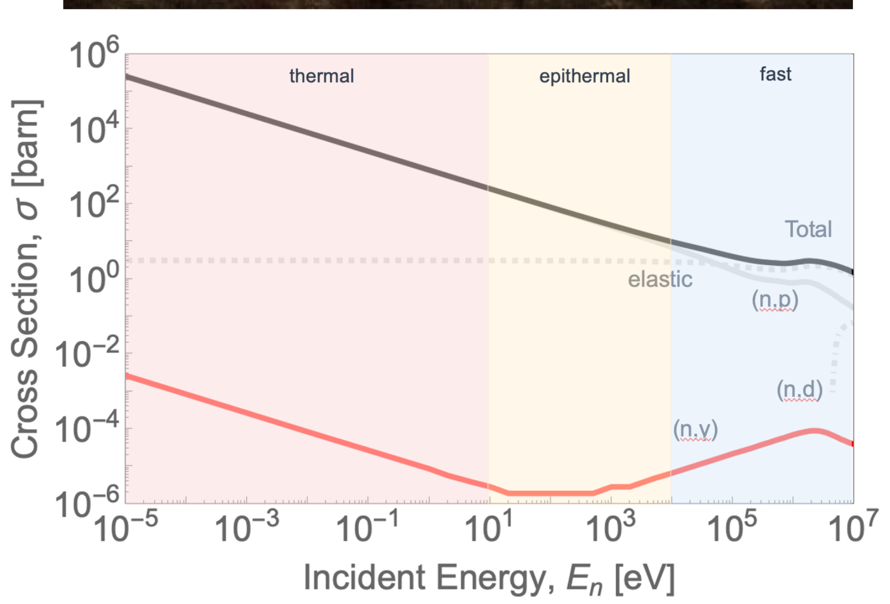


Figure 1. Energy-dependent cross-sections for neutron interactions on ^{3}He.

^{3}He Radiative Capture

Radiative (neutron) capture unambiguously signals the presence of ^{3}He via a secondary 20.578 MeV γ-ray

^{3}He has a non-trivial likelihood of interaction with cosmic-ray induced neutrons, including :

- ^{3}He(n, n)^{3}He - elastic scattering
- ^{3}He(n, p)^{3}H – triton production
- ^{3}He(n, d)^{2}H – deuteron production
- **^{3}He(n,γ)^{4}He (radiative capture)**

The detectability of this secondary signature was evaluated by leveraging the thermal neutron flux measured in-situ in lunar orbit [6] and known ^{3}He abundance levels at the lunar surface.

Conclusions

We evaluated the practicality of ^{3}He prospecting via the detection of the unique 20.578 MeV γ-ray from neutron capture

Orbital-based survey *impractical* due to LONG exposure requirements

Surface-based survey *impractical* due to LONG exposure & LARGE instrument requirements

Challenges:
Small radiative capture cross section
ppb-level ^{3}He abundance
Low thermal n flux @ lunar surface

The flux of secondary 20.578 MeV gamma-rays from ^{3}He(n,γ)^{4}He is **$\leq 10^{-11}$ γ cm^{-2} s^{-1}** for abundance levels ≲10 ppb by weight. Detection therefore requires a large (meter-class) gamma-ray spectrometer, long dwell times, or a combination of both.

A similar analysis shows that surface-based prospecting based on radiative capture is also impractical, even if using an artificial source of thermal neutrons (e.g. neutron generator or radiological source) is employed.

Acknowledgements

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- **Macroscopic Cross-section: Probability of neutron capture per unit path length**

$$\Sigma_a = N_A \left(\frac{w}{A_{^3\mathrm{He}}} \right) \sigma \rho \ \mathrm{cm}^{-1}$$

Weight fraction; Molar mass; Cross Section; Density

- ***Probability of radiative capture***

Conversion efficiency is LOW due to small cross-section and low 3He abundance

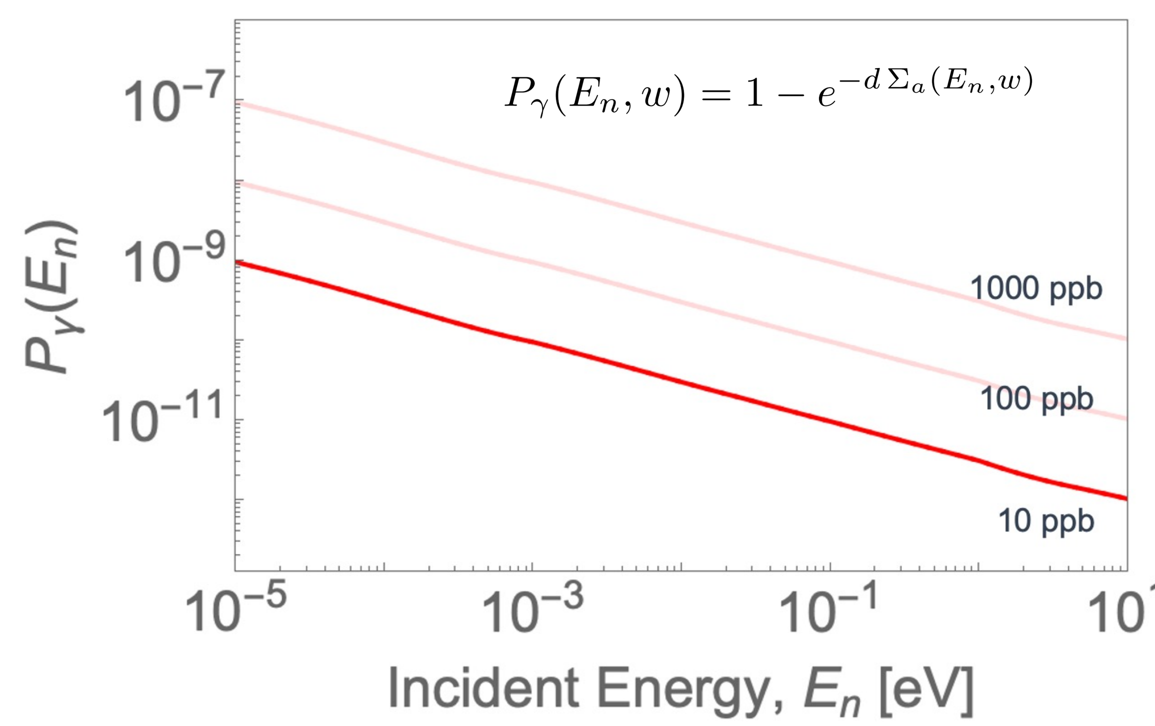

Figure 2. Probability of radiative neutron capture on ^{3}He. The probability of capture is shown as a function of incident neutron energy and ^{3}He abundance. Neutron pathlength was 100 cm.

- ***Flux of radiative capture γ-rays***

Flux is LOW due to small conversion efficiency

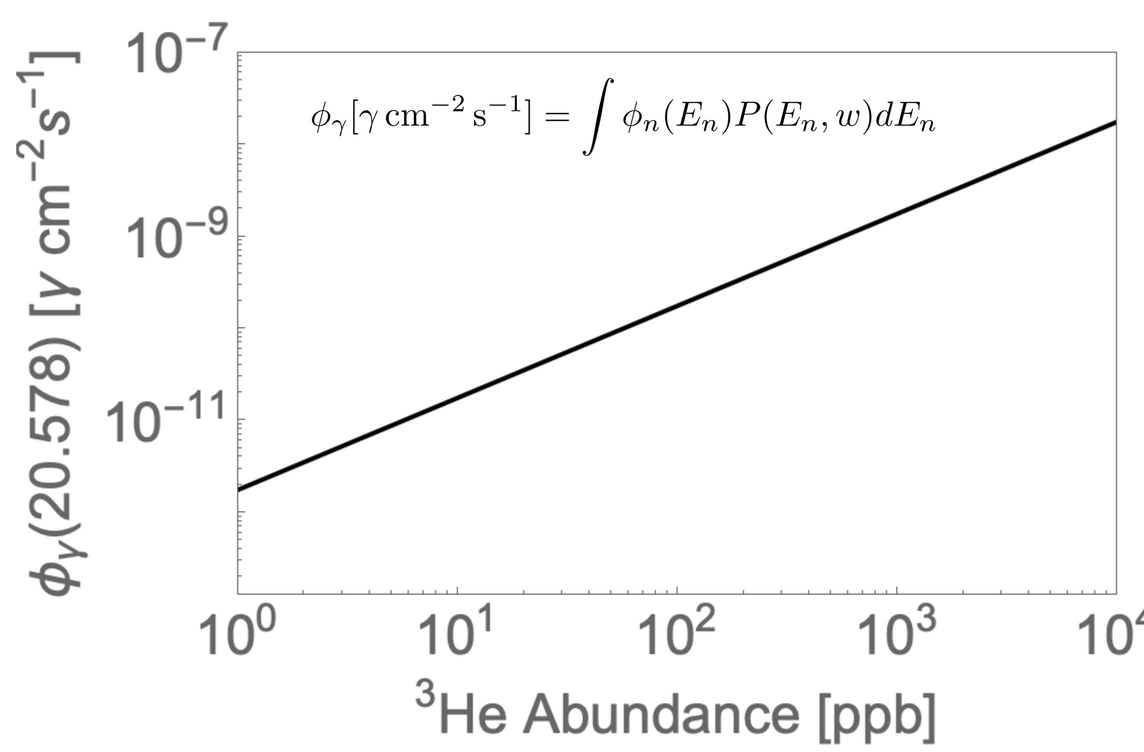

Figure 3. Flux of 20.578 MeV g-ray due to radiative neutron capture on ^{3}He. Flux (γ cm^{-2} s^{-1}) is shown as a function of ^{3}He abundance.

^{3}He Knowledge Gaps

The viability of ^{3}He remote sensing depends on inputs, the most critical of which is the ***abundance*** level of this isotope.

Apollo samples provide important, but limited, information. New lunar samples, including depth profile measurements, may change the calculus; laboratory measurements, of ^{3}He implantation, retention, adsorption, and migration, are also important.

Absent information that fills these knowledge gaps, or the presence of ^{3}He abundances at ppm-levels, prospecting based on radiative capture will remain impractical.

Other approaches are currently under study.

- Recommendation:
  - Prioritize depth profile measurement
  - Comprehensive evaluation of ^{3}He migration
  - Update estimates filled knowledge gaps

^{3}He Process Modeling

Modeling ^{3}He processes to better understand distribution and abundance across the Moon.

We have initiated a simulation effort to better understand ^{3}He deposition/migration on lunar surface. The Monte Carlo-based simulation tracks the surface-bound exospheric transport of ^{3}He on the Moon.

Particles implanted within lunar regolith undergo thermally driven desorption from grain surfaces where they subsequently hop across the lunar surface ballistically. The process is driven by spatial and temporal interpolations of bolometric temperature data [7].

^{3}He is continuously introduced to the sun-lit region of the domain using a user-defined rate. Adsorbed particles are physically bound to the surface for a period of time that depends on local temperature and is calculated by an Arrhenius-type equation [8].

Upon desorption, the particle speed is sampled from a Maxwell-Boltzmann thermal distribution corresponding to the local surface temperature. Particles with speeds less than the gravitational escape speed traverse a sub-orbital trajectory, while others are lost to space.

The model uses orbital mechanics to calculate the time of flight and landing location where it will re-adsorb.

Modeling Near-Surface Abundance

Preliminary simulation outputs show evidence of ^{3}He migration toward the poles and with subsequent enhancement of adsorbed ^{3}He within PSRs

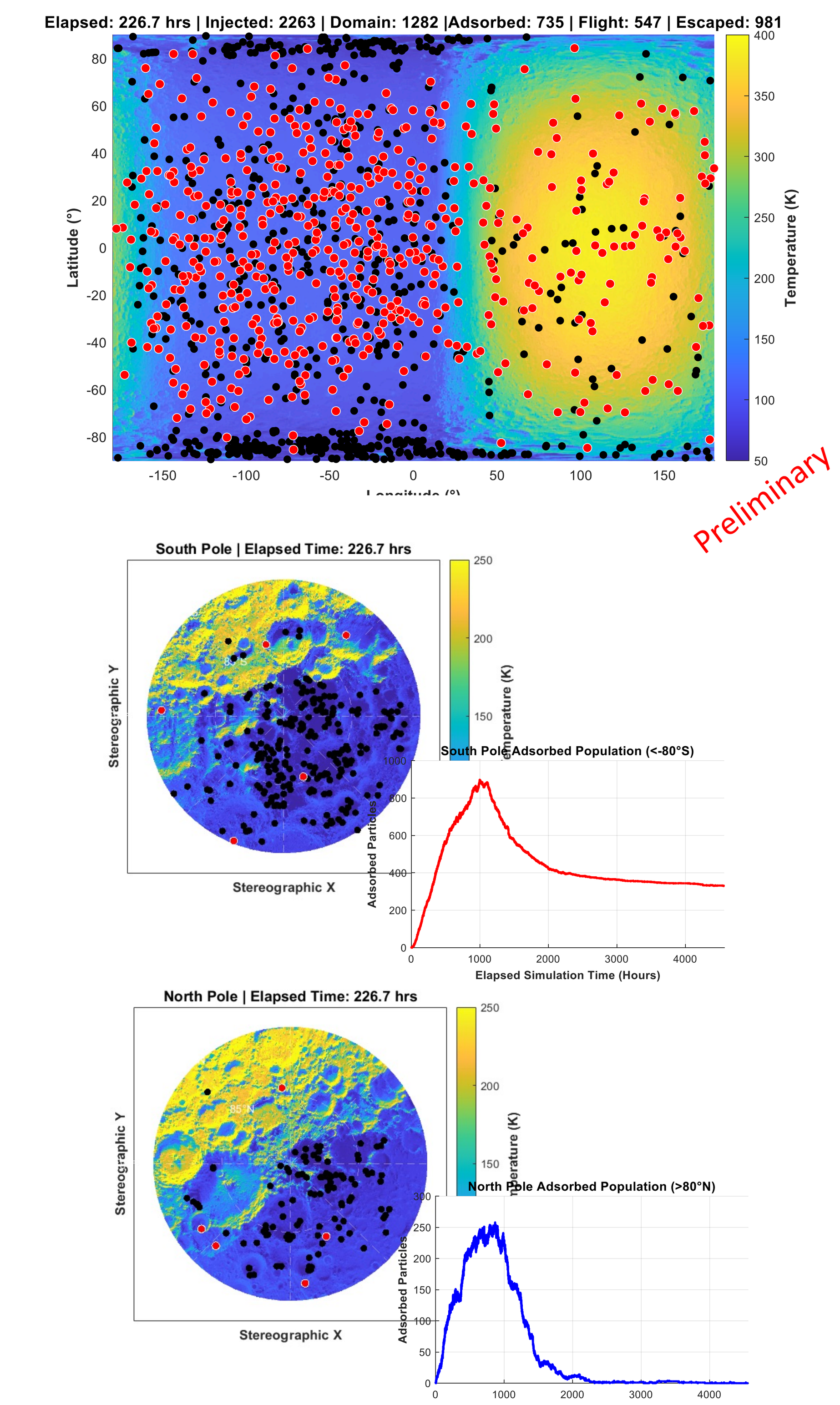

Figure 4. Preliminary simulation outputs of ^{3}He loss/accumulation due to thermal desorption and diffusion. (top) Snapshot of lunar surface showing mobile (red) and adsorbed (black) ^{3}He nuclei ~1 diurnal cycle after injection. (middle, bottom) Lunar polar regions showing adsorbed 3He deposition; (insets) accumulation and loss as a function of time. NOTE: ^{3}He injection stopped at ~100 hours.

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