LUNAR ELEMENTAL ABUNDANCES FROM GAMMA-RAY AND NEUTRON MEASUREMENTS.  R. C. Reedy1 and D. T. Vaniman2, 1Mail Stop D436, Los Alamos National Laboratory, Los Alamos, NM 87545, USA (reedy@lanl.gov), 2Mail Stop D462, Los Alamos National Laboratory, Los Alamos, NM 87545, USA (vaniman@lanl.gov).

Introduction: The determination of elemental abundances is one of the highest science objectives of most lunar missions. Such multi-element abundances, ratios, or maps should include results for elements that are diagnostic or important in lunar processes, including heat-producing elements (such as K and Th), important incompatible elements (Th and rare earth elements), hydrogen (for solar deposits and regolith maturity), and key variable elements in major lunar provinces (such as Fe and Ti in the maria). Both neutron and gamma-ray spectroscopy can be used to infer elemental abundances; the two complement each other.

These elemental abundances need to be determined with high accuracy and precision from measurements such as those made by the gamma-ray spectrometer (GRS) [1] and neutron spectrometers (NS) [2] on Lunar Prospector. As presented here, a series of steps, computer codes, and nuclear databases are needed to properly convert the raw gamma-ray and neutron measurements into good elemental abundances, ratios, and/or maps.

Lunar Neutron Spectroscopy: Lunar Prospector (LP) is the first planetary mission that has measured neutrons escaping from a planet other than the Earth [2]. The neutron spectrometers on Lunar Prospector measure a wide range of neutron energies. The ability to measure neutrons with thermal (E<0.1 eV), epithermal (E=0.1-1000 eV), and fast (E=0.1-10 MeV) energies maximizes the scientific return, being especially sensitive to both hydrogen (using epithermal neutrons) and thermal-neutron-absorbing elements [3].

Neutrons are made in the lunar surface by the interaction of galactic-cosmic-ray (GCR) particles with the atomic nuclei in the surface. Most neutrons are produced with energies above about 0.1 MeV. The flux of fast neutrons in and escaping from the Moon depends on the intensity of the cosmic rays (which vary with solar activity) and the elemental composition of the surface. Variations in the elemental composition of the lunar surface can affect the flux of fast neutrons by about 25% [2,4], with Ti and Fe emitting more fast neutrons than light elements like O and Si.

Most elements moderate neutrons to thermal energies at similar rates. The main exception is when neutrons scatter from hydrogen, in which case neutrons can be rapidly thermalized [3].

The cross sections for the absorption of thermal neutrons can vary widely among elements, with major elements like Ti and Fe having high capture cross sections. Some trace elements, such as Sm and Gd, have such large neutron-absorption cross sections that, despite their low abundances, they can absorb significant amounts of thermal neutrons in the Moon [5].

Because the processes affecting neutrons are complicated, good modeling is needed to properly extract elemental information from measured neutron fluxes. The LAHET Code System (LCS) can be used to calculate neutron fluxes from GCR interactions in the Moon [4].

Lunar Gamma-Ray Spectroscopy: The main sources of planetary gamma rays are the decay of the naturally-occurring radioactive isotopes of K, Th, and U and the interactions of GCRs with atomic nuclei in the planet’s surface. Most “cosmogenic” gamma rays are produced by fast and thermal neutrons made in the planet’s surface by GCRs, and their production rates can vary with time. Over 300 gamma-ray lines have been identified that can be emitted from planetary surfaces by a variety of production mechanisms [5]. There exist nuclear databases that can be used to identify and quantify other gamma-ray lines. Use will be made of gamma rays from major elements, particularly those from Si and O that have not been routinely used in the past.

The fluxes of gamma rays from a given element can vary depending on many factors besides the concentration of that element. For example, the fluxes of neutron-capture gamma rays in the planetary region of interest depend on (1) the total cross section for elements to absorb thermalized neutrons [5] and (2) on the hydrogen content of the top meter of the surface [e.g., 3]. The fluxes of the fast neutrons that induce inelastic-scattering and other nonelastic-scattering reactions can vary with the composition of the surface [4].

Data Analysis: There are several key steps in preparing gamma-ray data into a form from which accurate elemental abundances can be determined. One needs to identify, quantify, and remove or correct for all backgrounds in the gamma-ray spectra. Among the more important of these backgrounds are features made by the decay of radioactivities made in the GRS by cosmic-ray particles and the prompt and decay gamma rays emitted from the material surrounding the active elements of the LP GRS and from the LP spacecraft. Gamma-ray spectra obtained during the cruise to the Moon or those measured while LP was at various distances from the Moon can be used to distinguish features in the gamma-ray spectra that are from the Moon and those that are made on the LP spacecraft.

Each background-corrected spectrum will be analyzed with existing gamma-ray spectral-unfolding codes to identify the energies and intensities of all peaks. These peaks will be examined when there are potential interferences in the analysis of a given gamma-ray line [5]. Such interferences could be a problem for determining Mg and Al using some of their inelastic-scattering gamma rays, such as the 1.369-MeV gamma ray from Mg that is also readily made from Al and Si.

The key set of data needed to get elemental abundances from the fluxes of gamma rays in the processed spectra are good values for the fluxes of gamma rays that should be emitted from a given region for known or nominal elemental abundances. Such flux determinations were done for analysis of the Apollo gamma-ray data [5]. The codes to do such calculations and the nuclear data used in such calculations
have been improved much since then.

Since about 1990, improved computer codes, such as LCS [4], that numerically simulate the interactions of GCR particles with matter have been developed at Los Alamos. These codes have been well tested using measurements from lunar samples and meteorites at accelerators. The output from LCS includes the fluxes of protons and neutrons as a function of depth in the Moon and the fluxes escaping from the Moon. These particles produce the nonelastic-scattering gamma rays. LCS can also calculate the rates for the capture of thermal neutrons by various elements.

These LCS-calculated particle fluxes or capture rates need to be converted into production rates for the gamma rays of interest as a function of depth in the Moon’s surface using several sets of nuclear data, such as cross sections for nonelastic-scattering reactions or gamma-ray yields for neutron-capture reactions. The fractions of these gamma rays that escape into space without undergoing an interaction will then be calculated to give the expected fluxes of gamma rays at the LP GRS.

Preparing and Interpreting Elemental Maps: The elemental abundances and ratios obtained from gamma-ray and neutron spectra for various regions and features of the Moon will be compiled. The precision and accuracy of these results need to be examined closely. Large regions of the Moon with known or well-inferred compositions need to be identified that could be used for “ground truth” in testing these elemental results. Ground-truth regions and counting rates for various energy bands in the LP GRS data for those lunar regions can be used to create additional elemental maps in a manner similar to that done for Th, Fe, and Ti from the Apollo GRS.

Scientific Studies: A few of the studies of the Moon that we want to do are noted below.

Mapping of Highland Lithologies. Some of the key parameters in lunar highland analysis, such as Ca/Al and Al/Si ratios, are unlikely to be determined accurately enough from the LP data to be useful. However, other questions in highland studies are almost certain to be addressable with elements that will be well determined from the LP GRS and NS data.

The question of lunar granite occurrences is still open. Granitic impact products suggest granitic areas large enough to contain significant impacts without large-scale admixture of non-granitic regoliths or lithologies; we can test whether these zones of impact are large enough to be seen by the LP instruments. Regions with high contents of Si or high K/Th ratios might represent granite or other rare lunar components.

Although KREEP may be principally derived from a localized region beneath the lunar nearside [e.g., 1], there is no certainty that other lunar incompatible-element enrichments have not been isolated at other times and places in the highlands. Maps of K, Th, and REE across the entire Moon can extend “KREEP” studies into a more complete understanding of late-stage lunar crustal evolution.

It may be possible to map volatile-element depletions from Lunar Prospector data. Silica volatilization is known from a variety of Si-depleted compositions. The Si/O ratio could be used to test for the presence of Si-depleted impact melts extensive enough to approach the scale of the footprints for the LP GRS.

Mapping of Mare Basalt Lithologies. In mapping mare basalts, the elements most readily measured with the Lunar Prospector gamma-ray instrument (Ti, Fe, Th, K) are particularly suited to recognize and map the principal known varieties of lunar basalts, including “high-Ti” and “high-K” basalt types. Distinguishing low-Ti from very low Ti (<1.5% TiO2) classes may be difficult. Some high-K basalts (>0.4% K2O) may be readily identifiable, but it will again be important to determine to how low a level the gamma-ray K data are reliable for mapping.

Mapping of Soil Maturity and Hydrogen Indices. The Lunar Prospector neutron data can provide a new view of regolith maturity using H content, which should vary directly with regolith maturity. Effects such as enhanced H retention in ilmenite-rich regolith can be addressed by the examination of Ti abundances and Ti/Fe ratios along with the epithermal (and thermal and fast) neutron data. The value of a global map of lunar soil maturity is immense. Our present understanding of regolith maturity is largely biased toward mare regions and away from heavily-cratered terranes. This implies an incomplete understanding of the most evolved lunar regoliths. Mature regolith has value in resource applications and in targeting future exploration for understanding impact and solar-emission history in the vicinity of Earth.

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