REGOLITH EXPOSURE OF LUNAR METEORITES BASED ON NEUTRON CAPTURE INDUCED SHIFTS IN SAMARIUM ISOTOPIC COMPOSITION. K. C. Welten[1], T. L. Owens[2], D. J. DePaolo[2] and K. Nishiizumi[1], [1]Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA (kcwelten@berkeley.edu); [2]Center for Isotope Geochemistry, University of California, Berkeley, CA 94720, USA.

Introduction. Most lunar meteorites have unique cosmic-ray exposure (CRE) histories with long exposure times on the Moon, followed by very short transfer times from the Moon to Earth, typically 10^3-10^6 yr. Due to these short transfer times of lunar meteorites in space, the inventories of most cosmogenic radionuclides with half-lives of 10^5-10^7 yr contain contributions from exposure in the lunar regolith. The radionuclide results indicate that about half of the lunar meteorites were irradiated at depths of <1000 g/cm^2 (<5 m) during the last 10 Myr on the Moon [1]. While the cosmogenic radionuclides only constrain the irradiation conditions during the last few Myr, the concentrations of stable cosmogenic noble gases in lunar meteorites suggest CRE ages of ~100 Myr to 2 Gyr [2]. However, the details of this exposure on the Moon are not well constrained, because the cosmogenic noble gases do not provide reliable information on the average irradiation depth. Consequently, it is not clear how long the lunar meteorites were exposed near the surface of the Moon and if they were exposed at a constant depth, or if their exposure conditions in the lunar regolith changed with time as a function of lunar impact events. To fill this gap in knowledge we measured the stable isotope composition of Samarium (Sm). Since ^{149}Sm has an exceptionally large neutron-capture cross section (σ_{th}=41,000b), the ^{150}Sm/^{149}Sm ratio increases from their average solar system abundance if Sm is subjected to bombardment by low-energy neutrons. The degree of this shift is a function of the integrated low-energy neutron dose, which is much higher for 2π exposure on the lunar surface than for 4π exposure as a small object in space. The depth dependence of the lunar neutron flux is well understood based on (previous) measurements of the lunar neutron flux [3] and of neutron-capture produced ^{41}Ca in the Apollo 15 drill core [4]. In this study, we measured the isotopic composition of Sm in 5 lunar meteorites and discuss their exposure history on the lunar surface.

Meteorite samples. We selected ALH 81005, MAC 88105, LAP 02205, QUE 93069 and QUE 94281. The cosmogenic radionuclide concentrations [5-8] show that they were ejected from different depths on the lunar surface, ranging from 75 ± 15 g/cm^2 for QUE93, 165 ± 15 g/cm^2 for ALH81, 295 ± 15 g/cm^2 for QUE94, 380 ± 20 g/cm^2 for MAC88 and 700 ± 30 g/cm^2 for LAP02. Cosmogenic noble gas concentrations in four of these meteorites suggest that they had CRE ages in the lunar regolith ranging from 400 ± 60 Myr for QUE94 to 1000 ± 400 Myr for QUE93 [2].

Chemical separations. We dissolved aliquots of 60-100 mg in HF/HNO$_3$. After complete dissolution of the samples, we separated the REE's from the major elements using a 5 ml Dowex AG50W-X8 cation column and then separated Sm and Gd from the other REE's using a 1.4 ml Eichrom LN column [9]. We typically loaded 100-200 ng of the Sm fractions on a Re double filament and 100 ng of a terrestrial Sm standard from Ames high purity metal.

TIMS measurements. We measured the isotopic composition of Sm on a Thermo Finnigan Triton multi-collector instrument. We simultaneously measured the seven isotopes of Sm as well as interfering species of ^{143}Nd on the low-mass side and ^{155}Gd on the high-mass side. We corrected the ^{144}Sm, ^{148}Sm and ^{150}Sm signals for Nd interferences, based on the measured ^{143}Nd/^{152}Sm ratios, resulting in reliable ^{144}Sm/^{152}Sm ^{144}Sm/^{152}Sm ratios consistent with terrestrial Sm. Typical blank levels of our chemical separation procedures are ~20 pg Sm. Results for ^{149}Sm/^{152}Sm and ^{150}Sm/^{152}Sm ratios are shown in Table 1. Errors represent 2σ uncertainties.

Table 1. Measured Sm isotope ratios in lunar meteorites.

Sample	^{149}Sm/^{152}Sm	^{150}Sm/^{152}Sm	ε(^{150}Sm)
ALH 81005	0.513247±11	0.279382 ± 8	122.5 ± 0.3
LAP 02205	0.516649±21	0.276175±19	6.3 ± 0.7
MAC 88105	0.51413 ± 5	0.27855 ± 5	92.4 ± 2.0
QUE 93069a	0.512514±11	0.280169 ± 9	151.0 ± 0.3
QUE 93069b	0.512547 ± 6	0.280139 ± 5	150.0 ± 0.2
QUE 94281	0.515155 ± 5	0.277686 ± 3	61.2 ± 0.2

Results and discussion. The measured Sm isotopic compositions of the lunar meteorites show large isotopic shifts in ^{149}Sm/^{152}Sm (−4-84 ε units) and ^{150}Sm/^{152}Sm (6-150 ε units). The ^{149}Sm/^{152}Sm and ^{150}Sm/^{152}Sm ratios of all 5 lunar meteorites plot on a line with slope −1 (Fig. 1), confirming that the isotope shifts are due to production of ^{150}Sm from ^{149}Sm by neutron capture. The isotopic shifts in ALH81, MAC88, and QUE94 are similar to those found in the Apollo drill cores [9-13], while the Sm isotopic shift in QUE93 is ~15% higher than the largest shift detected in the Apollo samples.. The isotopic shift in LAP02 is much lower than in the Apollo samples, which is consistent with its ejection depth of ~700 g/cm^2.

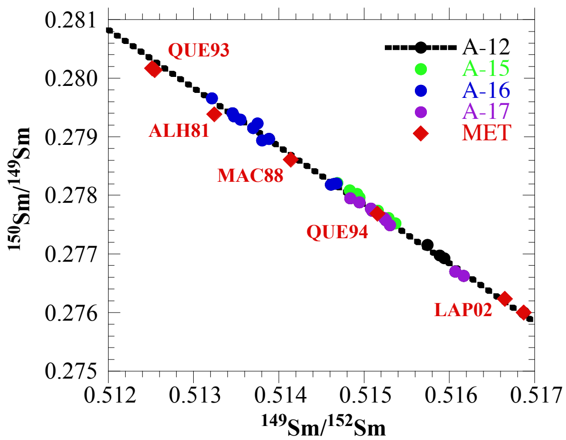

Figure 1. Correlation between ^{150}Sm/^{152}Sm and ^{149}Sm/^{152}Sm ratios in lunar meteorites in comparison with literature values of Apollo samples [9-13].

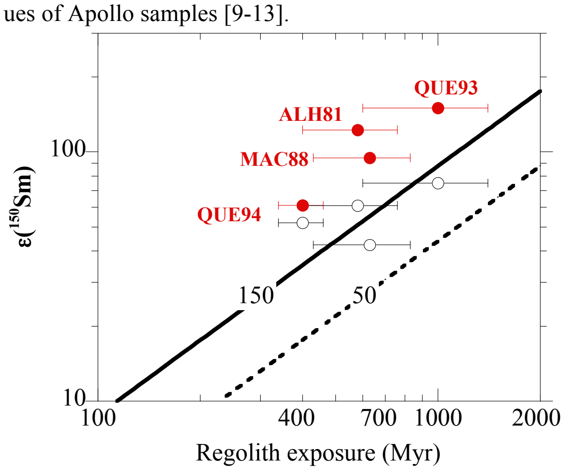

Figure 2. Measured isotopic shift in ^{150}Sm/^{152}Sm ratio (solid symbols) in lunar meteorites as a function of noble gas regolith exposure ages [2] in comparison with calculated isotopic shifts for depths of 50 and 150 g cm^{-2} in Apollo 15. Open symbols include corrections for different composition of lunar meteorites.

The measured Sm isotopic shifts are higher than the expected shifts based on published regolith exposure ages and theoretical neutron capture rates for Apollo 15 (Fig. 2). These large shifts are partly due to the ~50% lower macroscopic cross sections for ALH81, QUE93 and MAC88, which results in higher neutron capture rates [14,15]. If we make a first-order correction for this effect, the values agree much better with the regolith exposure ages, but only if we assume that the lunar meteorites were exposed near the maximum thermal neutron production depth of ~150 g/cm^2. This is significantly deeper than the typical depth of 50-100 g/cm^2 that is used to calculated the regolith exposure ages of lunar meteorites based on cosmogenic noble gases [2]. In addition, the isotopic shift in QUE94 still falls above the maximum value for an age of 400 Myr. The combined evidence of cosmogenic radionuclides and Sm isotopes suggest that the cosmogenic noble gases underestimate the regolith exposure time. A possible explanation is the loss of cosmogenic noble gases during compaction of the lunar regolith into consolidated rock or during ejection of the meteorites from the Moon, as was also proposed for solar gases [2]. The measured isotopic shifts can be explained by CRE ages of ~700 Myr for ALH81, ~900 Myr for QUE 94, ~1.0 Gyr for MAC 88, ~1.1 Gyr for LAP and ~1.2 Gyr for QUE 93 if they were exposed at the same depth from which they were ejected. An alternative explanation for the small isotopic shift in LAP02 is a CRE age of 70-100 Myr at a depth of 100-200 g/cm^2, but this requires a unlikely complex scenario of exposure near the surface, followed by burial at a depth of ~700 g/cm^2.

Conclusions. The measured isotopic compositions of Sm in 5 lunar meteorites show large variations in ^{149}Sm/^{152}Sm and ^{150}Sm/^{152}Sm due to neutron capture. The observed isotopic shifts can best be explained by CRE ages of 700-1200 Myr in the lunar regolith. These ages are significantly longer than the ages of 400-1000 Myr based on cosmogenic noble gases, suggesting that the cosmogenic noble gas inventory in some of these meteorites was affected by diffusion losses, possibly during ejection of the meteorites from the lunar surface. This implies that the Sm (and Gd) isotopic record of lunar meteorites is more reliable to study regolith exposure histories than the noble gas record.

Acknowledgments. This work was supported by a NASA Cosmochemistry grant. We thank MWG for allocation of the lunar meteorite samples.

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