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SCR ^{21}Ne AND ^{38}Ar IN LUNAR ROCK 68815: THE SOLAR PROTON ENERGY SPECTRUM OVER THE PAST 2 MYR;

D. H. Garrison[1], M. N. Rao[2], D. D. Bogard
(NASA Johnson Space Center, Houston, TX 77058; 1-also Lockheed-ESC; 2-also Lunar & Planetary Inst.),
and R. C. Reedy (Los Alamos Natl. Lab., Los Alamos, NM 87545)

Abstract: We determined concentration profiles of ^{21}Ne, ^{22}Ne, and ^{38}Ar produced by solar protons as a function of depth in oriented lunar rock 68815. A comparison with model predictions indicate a solar proton flux J(4π; E >10 MeV) of 100-125 p/cm^2/s and a rigidity R$_o$ of 85-100 MV, assuming an erosion rate of 1-2 mm/Myr. These results for 68815 and similar results on 61016 define the integrated solar proton energy spectrum at the moon over the past ~2 Myr.

Previous Work: For oriented rock 61016, which like 68815 has a simple ~2 Myr exposure history [1], we recently resolved SCR ^{21}Ne, ^{22}Ne, and ^{38}Ar produced by nuclear interactions of energetic (~10-100 MeV) solar protons [2,3]. Concentrations of the SCR component significantly decreased with sample depth and gave the first depth profiles for stable, SCR nuclides. The ^{21}Ne/^{22}Ne ratios produced by solar (SCR) and galactic (GCR) protons were easily resolved. These SCR concentration profiles matched theoretical production profiles for a 4π proton flux above 10 MeV of J = 100 p/cm^2/s and an exponential rigidity spectral parameter [4,5], R$_o$, between 70 and 85 MV [3]. Several investigators have reported in 68815 the presence of SCR radionuclides [6,7,8,9] and possibly of SCR ^{3}He and ^{21}Ne [10]. The ^{26}Al and ^{53}Mn depth profiles were consistent with $J_{>10}$ = 70 p/cm^2/s and R$_o$ = 100 MV [6]; the profile for SCR ^{14}C (in the same 68815,292 depth column as our samples) yielded $J_{>10}$ = 144 p/cm^2/s at R$_o$ = 85 MV, or $J_{>10}$ = 91 p/cm^2/s at R$_o$ = 100 MV [7]; depth profiles of SCR ^{81}Kr suggested $J_{>10}$ = 160 p/cm^2/s at R$_o$ = 85 MV [8]. The nearly flat depth profile for ^{10}Be in 68815 suggested a softer proton spectral shape than previous work [9].

Experimental: From 10 carefully prepared and documented depth samples (0 to 4.3 cm) of 68815,292, gases were extracted in either two or three temperature steps of 500°C and 1600°C or 350°C, 950°C, and 1600°C. Isotopic abundances were determined by mass spectrometer, using techniques previously described [3]. Chemical composition of the samples (electron microprobe analysis by V. Yang, NASA/JSC) indicated a mixture of 80% plagioclase, 12% olivine/pyroxene, and 8% glass. The Mg concentration is 3.74%.

68815 Results: A 3-isotope correlation plot for all neon data (Fig. 1) indicate mixing between an implanted solar component with ^{20}Ne/^{22}Ne = 12.6 (determined by the surface sample) and a cosmogenic component with variable composition. (All samples released solar-implanted Ne and Ar, some at 1600°C, which we assume was incorporated into high temperature glass phases during breccia formation.) The theoretical field shown for SCR Ne was calculated using the measured major elemental concentrations, and, due to the presence of Mg, lies slightly closer to GCR Ne in 68815 than in 61016. The isotopic variation of cosmogenic Ne in 68815 is attributed to variable mixtures of solar proton-produced (SCR) Ne with galactic-produced (GCR) Ne and is shielding dependent over the range represented by these sample depths. Extrapolation of temperature data for individual samples to cosmogenic ^{20}Ne/^{22}Ne = 0.9 suggests a cosmogenic ^{21}Ne/^{22}Ne end-point for surface samples of ~0.66. This ratio is similar to the SCR + GCR value of 0.64 observed in 61016 and the predicted value of 0.65 for the composition and shielding of 68815.

Total (GCR + SCR) cosmogenic ^{21}Ne and ^{38}Ar concentrations for each sample are plotted vs. depth in Figs. 2a and 2b. Cosmogenic ^{22}Ne concentrations show a profile similar to ^{21}Ne. Surface-implanted neon and argon were removed by lever rule correction assuming trapped ^{20}Ne/^{22}Ne = 12.6 and ^{36}Ar/^{38}Ar = 5.35. Cosmogenic ^{21}Ne and ^{38}Ar comprise 84.5-99.8% and 23-84.6%, respectively, of the total isotopic releases. Since GCR production rates vary little over 0-43 mm, the systematic increase in concentrations of cosmogenic ^{21}Ne and ^{38}Ar with decreasing shielding is due to production by solar protons. These SCR production profiles are similar to the ^{21}Ne and ^{38}Ar profiles found in lunar rock 61016 [2,3] and to radionuclide profiles measured in 68815 [6-9]. Assuming the ^{21}Ne concentration of 0.184×10^{-8} cm^{3}STP/g in the deepest sample (42 mm) represents only GCR production, and assuming a production rate of 0.099×10^{-8} cm^{3}STP/g/Myr [11], we obtain a GCR exposure age of 1.8 Myr. Similarly, the cosmogenic ^{38}Ar concentration of 0.195×10^{-8} cm^{3}STP/g measured in the same sample and a production rate of 0.11×10^{-8} cm^{3}STP/g/Myr [11] gives a GCR exposure age of 2.1 Myr. Considering uncertainties in production rates and absolute abundance, these exposure ages suggest that <10% of the ^{21}Ne and ^{38}Ar concentrations in the 42.8 mm sample are due to SCR production.

Solar Proton Energy Spectrum: We now compare the SCR depth profiles with theoretical predictions for different proton fluxes, rigidity, and surface erosion rates. Theoretical SCR + GCR production curves [4,5] are shown (Fig. 2) for a 4π proton flux J (E >10 MeV) of 100 p/cm^2/s and four values of R$_o$. Each theoretical profile is normalized to the deepest sample, uses a measured rock density of 2.3 g/cm^3, and assumes a surface erosion rate (Q) of 1 mm/Myr and a depth-constant GCR component. Profile shapes are not especially sensitive to Q or sample density, but are more sensitive to J and R_o [3]. Because variations in J and R_o have opposite effects on the curve fit, only ranges and not unique values can be derived. Additional constraints are the close agreement between calculated and expected GCR exposure ages and the observation that Ne isotopic ratios from the deeper samples fall close to expected GCR values (Fig .1). Both observations indicate <10% SCR production at depths of ~42 mm, and thus provide an upper limit to R_o of ~100 MV. The values of J, R_o, and Q which give the best fit to the data were determined using a least squares technique where all parameters but one were fixed, the optimal value of the variable determined by iteration, and the process repeated for different fixed parameter values. This yielded optimal fit combinations for J = 90-140 p/cm^2/s and R_o = 85-100 MV. For a depth-variable GCR component, the optimal range of values of R_o stays the same, but the values of J and the SCR component at 42 mm depth increase somewhat, the latter usually exceeding our 10% limit. No values of R_o as low as 70 MV gave optimal fits to the data. Values of Q = 0-3 mm/Myr are all possible within these optimal fits; higher values of Q give higher values of J.

Oriented lunar rocks 68815 and 61016 provide our best evidence for the long-term flux and energy spectrum of solar protons. From Ne and Ar results, we conclude that the best parameters to describe the average solar energy spectrum over the past 2 Myr are J = 100-125 p/cm^2/s, R_o = 85-100 MV, and erosion = 1-2 mm/Myr. These ranges can be further constrained by fixing specific parameters. The 68815 and 61016 Ne and Ar profiles imply a solar proton spectrum that is less energetic than that suggested by earlier radionuclide data [6], but similar to more recent radionuclide data [7-9].

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Fig. 1 (Below) Neon 3-isotope correlation plot for temperature extractions of depth samples of 68815. Uncertainties are ~1% and fall within the symbols. The 350°C data (not shown) represent 0.4-2% of the total release (except 0.1 mm sample). Implanted solar wind and solar flare compositions and the theoretical SCR Ne field produced *in situ* by energetic solar protons are also shown.

Fig. 2 (Right) Cosmogenic ^{21}Ne (upper) and ^{38}Ar (lower) concentrations (symbols) vs. depth from the rock surface. Uncertainties are ~±3%, or approximately twice the symbol size. Sample thickness ranged from ~1mm near the surface to ~3mm at the deepest location. Surface samples with >96% solar-implanted Ne and Ar are not shown. Lines represent theoretical SCR concentrations for the same depths, each normalized to the deepest sample.