PRODUCTION RATES OF COSMOGENIC NUCLIDES IN THE KNYAHINYA L-CHONDRITE.

K. J. Kim[1] and R. C. Reedy[1], [1]Institute of Meteoritics, MSC03-2050, University of New Mexico, Albuquerque, NM 87131-0001 USA (kkim@unm.edu; rreedy@unm.edu).

Introduction: The production rates of spallogenic radionuclides and stable isotopes in the L-chondrite Knyahinya were investigated using the MCNPX code. Numerous cosmogenic nuclides had been measured in many Knyahinya samples [1,2,3]. The pre-atmospheric size and sample locations of Knyahinya are well known [1], thus Knyahinya is a good test case for cosmogenic-nuclide production-rate calculations [e.g., 2,4]. Our calculated profiles were compared to the measurements to determine effective proton fluxes.

Calculations: The MCNPX (Monte Carlo N Particle eXtended) code [5] combines the latest versions of the LAHET code for high-energy particles and the neutron code MCNP used by Masarik and co-workers [e.g., 2,3,6]. Using version 2.4.k of the MCNPX code with its default parameters, fluxes of protons and secondary neutrons were calculated for a series of 86 concentric spherical shells inside a 45 cm sphere, assuming a density of 3.7 g/cm^3 and an L-chondrite bulk composition. The spectral shape of the incident galactic-cosmic-ray (GCR) protons was the same as that of [6]. Production rates of cosmogenic nuclides were then calculated using these neutron and proton fluxes, compositions of the analyzed Knyahinya samples (bulk [1,3] or non-magnetic fractions [2]), and our most-recent sets of neutron and proton cross sections for all major targets.

We used both the CEM (Cascade-Exciton Model) option of MCNPX and the default physics model, Bertini (BER). CEM provides new approximations for the elementary cross sections used in the high-energy intranuclear cascade and other refinements. Production rates of all stable and radionuclides in Knyahinya were investigated and effective proton fluxes using both BER and CEM models were studied.

Results and discussion: Figure 1 shows the calculated fluxes of protons and neutrons in Knyahinya. The primary high-energy protons decrease as secondary low energy protons increase as the depth increases. However, the secondary neutron fluxes increase for all energies as the depth increases.

Figures 2-5 show our calculated production rates of ^{3}He, ^{10}Be, ^{21}Ne, and ^{53}Mn. An exposure age of 39 Ma was used for stable nuclides. Both BER and CEM gave very similar profiles for these nuclides. As expected, high-energy products like ^{3}He and ^{10}Be have fairly flat profiles while low-energy products like ^{21}Ne and ^{53}Mn increase with depth. Our calculated production rates were compared with the measured concentrations [1,2,3]. The shape of our calculated profiles agreed well with the measured depth profiles in Knyahinya. We determined the effective proton flux needed to match the measured data for each nuclide. However, the ^{10}Be data fit was poorer than for other nuclides. We fit our calculated rates to near-surface samples and the lower ^{10}Be values at greater depths.

Table 1 gives the effective proton fluxes for these nuclides from both MCNPX models. The effective fluxes for CEM models are lower by 5-13% than those for BER. Interestingly, high-energy products tend to have lower BER/CEM ratios. The effective fluxes for high-energy products tended to be higher. These results suggest that the calculated energy distribution of the fluxes might not be fully accurate. More work will be done to study these calculated particle fluxes.

The average effective proton fluxes for both BER and CEM are within the expected values of 4-5 p/cm^2/s. Assuming that the GCR flux did not change over this time period, the spread in our J values for various nuclides made by similar reactions indicates that work is needed to refine our cross sections. Other good test cases for cosmogenic nuclides that will be used to help refine our cross sections include the Apollo 15 deep drill core, terrestrial surface samples, and thick targets irradiated with high-energy protons.

Previous effective proton fluxes for Knyahinya were 4.8 [2] and 4.06 [4]. Our average value is close to the value of [2]. Because similar cross sections were used both here and in [2], the differences between our fluxes and those of [2] are due to differences in the codes used (such as the routines used for >5 GeV).The comparisons of our calculations with the measurements of cosmogenic nuclides in Knyahinya indicate that, while present calculations are fairly good, both the calculated particle fluxes and the adopted cross sections need to be improved.

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References: [1] Graf Th. et al. (1990) *Geochim. Cosmochim. Acta, 54,* 2511-2520. [2] Reedy R. C. et al. (1993) *Lunar Planet. Sci., 24,* 1195-1996. [3] Jull A. J. T. et al. (1994) *Meteoritics, 29,* 649-651. [4] Leya I. et al. (2000) *Meteorit. Planet. Sci,. 35,* 259-286. [5] Kim K. J. et al. (2003) *Lunar Planet. Sci., 34,* #1532. [6] Masarik J. and Reedy R .C. (1994) *Geochim. Cosmochim. Acta, 58,* 5307-5317.

Table 1. Effective protons fluxes ($p/cm^2/s$) and their ratios for the two models used in this study.

Nuclides	BER	CEM	BER/CEM
^{10}Be	5.28	5.00	1.056
^{14}C	4.76	4.20	1.133
^{26}Al	3.92	3.52	1.114
^{26}Cl non-magnetic	5.20	4.92	1.057
^{53}Mn	4.64	4.40	1.055
^{3}He	6.20	5.84	1.062
^{21}Ne	4.52	4.16	1.087
^{22}Ne	4.64	4.20	1.105
^{36}Ar	3.56	3.28	1.085
^{36}Ar	3.80	3.48	1.092
Eff. avg. proton flux	4.63	4.28	1.080

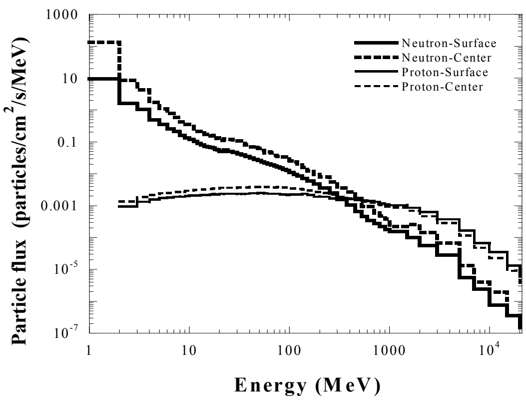

Fig. 1. Particle fluxes for both neutrons and protons as a function of their energies.

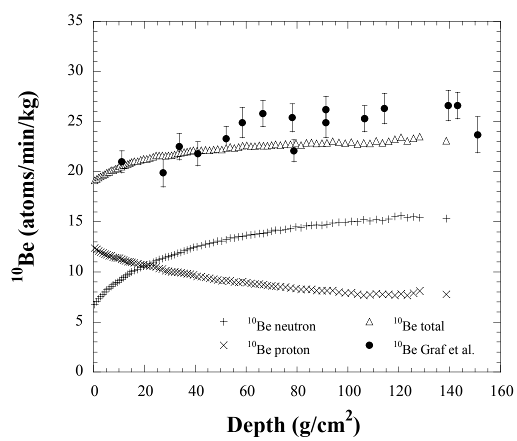

Fig. 2. Production rates of ^{10}Be as a function of depth.

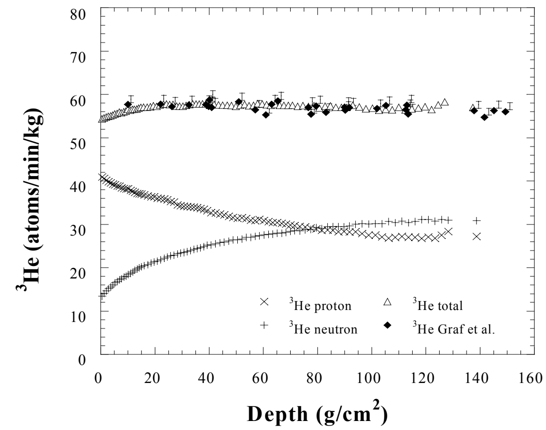

Fig. 3. Production rates of ^{3}He as a function of depth.

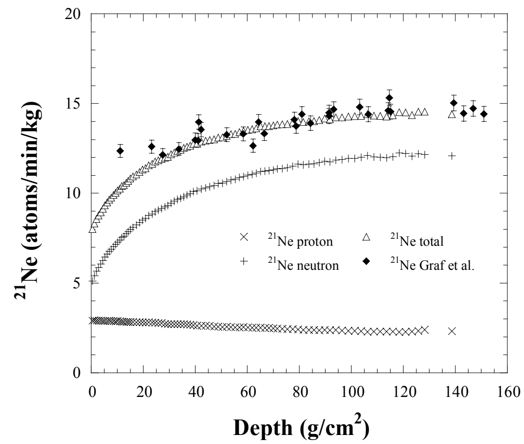

Fig. 4. Production rates of ^{21}Ne as a function of depth.

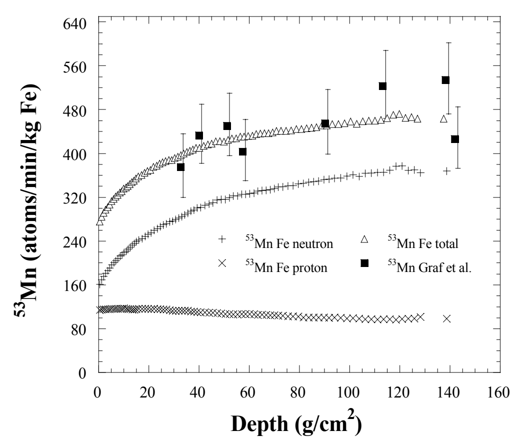

Fig. 5. Production rates of ^{53}Mn as a function of depth.