COSMOGENIC-RADIONUCLIDE PRODUCTION RATES IN MINI-SPHERULES.*

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The cosmogenic radionuclides 1.5-Ma ^{10}Be, 0.7-Ma ^{26}Al, and 3.7-Ma ^{53}Mn measured in small "cosmic spherules" have been used to study the exposure histories of these spherules in (1-6). Some of the original measurements (e.g., 1-4) showed from the high ^{26}Al contents of some spherules that they had received irradiation by protons in the solar cosmic rays (SCR) and thus were not pieces from the insides of meteorites. The cosmogenic-nuclide data suggested that the spherules had been small objects in space. The fairly high contents of ^{10}Be indicated that the spherules had been irradiated for $\gtrsim 10^6$ years. Previously I reported calculated production rates for cosmogenic radionuclides in very small stony objects (7), in metallic spherules of small radii (8), and in interstellar space (9). Here I report calculated production rates for several radionuclides in stony objects with radii up to 5 g/cm^2 ("mini-spherules") using the averaged chemistry of (6) for a series of stony spherules (which, in weight percent, was O=40.7%, Mg=17%, Al=1.4%, Si=16.5%, Ca=1.4%, and Fe=22%).

Calculation of the Production Rates. The fluxes for solar protons were those that fit the ^{26}Al and ^{53}Mn in lunar rock 68815 (10). Three exponential-rigidity spectral shapes with R_o from 70 to 100 MV were used with flux normalizations that fit the 68815 radionuclide data, although I used higher flux normalizations (given in Table 1) than (10) did for the lower values of R_o. These flux normalizations apply to 1 AU, and SCR fluxes are lower for greater distances from the Sun. Also used were the galactic-cosmic-ray (GCR) proton fluxes at 1 AU and interstellar (IS) space of (11). The other ISGCR fluxes in (7) were not considered here, and the ISGCR rates should be considered uncertain by ~50% because of the uncertainties in the ISGCR fluxes of protons (cf., 7,9). The same cross sections as used in (10) were used for ^{10}Be, ^{26}Al, and ^{53}Mn, and the ^{36}Cl production cross sections are from (12). Note that the cross sections for the production of ^{10}Be and ^{36}Cl are fairly uncertain, especially at low proton energies (10,12).

The radii considered include "zero" (small enough such that the whole object sees the same flux of SCR protons) and 0.5, 1, 2, 3, and 5 g/cm^2 ($\approx$0.15–1.7 cm for a density of 3 g/cm^3). The spherules were divided into 8 zones of equal mass, and the production rates in the inner 1/2 and inner 1/4 as well as an average over the whole spherule were determined from the rates for these zones. The averages for inner zones would apply if the mini-spherule lost the outer 1/2 or 3/4 of its pre-atmospheric mass in passing through the Earth's atmosphere.

Results and Discussion. The production rates of these four cosmogenic radionuclides by both SCR and GCR protons in very small objects are given in Table 1. (To get ^{53}Mn production rates per kg-Fe, divide by 0.22.) The ^{10}Be and ^{36}Cl rates are fairly uncertain, especially for the SCR, but are given here to show that the SCR-production of these two radionuclides should be low. As noted in (10), the ^{10}Be activity in the very top of lunar rocks is $\lesssim$1 dpm/kg, lower than the calculated rates, $\approx$1.5–2 atoms/(min kg), so the ^{10}Be rates here could similarly be high. SCR-produced ^{36}Cl has been seen in lunar soils (12), but the calcium content here is much lower, hence the low rates for SCR-produced ^{36}Cl. The GCR production rates in the mini-spherules considered here should be slightly higher than those in Table 1 due to the build-up of some secondary particles (13). The SCR production rates in the surface of a big object are half of the SCR rates in Table 1.

The production rates of ^{26}Al and ^{53}Mn for the very surface and center and for zonal averages in mini-spherules are given in Table 2. The production rates in spherules as small as 0.5 g/cm^2 can be considerably less than that in a very small object. For example, the average ^{26}Al or ^{53}Mn activities in a spherule of radius 0.5 g/cm^2 are about half of those in Table 1. The SCR production rates in the center of a spherule of radius 3 g/cm^2 ($\approx$1 cm) are fairly small and approaching the levels expected for GCR production. The production rates in the surface of a 5 g/cm^2 spherule are approaching those for a 2π exposure geometry. While the production rates in the very surfaces of these mini-spherules are fairly high, the loss of 1/2 the mass (the outer 20.63% of the radius) considerably reduces the radionuclide's activity. If no surface material is lost (the "average" rate), the production rates for a spherule are relatively high. The uncertainty in the spectral shape of solar protons averaged over the last ~1 Ma, $R_o\approx$70–100 MV (10), affects the rates in very small objects (Table 1) much more than those for mini-spherules, especially the larger ones.

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Table 1. Nuclide production rates, atoms/(min kg), in very small ($R \lesssim 0.1$ mm) stony objects by primary GCR protons at 1 AU and in interstellar (IS) space and by solar protons with 3 spectral shapes. For solar protons, the 4π integral fluxes above 10 MeV, J_{10}, in protons/(cm^2 s) are given.

Nuclide	GCR (1 AU)	GCR (IS)	R_o=70 MV J_{10}=150	R_o=85 MV J_{10}=100	R_o=100 MV J_{10}=70
^{10}Be	≈7.7	~28.	~3.1	~3.7	~4.0
^{26}Al	9.5	72.	920.	631.	453.
^{36}Cl	≈2.6	~10.	~0.7	~0.8	~0.9
^{53}Mn	12.7	88.	1133.	801.	585.

Table 2. Solar-proton production rates in spherules of various radii using the spectral shapes (R_o) and flux normalizations in Table 1. Locations are the very surface and center, and mass-weighted averages for the whole and inner 1/2 and 1/4, by mass, of the spherule.

Radius (g/cm^2)	Location	^{26}Al 70 MV	^{26}Al 85 MV	^{26}Al 100 MV	^{53}Mn 70 MV	^{53}Mn 85 MV	^{53}Mn 100 MV
	Surface	661.	478.	357.	842.	624.	471.
0.5	Average	481.	375.	293.	647.	507.	397.
	Inner 1/2	422.	340.	271.	577.	464.	369.
	Inner 1/4	400.	326.	262.	548.	446.	357.
	Center	371.	307.	250.	509.	421.	341.
	Surface	600.	436.	327.	761.	567.	430.
1.0	Average	357.	292.	237.	484.	397.	321.
	Inner 1/2	291.	250.	209.	399.	342.	284.
	Inner 1/4	269.	235.	199.	369.	322.	270.
	Center	241.	216.	185.	330.	295.	251.
	Surface	547.	396.	298.	689.	512.	390.
2.0	Average	243.	210.	177.	331.	286.	240.
	Inner 1/2	177.	165.	146.	242.	225.	198.
	Inner 1/4	157.	150.	135.	215.	205.	183.
	Center	133.	132.	121.	182.	180.	164.
	Surface	521.	376.	282.	654.	485.	368.
3.0	Average	186.	166.	144.	254.	226.	195.
	Inner 1/2	123.	121.	112.	168.	165.	151.
	Inner 1/4	106.	108.	101.	144.	146.	137.
	Center	86.	92.	88.	117.	124.	119.
	Surface	496.	355.	265.	620.	456.	345.
5.0	Average	127.	118.	106.	173.	161.	143.
	Inner 1/2	71.	76.	74.	97.	103.	100.
	Inner 1/4	58.	65.	65.	79.	88.	87.
	Center	44.	52.	54.	60.	70.	73.