COSMOGENIC-NUCLIDE PRODUCTION BY PRIMARY COSMIC-RAY PROTONS

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ABSTRACT

The production rates of cosmogenic nuclides were calculated for the primary protons in the galactic and solar cosmic rays. At 1 AU, the long-term average fluxes of solar protons usually produce many more atoms of a cosmogenic nuclide than the primary protons in the GCR, the exceptions being nuclides made only by high-energy reactions (like Be-10). Because the particle fluxes inside meteorites and other large objects in space include many secondary neutrons, the production rates and ratios inside large objects are often very different from those by just the primary GCR protons. Thus it is possible to determine, by examining its cosmogenic nuclides, if a small object, such as found among deep-sea spherules, was small in space or broken from a meteorite. Because heliospherical modulation and other interactions change the GCR particle spectrum, the production of cosmogenic nuclides by the GCR particles outside the heliosphere will be different from that by modulated GCR primaries. Production rates and ratios for cosmogenic nuclides would be able to identify small particles, possibly interstellar in origin, that were exposed to an unmodulated spectrum of GCR particles and to characterize the spectrum of particles to which they were exposed.

1.   Introduction. The energetic particles in the cosmic rays are about 90% protons and induce a wide variety of nuclear reactions in extra-terrestrial matter (1). Relatively low energy (~10- to 100-MeV) particles are emitted occasionally from the sun--the so-called solar cosmic rays (SCR). The SCR particles are rapidly stopped in matter (within a few centimeters) and produce a high density of product nuclei very near the surface. The high-energy (~1-GeV) galactic cosmic-ray (GCR) particles produce a large cascade of secondary particles, especially neutrons, that penetrate meters into solid matter. The flux of GCR particles in the solar system varies with solar activity and is lowest at periods of maximum solar activity. Most studies of cosmogenic nuclides have been for large objects (the Earth, moon, and meteorites) and for long periods of time (averaged over many solar cycles). Recently, there has been more interest in cosmogenic nuclide production in very small objects (2) and also in the production variations over a solar cycle (3), outside the solar system (4), or for periods of unusual solar activity (5).

2.   Primary Cosmic-Rays. The spectrum of solar protons is well approximated by an exponential function in rigidity (6); it has an average spectral shape over the last million years (1) of R_0 = 100 MV. Castagnoli and Lal (5) give an equation for the spectral shape of the GCR as a function of a solar modulation parameter (M). For the GCR protons, spectra like those for the last two solar minima (M = 375 MeV) and maxima

(M = 950 MeV) (1,5) were used, as well as one that is similar to the average over a solar cycle (M = 550 MeV). A fourth GCR spectrum was the expression of (5) for no modulation (M = 0), possibly like that of the GCR particles outside the solar system in the local interstellar space (IS). The shape for the expression with M = 0 is very similar to (E + 1050) to the −2.87 power, with E in MeV. Such an unmodulated spectrum could be approached in the solar system during the long periods of essentially no solar activity that occur about every few hundred years (1,5). One estimate of the proton spectrum at the source of GCR particles is a power law in rigidity. At high energies, this rigidity power law was assumed to have the same intensity and shape as that observed in the solar system. As any source GCR-particle spectrum is modified by passage through ~5 g/cm^2 of matter, this pure rigidity power-law spectrum overestimates the proton fluxes at lower energies, especially below ~100 MeV (6). Production rates for seven cosmogenic nuclides were calculated with these proton spectra and with cross sections for proton-induced reactions (see Table I). The production rates of these nuclides observed in meteorites (with typical radii of 10 to 30 cm) are also shown in Table I.

3.   Cosmogenic-Nuclide Production Rates. Production by solar protons usually dominates that by primary GCR protons. Only nuclides made mainly by high-energy protons, such as Be-10 and Cl-36, have very low production rates by the low-energy solar protons. These high rates by solar protons only occur very near the surface, and solar-proton production rates become relatively unimportant below depths of a few centimeters (1,6). Only the GCR source spectrum exceeds the solar-proton production rates, mainly because of its high fluxes at lower energies. In most meteorites, production by solar protons is usually not observable because the surface layers are removed by ablation during the meteorite's passage through the Earth's atmosphere. The ratio of the amount of a nuclide readily made by solar protons (for example, Al-26) to that of a high-energy product (such as Be-10) is a good indicator of the object's size when it was irradiated in space. Activities of Al-26 and Be-10 were measured in several groups of small (0.3- to 0.5-mm) spherules collected from sediments on the ocean floor (2). The Al-26/Be-10 ratio and the Al-26 activity were quite high in several of them, which indicate that those spherules probably came from parent bodies less than a few centimeters in diameter. Studies of such small objects would be interesting because they may be different from the forms of solar system matter found in most meteorites.

The production rates of nuclides by GCR protons in interstellar space are high, similar to the rates produced by both primary and secondary GCR particles in meteorites. The relatively low-energy protons normally removed by solar modulation in the inner solar system have produced about the same number of nuclides as are made by secondary neutrons in meteorites. These high production rates, plus the relatively low loss of product nuclides by recoil in small grains (4), mean that one should be able to identify grains that were irradiated in interstellar space. Such grains may have been incorporated in meteorites or could enter the Earth's atmosphere as cosmic dust. The cross sections as a function of energy for making secondary neutrons are similar in shape to those for producing He-3. The He-3 production rate in interstellar space is 4 times that for the average over a solar cycle, and the flux of

protons above 1 GeV in interstellar space is 2.4 times that for the solar-cycle average. Thus, the production rates of cosmogenic nuclides by GCR particles that have not been modulated are higher (by factors up to 3 to 4) than those observed near the Earth during long periods of typical solar activity.

During periods of normal solar variations, the extremes in the activity of the sun and its subsequent modulation of the GCR particles are represented by the solar minimum and maximum used in Table I. The ratio of 2.4 for the He-3 production rates between these extremes is about the variation that would be expected for the production of secondary neutrons. When Evans et al. (3) measured the activities of short-lived radionuclides in a number of meteorites that fell from 1967 to 1978, the activities varied by about a factor of 3. Some of these variations probably were caused by differences in the meteorites' sizes or shapes or in the sample location. However, the calculations reported here show that most of these radioactivity variations are caused by the solar modulation of the GCR-particle flux. The observed radioactivity variations correlated well with other indicators of solar activity (3). Larger variations in nuclide production rates would be expected if the solar activity exceeded one or both of the average extremes used here.

In Table I, the ratio of the GCR production rates typically observed in meteorites to the solar-cycle-averaged rates for primary GCR protons ranged from 2.3 to 8.0. Because the flux of primary protons inside a meteorite is attenuated by nuclear interactions, the ratios of observed activities to those made only by the primary GCR protons should be even larger. These relatively low contributions by the primary particles illustrate the importance of secondary particles in nuclide production in large objects like meteorites. This big difference between nuclide production by primaries only and by the fully developed secondary cascade present in most meteorites indicates that small meteorites without a fully developed cascade could have some unusual production rates or ratios. Studies of such small meteorites also would help us understand the production and transport of secondary particles in meteorites.

4.   Conclusions. The calculations and results in Table I show that the production of cosmogenic nuclides can vary considerably with both the size of the extraterrestrial object and the amount of the solar modulation of the primary GCR particles. Very small objects have high production rates by solar protons. Typical meteorites are large enough that the cascade of secondary particles dominates nuclide production. Intermediate-size objects could have some unusual production rates and ratios. Temporal and spatial variations in nuclide production can also result from differing GCR-particle modulation. Variations by factors of 2 to 3 can occur during a normal solar cycle, and even larger deviations can occur when solar modulation is much stronger or weaker than usual.

References
1. Reedy, R. C., et al., (1983), Science 219, 127-135.
2. Raisbeck, G. M., et al., (1983), In Lunar and Planetary Science XIV (Lunar and Planetary Institute, Houston), pp. 622-623.
3. Evans, J. C., et al, (1982), J. Geophys. Res. 87, 5577-5591.
4. Ray, J., and H. J. Völk, (1983), Icarus 54, 406-416.
5. Castagnoli, G., and D. Lal, (1980), Radiocarbon 22, 133-158.
6. Reedy, R. C., and J. R. Arnold, (1972), J. Geophys. Res. 77, 537-555.

TABLE I. Nuclide Production Rates by Primary Cosmic-Ray Protons, Assuming C2-Chondritic Chemistry.

	10^6 years Av SCR	Solar Max. GCR	Solar Av GCR	Solar Min. GCR	Local IS GCR	GCR Source	Typical Meteorite
Parameter	$R_o=100$	M=950	M=550	M=375	M = 0	$R^{-2.65}$	
Integral Flux[a]	70	1.21	1.80	2.39	4.33	4.33	
Nuclide			(atoms/minute/kg)				
He-3	66.	190.	318.	459.	1258.	4095.	900.
Be-10	4.1	5.0	8.1	11.5	28.6	60.8	22.
Ne-21	395.	11.6	20.8	31.7	117.	1603.	150.
Al-26	344.	3.9	7.5	11.9	56.	1344.	60.
Cl-36	0.9	1.8	3.1	4.5	11.2	20.1	7.
Ar-38	72.	3.3	5.5	8.0	24.4	260.	20.
Mn-53	590.	7.6	13.6	20.8	90.	2177.	105.

[a] In protons/cm^2/s: solar protons for E > 10 MeV, GCR for E > 1 GeV.