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Factors affecting production rates of cosmogenic nuclides in extraterrestrial matter

R.C. Reedy *

Planetary Science Institute, 1700 E Fort Lowell, Suite 106, Tucson, AZ 85719-2395, USA

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A B S T R A C T

Good production rates are needed for cosmic-ray-produced nuclides to interpret their measurements. Rates depend on many factors, especially the pre-atmospheric object's size, the location of the sample in that object (such as near surface or deep inside), and the object's bulk composition. The bulk composition affects rates, especially in objects with very low and very high iron contents. Extraterrestrial materials with high iron contents usually have higher rates for making nuclides made by reactions with energetic particles and lower rates for the capture of thermal neutrons. In small objects and near the surface of objects, the cascade of secondary neutrons is being developed as primary particles are being removed. Deep in large objects, that secondary cascade is fully developed and the fluxes of primary particles are low. Recent work shows that even the shape of an object in space has a small but measureable effect. Work has been done and continues to be done on better understanding those and other factors. More good sets of measurements in meteorites with known exposure geometries in space are needed. With the use of modern Monte Carlo codes for the production and transport of particles, the nature of these effects have been and is being studied. Work needs to be done to improve the results of these calculations, especially the cross sections for making spallogenic nuclides.

1. Introduction

Cosmic-ray-induced (cosmogenic) nuclides, such as ^{10}Be, ^{26}Al (the 0.7-Myr ground-state isomer), and ^{3}He, are important because of their broad applications to many extraterrestrial and terrestrial studies, such as determining exposure ages of solar-system matter [1] and of surface features on the Earth's surface [2]. This work considers the factors that can affect the production of cosmogenic nuclides in extraterrestrial material, mainly meteorites and lunar samples.

Many long-lived cosmogenic nuclides, such as ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, and ^{41}Ca, are measured by accelerator mass spectrometry (AMS) and used for many applications [1,3]. AMS occasionally measures a few other cosmogenic radionuclides, such as ^{32}Si, ^{53}Mn, ^{59}Ni, ^{60}Fe, and ^{129}I. There have been a number of reviews of these AMS-measured cosmogenic nuclides [e.g., 3,4]. Many references are given below, but they are far from complete and are intended to help the reader to find additional related work.

Typical uses of cosmogenic nuclides include determining an object's exposure age (how long an object was exposed to cosmic-ray particles) and its "shielding" (the object's pre-atmospheric size and the location of a sample inside the pre-atmospheric object) [1,5]. Measurements of cosmogenic nuclides in one object can range from one nuclide in only one sample to a large number of cosmogenic nuclides in many samples from that object. The more measurements made for an object, the better is the interpretation of its cosmic-ray record. For some lunar meteorites, a set of measurements can be used to study the sample's depths in both the Moon and the meteoroid, the size of the meteoroid, the lengths of those exposures, and how long the samples was on the Earth's surface (its terrestrial age) [e.g., 6].

Production only occurs near the pre-atmospheric surface, because cosmic-ray particles are removed or stopped as they enter an object. A depth of more than 3 m in a solid body is enough to remove almost all cosmic-ray particles. Almost all objects spent most of their life in such deep locations unexposed to cosmic rays. Only when that object is near the pre-atmospheric surface does production of nuclides begin. Production rates vary with location of a sample in its parent body.

Production profiles for cosmogenic nuclides are known by many measurements to vary with depth in the Moon [7] and meteorites

* Address: 152 Monte Rey Dr., Los Alamos, NM 87544, USA. Tel.: +1 (505) 672 9519.

E-mail address: reedy@psi.edu

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[8], and those profiles have been confirmed by detailed calculations [8,9]. These variations can be different, depending on the nuclide because of the different nature of the particles that make nuclear reactions. Some nuclides are made mainly by high-energy (energies above ~100 MeV, such as ^{10}Be made in iron), many by nuclear reactions with low-energy (~5–100 MeV) neutrons (such as ^{26}Al in silicates), and a few nuclides are made mainly by neutrons near thermal energies (such as ^{41}Ca in silicates). Many experimental studies and theoretical studies have been done of cosmogenic nuclides and their production systematics [e.g., 1,5].

2. Production of nuclides by cosmic rays

2.1. Solar energetic particles

There are two types of energetic particles in the inner solar system that can produce nuclides – solar energetic particles (SEP) and galactic cosmic rays (GCR) [1,7]. SEPs, also called solar cosmic rays, are emitted irregularly from the Sun and mainly have energies below 100 MeV. The energetic particles from the Sun consist mainly of protons with about 1% each of alpha particles and heavier nuclei. The fluxes of and spectral shape of SEPs can very widely from event to event [7]. SEPs interact in the top few millimeters of the pre-atmospheric surface and are almost always stopped by ionization energy losses before reacting. Most meteorites have many centimeters of surface removed by ablation while entering the Earth's atmosphere, and few keep SEP-produced nuclides. Some meteorites have SEP-produced nuclides, and the presence of such nuclides indicates that the sample was very near the pre-atmospheric surface. Several samples in the Sutter's Mill carbonaceous chondrite have SEP-produced radionuclides [10].

SEPs have mainly been studied in lunar samples returned by the Apollo missions. Apollo samples have been very good for the study of SEPs and the nuclides that they made as essentially no material was removed in their collection on the Moon and transport to Earth. SEP-produced nuclides in lunar samples have been used to study both the nature of SEP particles for various time periods in the past and the exposure records of those samples. Often, the surface exposure ages of lunar samples can also be determined [11]. Protons from the Sun make almost all such SEP-produced nuclides. In the very top few millimeters of some samples, solar alpha particles make some nuclides, such as ^{59}Ni [12,13].

The profile of SEP-nuclides in the top few centimeters of a lunar samples have often been used to study the history of energetic particles from the Sun. The fluxes and spectral shape as a function of energy of solar protons have been determined from several lunar samples [7,11]. These fluxes are well determined because the cross sections for the proton-induced reactions making these nuclides have been measured well using AMS measurements [e.g., 14]. The inferred results for the history of SEPs over the last few million years suggest that their fluxes might have changed [11]. However, many SEP-produced nuclides have only been measured once or a few times, and more measurements using AMS of the profiles of SEP-produced nuclides in documented lunar samples are needed for many of these nuclides, such as ^{14}C, ^{41}Ca, and ^{36}Cl.

2.2. Galactic cosmic rays

GCR particles typically have energies of ~0.1–10 GeV/nucleon, make many secondary particles (especially energetic neutrons), and are always present in the inner solar system [7]. They are about 87% protons, 12% alpha particles, and ~1% heavier nuclei. Almost all of the cosmogenic nuclides observed in meteorites and most in lunar samples are made by GCR particles.

The fluxes of GCR particles are affected by the magnitude of solar activity and vary by a factor of about 2 over a typical solar cycle. For periods longer than ~1 kyr but less than ~0.1 Gyr, their fluxes averaged over long time periods have not varied much, probably about 20% or less. Their fluxes more than ~0.1 Gyr ago are not well determined. For studies of the nuclides that they make, their flux is assumed constant over time. It is hard to well determine the fluxes of GCR particles in the past from measurements of cosmogenic nuclides due to the lack of very good production rates and independently-determined exposure ages. The cross sections for the energetic neutrons that make most GCR-produced nuclides have not been measured. Usually proton-induced cross sections are used with some adjustments in certain cases, such as for neutron-rich products like ^{14}C [7] and ^{10}Be [15]. Some cross sections for reactions induced by high-energy (above about 70 MeV) neutrons have been [16] or are being measured.

GCR particles can penetrate to depths of meters in solid matter. Each GCR particle makes ~10 secondary particles. Most charged secondary particles are stopped before they can interact. Neutrons are more penetrating and are the dominant secondary particle in the top few meters of dense matter. The profiles of their fluxes in matter are dependent on their energies, with high-energy particles peaking at or near the surface and with fast (E~1–20 MeV) neutrons usually being most intense at depths of ~20–50 g/cm^2. In objects with radii more than about 75 g/cm^2, the fast neutrons can scatter enough times to be slowed to near thermal (E~0.02 eV) energies. In thick matter with no or very little hydrogen, the peak for the fluxes of thermal neutrons is at depths of about 150 g/cm^2. Many meteoroids, especially stony ones, appear to have been too small in space to have had high fluxes of thermalized neutrons.

3. Modeling production rates

3.1. Solar energetic particles (SEPs)

For SEPs, the energies of secondary particles are low enough that only reactions for the primary solar energetic particles need to be considered. The fluxes of solar energetic particles in matter are calculated using the spectra of those particles in space and the slowing of those particles by ionization energy losses in matter [7]. The fluxes and spectral shapes (fluxes as a function of energy) of solar particles in space have often been measured. Their spectra tend to be flatter at lower energies and steeper at the higher energies and are fairly well described over all energies by using an exponential shape for the particles' rigidity, R, which is the momentum per unit charge (pc/ze) and usually has units of megavolts (MV) [7]. The shapes of such spectra are given by an exponential expression of the form $\exp(-R/R_0)$. Typical values for R_0 are about 50–100 MV [11]. For narrower energy ranges, a power law in energy has been used, such as for solar alpha particles in [12]. The spectra of these particles in matter are calculated using the free-space spectra and the well-determined expressions for the slowing of charged particles in matter [7].

As noted above, many proton cross sections were measured to enable detailed studies of the record for solar-proton-induced nuclides. With a known composition, production rates are well determined from the calculated fluxes and cross sections as a function of energy [7,10].

3.2. Galactic cosmic rays (GCRs)

Rates for the production of GCR-produced nuclides have been estimated or determined in various ways. In the 1950 and 1960, there were few measurements, and often a rate was the average