The Nuts and Bolts of Cosmogenic Nuclide Production

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INTRODUCTION

Cosmic rays are high-energy charged particles that impinge on the Earth from all directions from space. The majority of cosmic ray particles are atomic nuclei, but they also include electrons, positrons, and other subatomic particles. Typical energy levels range from a few mega–electron volts (MeV) up to ~10^20 eV, with a maximum energy of a few hundred MeV per nucleon (Eidelman et al. 2004).

For the purposes of in situ and atmospheric cosmogenic nuclides, the term cosmic rays usually refers to galactic cosmic rays, which originate from sources outside the Solar System. Supernova explosions, which occur approximately once every 50 years in our galaxy, produce most galactic cosmic rays, with energies of up to 10^{15} eV (Eidelman et al. 2004; Diehl et al. 2006). The galactic cosmic ray flux is generally assumed to be isotropic and to have been approximately constant over the last 10 million years (Leya et al. 2000). Good entry-level reviews on cosmic ray physics can be found, for example, in Rossi (1964) and in reviews on geologic applications of cosmogenic nuclides (Gosse and Phillips 2001; Dunai 2010). In the following section, we draw from these sources, and their references, to introduce the nature of cosmic ray particles and the mechanisms of cosmogenic nuclide production.

Nucleons

The high energies of the primary (and many secondary) cosmic rays are well in excess of the binding energies of atomic nuclei (typically 7–9 MeV per nucleon). Consequently, the dominant nuclear reaction is that of spallation, the process by which nucleons are sputtered off target nuclei. Spallation-produced nucleons largely continue in the direction of the impacting particle and can retain enough energy to keep on inducing spallation in other target nuclides, producing a nuclear cascade in the Earth’s atmosphere (Fig. 1).

Because neutrons do not lose energy through ionization as do protons, the composition of cosmic rays undergoes changes from proton-dominated to neutron-dominated over the course of the nuclear cascade. At sea level, neutrons constitute 98% of the nucleonic cosmic ray flux. However, energy losses incurred with each interaction result in the mean energy of the secondary neutron flux being significantly lower than that of the primary flux (Fig. 1).

Muons

In addition to producing secondary atmospheric neutrons, collisions of high-energy primary cosmic rays with atomic nuclei high in the atmosphere produce elemental particles known as pions, which decay within a few meters of travel to either positively or negatively charged muons. Muons can be considered the heavier brother of the electron (206.7 times heavier).

Muons interact only weakly with matter—therefore, they have a much greater penetration depth than nucleons, and hence are the most abundant cosmic ray particles at sea level. However, due to stronger interaction with matter, the...
Nuclear reactions in the atmosphere produce the nuclear cascade, particles carrying n, p, α: secondary cascade carrying the nuclear (>10 MeV) secondary P, N: high-energy ±±±± residual nuclei are “cosmogenic nuclei” e

**COSMOGENIC NUCLIDES**

Cosmogenic nuclides are the products of interactions of primary and secondary cosmic ray particles with atomic nuclei. At the Earth’s surface, more than 98% of the cosmogenic nuclide production arises from secondary cosmic ray particles, such as neutrons and muons. Depending on the energy of these particles, a range of nuclear reactions can produce cosmogenic nuclides (Fig. 1).

**Spallation**

In spallation reactions, high-energy nucleons (largely neutrons at ground level) collide with atomic nuclei (“target nuclei”) and knock off protons and neutrons, leaving behind a lighter residual nucleus. The mass difference between a target nucleus and the lighter product is usually a few atomic mass units. Thus, target elements with nuclide masses nearest to the resulting cosmogenic nuclide usually contribute most to its production.

**Neutron Capture**

The majority of neutrons in the nuclear cascade eventually slow down to energies corresponding to the temperature of their surroundings. These “thermal” neutrons (energies of ca 0.025 eV) can subsequently be captured by nuclei. Some thermal neutron–capture reactions have very high probabilities of occurrence and can produce appreciable amounts of cosmogenic nuclides (e.g. ³He, ³⁶Cl).

**Muon Reactions**

There are two main types of muon reactions leading to cosmogenic nuclide production: negative muon capture and high-energy (fast) muon interactions. Negative muons that have been decelerated by ionization to thermal energies (termed “stopped muons”) can be captured by an atom’s electron cloud, and they quickly cascade to the lowest electron shell. There they decay, or are captured by the nucleus where they neutralize one proton. The probabilities for negative muon–capture reactions are much lower than those involving neutrons.

Fast muons give rise to Bremsstrahlung (“braking radiation”), which produces gamma ray photons. This phenomenon occurs when charged particles slow down due to interactions with other charged particles. Such muon-derived gamma rays can be of sufficiently high energy to produce secondary neutrons from nuclei, the so-called photoneutrons, which may produce cosmogenic nuclides. They generally have a very low abundance and become important only at depths greater than 20 m below the Earth’s surface, where fast muons remain as the sole reaction-inducing “survivors” of the cosmogenic cascade.

**PRODUCTION RATES AND SCALING FACTORS**

The production rates of cosmogenic nuclides are a function of the energy spectrum of the impacting cosmic ray particles and the corresponding reaction probabilities for target nuclei (Reedy 2013). The energy spectrum itself is a function of altitude and position in the geomagnetic field. As discussed in von Blanckenburg and Willenbring (2014 this issue), nuclide production occurs both in atmospheric gases (“atmospheric”) and in the minerals of the upper several meters of the Earth’s surface (“in situ”).

In the atmosphere, nuclide production rates are typically estimated from theoretical and/or numerical models (e.g. Masarik and Beer 1999), while nuclide delivery is computed from atmospheric circulation models (Heikkinen et al. 2013). In contrast, terrestrial production rates of in situ cosmogenic nuclides are typically experimentally established at sites that have independently determined ages (e.g. moraines, lava flows) and well-constrained exposure histories (i.e. no significant prior exposure, erosion, burial, or other disturbance that can impact the cosmogenic nuclide inventory in the rock since initial exposure) (Gosse and Phillips 2001; Dunai 2010).

Identifying suitable calibration sites for terrestrial production rates requires careful characterization, and the number and geographic distribution of these sites remain limited. Scaling factors are required to translate the local production rates obtained at calibration sites to values valid elsewhere on the globe, where practitioners may use cosmogenic nuclides to obtain exposure ages and rates of geological processes. Again, this is because the cosmic ray energy spectrum varies spatially. Scaling factors must also account for temporal variations in geomagnetic and atmospheric shielding at a given location that can affect the cosmic ray flux and its energy spectrum (Fig. 2).

**Geomagnetic and Atmospheric Shielding**

Primary cosmic rays are charged particles and are thus affected by Earth’s magnetic field. At a given location, particles with kinetic energy below a certain threshold cannot penetrate the Earth’s magnetic field and approach the Earth’s surface. This threshold is referred to as the “cutoff rigidity,” or $R_C$, and is defined as the momentum of a particle per unit charge (in gigavolts, GV).
Secondary neutrons produced in the atmospheric nuclear cascade attain a maximum flux at an altitude of about 16 km (Lal and Peters 1967). Below that level, their abundance decreases approximately exponentially with atmospheric depth, which is described by the attenuation length (Fig. 2a). As a rule of thumb, the nucleonic cosmic ray flux decreases by half for every 1000 m decrease in altitude (Dunai 2010).

Systematic changes in the secondary cosmic ray spectrum as a function of atmospheric depth and Rc lead to corresponding variations in attenuation lengths (Lifton et al. 2014). Current scaling models account for this variation by directly varying attenuation lengths (Dunai 2001; Desilets and Zreda 2003) or by parameterizing altitudinal and latitudinal variation in other ways (Lal 1991; Lifton et al. 2014).

It is worth noting that while meteoric cosmogenic nuclides, such as 10Be, are also produced in the atmosphere largely by spallation reactions, applications of such meteoric 10Be are instead concerned with fluxes of the nuclide from the total inventory in the atmospheric column above a given site (Willenbring and von Blanckenburg 2010). It is significant that >99% of the atmospheric inventory is produced above 3 km altitude—thus, no altitude scaling is required for most of Earth’s surface. Rather, the 10Be production signal is dominated by the high cosmic ray fluxes in low Rc regions (Willenbring and von Blanckenburg 2010).

Once produced, meteoric 10Be quickly adsors to aerosol particles that are transported by atmospheric circulation and delivered to the Earth’s surface by either dry or wet deposition. Combination of 10Be production and atmospheric general circulation models indicates that 10Be fluxes are dominated by wet deposition—therefore, mid-latitudes that experience high precipitation also experience the highest fluxes (Willenbring and von Blanckenburg 2010; Heikkilä et al. 2013).

Modern Rc values are approximately zero near the poles, where essentially all energies present in the primary flux can penetrate the magnetic field. This value increases to approximately 17 GV near the equator (ca 50% of the polar flux at sea level) (Fig. 2a). At Rc < 1–2 GV (≥ ca 60° geomagnetic latitude), the lowest-energy particles do not have enough energy to generate an atmospheric cascade, and so toward the poles the increases in the number of particles that enter the atmosphere do not yield corresponding increases in the flux responsible for cosmogenic nuclide production.

The cosmic ray spectrum at high latitudes is not sensitive to temporal changes in the geomagnetic field. Hence, terrestrial production rates are usually normalized to hypothetical values at sea level and high latitudes. However, the effects of secular geomagnetic field variations on nuclide production become more pronounced with increasing Rc (at lower latitudes) and need to be considered when calculating nuclide production in the past (Dunai 2001; Desilets and Zreda 2003; Lifton et al. 2008; Fig. 3).

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Scaling Factors for In Situ Cosmogenic Nuclide Production

Computationally complex calculations are required to consider the effects of spatial and temporal variations in the geomagnetic field and atmospheric pressure on scaling of in situ nuclide production. To allow nonspecialists to perform these analyses, user-friendly calculators are now available (e.g., Balco et al. 2008). The scaling factors that are currently used perform well for generally describing the relative flux of cosmic rays as a function of altitude, latitude (Stone 2000; Dunai 2001; Desilets and Zreda 2003; Balco et al. 2008; Lifton et al. 2008), variations in geomagnetic field strength (Dunai 2001; Desilets and Zreda 2003; Lifton et al. 2008), and changes in solar activity (Lifton et al. 2008). At latitudes greater than 30º and elevations below 3 km, their results are generally very similar (Balco et al. 2008). However, large differences between models (up to 30%) emerge for estimates at lower latitudes and higher elevations. These variations arise from the different neutron flux proxies used (neutron monitors, photographic emulsions) and their responses to changes in the neutron energy spectrum (Lifton et al. 2014).

Recent advances have made it feasible to consider the temporal changes in the energy spectrum quantitatively and estimate their influence on nuclide production (Argento et al. 2013; Lifton et al. 2014). Previously, this omission was due to the lack of detailed environmental neutron energy spectra and the lack of accurate neutron reaction probability functions; both have become recently available (Sato et al. 2008 and references therein; Reedy 2013). These new studies (Argento et al. 2013; Lifton et al. 2014) indicate that nuclide-specific scaling factors may be warranted for some nuclides, such as 3He. They also indicate that the larger contribution of protons at high elevations, which are undercounted by neutron monitors (Clem and Dorman 2000), needs to be considered for nuclide production.

CONCLUSIONS

This brief review presents the fundamental principles of cosmogenic nuclide production in the atmosphere and in terrestrial settings. The foundations for this science were initially laid over 50 years ago, but recent advances in our abilities to model temporal variations in nuclide production are certain to propel the field forward. In the coming years, these developments will help to ensure that the rapid progress in accurately measuring cosmogenic nuclides (Christl et al. 2014 this issue) will be matched by our understanding of the rates at which these nuclides are produced.

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REFERENCES


