PRODUCTION SYSTEMATICS OF COSMOGENIC NUCLIDES IN THE EARTH

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The high-energy (GeV) particles in the galactic cosmic rays (GCR) produce nuclides deep in any object exposed to them. Cosmogenic nuclides have been well studied since the 1950s in meteorites and lunar samples. In extraterrestrial matter, several approaches have been used to determine cosmogenic-nuclide production systematics. The work being done for terrestrial cosmogenic nuclides (e.g., Reedy et al. 1994a) follows the approach used for extraterrestrial nuclides.

For extraterrestrial cosmogenic nuclides, initial studies used activities of radionuclides to infer production rates. (For a long, constant exposure to cosmic rays, a radionuclide's decay rate approaches equilibrium with its production rate.) Irradiations of thick targets at high-energy accelerators were done to experimentally simulate GCR irradiations in space and helped in understanding the nuclear processes involved. Accelerators were also used with thin targets to measure cross sections for making these cosmogenic nuclides. Several models were developed for predicting the systematics of the production of cosmogenic nuclides, mainly semi-empirical fits. Recently, numerical simulations based only on physics have been used to study nuclear reactions and allow us to examine the details of how GCR particles interact with matter (Masarik and Reedy, this issue).

The terrestrial case is more complicated because of the Earth's atmosphere and strong geomagnetic field. Most GCR particles interact in the Earth's atmosphere, making mainly 14C. The Earth's thick (1033 g/cm²) atmosphere attenuates the flux of particles reaching the surface by several orders of magnitude. The large difference in the composition and density of the atmosphere compared to extraterrestrial matter makes it difficult to use data from extraterrestrial matter for nuclides made deep in the atmosphere. One major difference is that most pions made in dense extraterrestrial matter interact before they can decay, while most pions in the thin atmosphere decay to muons. These muons are weakly-interacting particles and can go much further than strong-interacting particles such as neutrons and pions. Below a few meters in the Earth's surface, muons are a major source of cosmogenic nuclides. Another complication is that the production rates of a nuclide in the Earth's surface can vary much with the sample's elevation and the location's geomagnetic latitude.

Most production rates of nuclides made in the Earth are now based on a few measurements made with natural samples. Generally, the production rate of a cosmogenic nuclide is converted from that determined at the location's elevation and geomagnetic latitude to the rate at sea level and a high geomagnetic latitude (>60°) with no cutoff of GCR particles. Most measurements have been done on material with a simple composition, often quartz (SiO₂) or calcite (CaCO₃).

Several studies have been done at accelerators on production systematics of terrestrial cosmogenic nuclides. Some irradiations were done at the Los Alamos Meson Physics Facility, usually using secondary neutrons near a beam-stop. These irradiations have yielded some production ratios, such as 10Be/14C/26Al in SiO₂ (Reedy et al. 1994b), and could be used to get relative production rates from pure elements. Some accelerators are also sources of muon beams. Work is also being done on measuring yields of nuclides from fast muons or muons stopping in various targets (Reedy et al. 1994c).

As the ratio of neutrons to protons in the Earth's surface is higher than in most meteorites and lunar samples, cross sections for the production of terrestrial cosmogenic nuclides by energetic neutrons are very important. However, only a few neutron cross sections have been measured for the nuclides...