SIMULATION OF COSMIC-RAY PRODUCTION OF ^{26}Al and ^{10}Be*;

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Recent advances in the analyses of long-lived radionuclides using tandem Van de Graaff accelerators have revolutionized the use of these isotopes (1). By accelerating the isotopes in a sample to high energies (tens of MeV), it is now possible to measure isotope ratios as low as $\sim 10^{-16}$ and detect $\sim 10^{7}$ atoms or less of rare radionuclides, such as 1.5-Ma (1.5×10^{6}-years) ^{10}Be (2), 0.7-Ma ^{26}Al (3), 0.3-Ma ^{36}Cl (4), and 5730-a ^{14}C (5). This technique is usually referred to as "accelerator mass spectrometry" or AMS. Such detection sensitivities are impossible with low-level counting techniques, being equivalent to detecting a few disintegrations per year, and have increased our ability to detect these long-lived radionuclides by many orders of magnitude. These new ultra-sensitive AMS techniques now allow the measurement of ^{26}Al, ^{10}Be, and several other long-lived radionuclides in samples where the concentrations of these isotopes are very low, such as in the surface of the earth or in very small samples of meteorites or the Moon (1).

At present, the use of cosmogenic nuclides to study histories of targets or of cosmic radiation (6) is limited by inadequately known production rates. Existing calculations (7-10) for production of these nuclides by nucleons and (in deeply shielded samples, such as below the Earth's surface) by muons could be improved with additional laboratory measurements of production rates (cross sections). Such experiments are needed because the ability of theoretical models to predict cross sections are often poor.

Neutrons. To measure the production rate due to the nucleon component (primarily neutrons (8)) of cosmic rays, several irradiations have been and several more will be conducted using spallation neutrons (11) produced by the beam stop of the ~1-mA 800-MeV proton beam at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF). Several targets, including silicon and quartz (SiO_2), and beam monitors were irradiated for about a day with the spallation neutrons. The energy of these particles was 0-800 MeV (12). The activities in the monitor foils and of the short-lived radionuclides, such as 15-h ^{24}Na, 2.6-a ^{22}Na, and 53-d ^{7}Be, produced in the silicon and quartz were determined by non-destructive high-resolution gamma-ray spectrometers at Los Alamos. At LAMPF, known amounts of aluminum and beryllium were then added to pieces of the silicon and quartz, the samples dissolved, the Al and Be separated and taken to San Diego, where they were further purified. The ^{26}Al/^{27}Al and ^{10}Be/^{9}Be ratios were then measured on the University of Pennsylvania's tandem Van de Graaff accelerator (2,3). The measured concentrations of these five radionuclides are given in Table 1. Additional measurements are planned for these and other beam-stop samples. Pieces of the Si and quartz have been sent to the University of Arizona in Tucson for analyses of their ^{14}C contents by A. J. T. Jull and D. J. Donahue. We plan to measure additional long-lived radionuclides or stable nuclides in other samples irradiated near the LAMPF beam stop.

The ^{7}Be/^{10}Be ratio in the Si is 5.2, which is less than the ratio of $\approx$7.6 measured in Si irradiated with 600-MeV protons. The production of ^{7}Be and ^{10}Be from oxygen can be deduced by using the Si measurements to subtract out the Si contributions in the quartz. The ^{7}Be/^{10}Be production ratio in oxygen is 1.6, which is much less than the proton-induced ratios in oxygen of 8.9 and 5.4 at 135 and 550 MeV, respectively (13, using revised half-lives). The ratio of ^{7}Be/^{10}Be is useful, as many more cross sections have been measured for ^{7}Be than for ^{10}Be. However, as evident from the above ^{7}Be/^{10}Be ratios and as previously inferred by (9), neutrons and protons produced these two isotopes in

relatively different yields and cross sections. We have not yet determined the neutron flux with sufficient precision to convert these measurements into cross sections but hope to do so soon with these and additional samples. We would like to do an irradiation at another location near the beam stop that has a different spallation-neutron spectrum.

These results yield ^{26}Al/^{10}Be ratios of 170 in Si and 7.8 in quartz. The ^{10}Be and ^{26}Al contents of quartz from glacially polished granitic rock, which had been exposed to cosmic rays in their present locations for ≈11,000 years, were also measured by AMS and gave an ^{26}Al/^{10}Be ratio of 5.7. This ratio is in agreement with the ratio of 7.8 from the spallation neutrons on quartz because of the absence at LAMPF of particles with energies above 800 MeV, which produce more ^{10}Be relative to ^{26}Al.

Muons. Two sets of irradiations with negative muons (μ^-) have been performed at the Stopped Muon Channel at LAMPF (14). The first muon irradiations used only stopped μ^- and consisted of three targets (quartz, calcium oxide, and potassium nitrate) mixed with nickel powder. The radioactive activation products ($^{56-58}$Co) in the nickel monitored the number of muons stopping in each target (15). A second set of muon irradiations used a μ^- beam with an energy of ≈70 MeV to expose a quartz target to energetic μ^- ahead of the area where five targets were successively exposed to stopped muons. The stopped muon targets were calcium carbonate, potassium chloride, quartz targets with ≈6% and 50% nickel (to study the competition between Ni and the quartz for the stopped muons), and tellurium (to determine the production of 16-Ma ^{129}I).

After each μ^- irradiation, the nickel was physically removed from the target powder and counted. At San Diego, known amounts of the elements of interest were added as carriers to the irradiated powders, and the samples were dissolved. The elements with the long-lived radionuclides were then chemically separated and purified. The ^{7}Be activities of the quartz were counted at San Diego and the ^{10}Be and ^{26}Al contents measured at Philadelphia. The ^{7}Be and ^{10}Be contents in the muon-irradiated quartz were relatively high, and the preliminary ^{7}Be/^{10}Be ratio was below unity, much lower than this ratio for neutrons and protons (see above). Also being measured are ^{36}Cl (from Ca and K) and ^{129}I (from Te) by AMS at the University of Rochester by P. Kubik and D. Elmore and ^{37}Ar and ^{39}Ar (from Ca and K) by D. Lal and R. Davis, Jr., with low-level gas counters.

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Table 1. Measured radionuclide concentrations (10^{10} atoms/g) in irradiations with spallation neutrons near the LAMPF beam stop. (Numbers in parentheses are the uncertainties.)

Target	^{7}Be	^{10}Be	^{22}Na	^{24}Na	^{26}Al
Si	40.1 (0.4)	7.69 (0.46)	553 (5)	316 (3)	1320 (90)
Quartz	162 (1)	93.0 (4.7)	256 (5)	145 (2)	722 (51)