ON THE PRODUCTION OF COSMOGENIC NUCLIDES BY HIGH-ENERGY SECONDARY PARTICLES: SIMULATION EXPERIMENTS WITH BEAM STOP NEUTRONS

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Few attempts have been made to study the role that energetic neutrons play in the production of cosmogenic nuclides in meteorites and the lunar surface (1,2,3). Production rates and ratios for charged-particle-induced reactions are well understood (e.g.4,5). However, within an extraterrestrial body the main contributions to the production of most cosmogenic nuclides come from secondary neutrons, as they are the majority of particles with $E < 300$ MeV and there are many neutrons with energies > 1 GeV (5-9). These secondary neutrons must be considered in calculations of the GCR production rates of cosmogenic nuclides in meteorites (6) and in the moon (10).

The type of particles inducing a nuclear reaction is important because the cross sections for producing a given nuclide from a target element can vary considerably with the incident particle (3). There are very few cross sections measured for neutron-induced reactions that produce cosmogenic nuclides, and the neutron energies for these measurements are almost always less than 15 MeV. Monoenergetic high-energy neutrons are not readily available, so we have looked for neutron sources which simulate situations in the interior of meteorites or lunar samples. High fluxes of energetic neutrons with a variety of special shapes are available at beam stops of charged particle accelerators.

In our experiment at the beam stop of the Los Alamos Meson Physics Facility we exposed metal foils of Mg, Al, Si, Ca, Ti, Mn, Fe, Co, Ni, Te, Lu, W and Au in three sets of irradiations with high fluxes of energetic neutrons. The incident proton energy was ≦ 800 MeV. Elements up to Ni are of relevance for the production of most cosmogenic radionuclides, especially for long-lived isotopes like 10-Be, 22-Na, 44-Ti, 53-Mn, 54-Mn and 59-Ni. Foils of elements with known cross sections for neutron induced reactions, such as (n,xn) reactions (11), or known spallation systematics, such as Fe (6), were used to determine the flux and spectral shape of the neutrons.

A wide range of products were formed and identified by their characteristic γ-radiation and half-life. Fig.1 shows nuclide yields in Ni for irradiations at different locations relative to the beam stop as a function of the reaction Q-values. The absolute yields depend on the integral neutron fluence which varied with location. The relative yields reflect the hardness of the neutron spectrum. Foils from irradiation 2006 have been exposed to a comparatively soft neutron energy spectrum.

A comparison of production rate ratios of irradiation 1112 and 1113 with results from the iron meteorite Aroos and the stone meteorite Bruderheim is given in Table 1. We normalized our results to the chemical composition of both meteorites. In case of Aroos only iron and nickel had to be considered as target elements. The 53-Mn/22-Na in our beam stop foils is large compared to that of Aroos (factor of 4), indicating that secondary particles with energies of several hundred MeV are more abundant in Aroos. This was expected as primary particles of > 1 GeV of energy are present in the GCR. However, in the lower energy regions, which are relevant for the production of spallogenic nuclides with reaction thresholds ≦ 50 MeV (e.g. 26-Al and 53-Mn), production rate ratios from the meteorites and the simulation experiments are similar, illustrating the role that secondary neutrons play in the production of cosmogenic radionuclides. The results of these experiments are being used to extend and improve model calculations of the production of cosmogenic nuclides in extraterrestrial bodies by GCR-secondaries.

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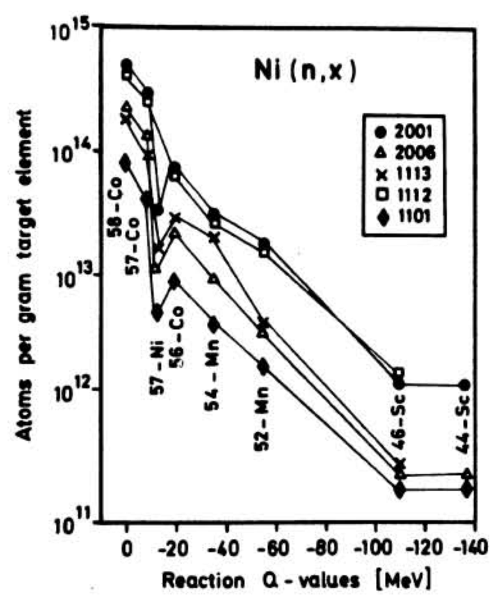
Table 1: Comparison of production ratios of cosmogenic radionuclides in Aroos, Bruderheim and this simulation experiment

Production ratio	Aroos	Monitor foils*) 1112	Monitor foils*) 1113	Bruderheim	Monitor foils*) 1112	Monitor foils*) 1113
54-Mn/22-Na	131	859	2200	1.1		
54-Mn/46-Sc	16	27	48	16	27	43
54-Mn/48-V	5.2	9	15	2.9	9.3	16
54-Mn/51-Cr	1.8	2.2	2.9	0.9	2.3	3.1
54-Mn/56+58-Co	3.9	3.5	3.3	7.1	4.3	36
54-Mn/57-Co	5.2	7.4	6.7	11	7.5	109

*)calculated, assuming the chemical composition of Bruderheim and Aroos.

Fig.1: Yields of isotopes from different irradiations of Ni with high-energy spallation neutrons.



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