NEW CROSS SECTION MEASUREMENTS FOR NEUTRON-INDUCED REACTIONS IN ELEMENTS FOUND IN EXTRATERRESTRIAL MATERIALS. J. M. Sisterson, Francis H. Burr Proton Therapy Facility, Massachusetts General Hospital, 30 Fruit Street, Boston MA 02114, jsisterson@partners.org.

Introduction: Small quantities of radionuclides (e.g. ^{14}C, ^{56}Co) and stable isotopes (e. g. ^{21}Ne) are produced when cosmic rays interact directly with extraterrestrial materials. These cosmogenic nuclide archives contain information about the history of the object itself as well as of the cosmic rays that fell upon it [e.g. 1, 2]. Good cross section measurements for relevant reactions producing the cosmogenic nuclides in the major elements found in extraterrestrial materials are essential input to the theoretical models used to interpret these archives [e. g. 3, 4].

Most primary cosmic rays are protons, therefore the cross sections for proton-induced reactions are the primary need. Most solar protons have energies <200 MeV and penetrate only the top few centimeters of a lunar rock. However, galactic cosmic rays (GCR) can have very high energies (up to 10^{20} eV) and penetrate deeply into the rock. At shallow depths, the measured depth profile of ^{14}C activity [1], for example, is made up of the contribution due to solar protons plus a background contribution due to GCR interactions. Thus, to get a good estimate of the solar proton flux from this depth profile, the GCR background must also be well determined.

It has been suggested that the GCR contribution to the cosmogenic nuclide archives includes radionuclides produced by the interactions of not only the primary GCR particles (~89% are protons) but also by the interactions of the secondary neutrons produced in these primary cosmic ray interactions, particularly at depth in an object [5]. We have already shown that this is a reasonable supposition using measured and calculated production rates for ^{22}Na in lunar rocks. When preliminary values for measured cross sections for selected neutron-induced reactions were used in the calculation of the GCR contribution, better agreement was obtained between the calculated and measured production rates [6].

There are very few reported measurements for many of the cross sections for relevant neutron-induced reactions [7, 8]. When there are no measured cross sections available to use as input to theoretical models, other strategies may be employed such as using the cross section for the corresponding proton-induced reaction or using cross sections calculated from a theoretical model such as MC-ALICE.

To remedy this situation, we have made a systematic study to measure as many cross sections as possible for relevant neutron-induced reactions. Cross sections were measured using two different techniques. Cross sections at unique neutron energies ranging from ~70 – 160 MeV were measured at iThemba LABS (iTL), South Africa [9, 10]. Energy integrated (or average) cross sections were measured at the Los Alamos Neutron Science Center (LANSCE) using neutron beams with a 'white' energy spectrum with energies ranging from 0.1 – 750 MeV [11].

Now many cross sections for neutron-induced reactions in Ti, Fe and Ni producing relatively short-lived radionuclides are well measured [9, 10]. From these measurements, we have shown that the above-mentioned strategies are good alternative options for only some energy/cross sections combinations [9, 10].

At this time, the yields of ^{14}C produced in SiO_2, Si and Al targets irradiated at LANSCE and SiO_2 targets irradiated at iTL with neutron beams of 73.3 and 111.8 MeV are being determined using Accelerator Mass Spectrometry (AMS). These cross section measurements will be the first to be completed for neutron-induced reactions producing long-lived radionuclides, the original motivation of our systematic study.

Experimental Method: At both LANSCE and iTL, the diameter of the neutron beam was larger than the target stack and the beam had uniform intensity. The primary target(s) thickness was designed so that the attenuation of the neutron beam was <10%. Monitor foils where included downstream of the primary target(s). Each irradiation was designed to measure the cross section for a particular reaction producing a long-lived or stable isotope so that the optimum number of atoms had to be produced to allow a good measurement of the yield using (AMS) or Mass Spectrometry.

These irradiation conditions allowed cross sections for many relevant reactions producing relatively short-lived radionuclides to be measured well in both the targets and monitor foils. The yields of these radionuclides were measured using non-destructive gamma-ray spectroscopy. Intrinsic Ge detectors were used for these measurements, which began soon after irradiation and continued for several months thereafter.

At LANSCE, average cross sections for neutron-induced reactions were measured. The neutron fluence was measured upstream of the target stack using a calibrated transmission chamber. Irradiation times could be as long as several days and the total neutron fluences ranged from 1.3E+10 to 1.8E+12 n/cm^2 at the irradiation position.

At iTL incident proton beams with energies of 80, 120 and 160 MeV were used to produce quasimonoenergetic neutron beams by the p+Be reaction. At each energy, two identical target stacks were irradiated in neutron beams produced at 0^o and 16^o to the incident proton beam. At 0^o, the neutron beam spectrum has a significant peak at high energies plus a lower energy continuum, while there is no high-energy peak in the spectrum at 16^o. Thus, the yield of a particular radionuclide was determined by subtracting the yield measured at 16^o (after suitable normalization) from that measured at 0^o to give a cross section measurement at an unique neutron energy. Due to beam time schedules, each irradiation and associated calibration runs had to be completed in a single weekend. With these time constraints, the total neutron fluences used in the irradiations ranged from 1.1E+10 to 9.35E+10 n/cm^2 and the neutron energies were from 70.7 to 151.6 MeV.

Results: To verify our measurement techniques at iTL, we included Cu monitor foils in many of our irradiations so that we could make a direct comparison of our measurements with the a set of reported cross section measurements made at high neutron energies [12]. The agreement between our new measurements and those in [12] is reasonable [9] giving us confidence that the cross sections that we will make good cross section measurements for those reactions for which there are no reported values at high energies.

For reactions in Ti, Fe and Ni we have completed our measurements of many cross sections for reactions producing relatively short-lived radionuclides at several neutron energies at iTL [10]. We have compared these cross sections to the average cross sections we measured at LANSCE [11]. In all cases, the values measured at unique energies are consistent with these average values, which is additional confirmation that our measurements made at iTL are reasonable.

Discussion and Conclusions: When no cross section measurements are available to use as input to theoretical model calculations, alternatives have to be sought. Often the cross sections for the equivalent proton-induced reaction are used or values obtained from nuclear model calculations. For reactions in Ti, Fe, Ni and Cu, we compared the measurements made at unique neutron energies, the average cross sections, and the theoretical values calculated using MC-ALICE [9, 10]. For reactions in Cu we also compared these values to the cross sections for the equivalent proton-induced reaction. These comparisons show that there are only some cross section/neutron energy combinations where the value obtained using either of these two alternative strategies is in agreement with the actual measured cross sections.

As a result, it is highly recommended that whenever possible, measured values for neutron-induced reactions should be used as input to theoretical calculations.

Acknowledgements: This work was supported by the National Aeronautics and Space Administration under Grants NAG5-7987, NAG5-10538 and CO503-0018-0005 issued through the Office of Space Science. We thank John Ullmann of LANSCE, Dan Jones of iTL and Andy Buffler, Frank Brooks, Saalih Allie and their students of the Physics Department at the University of Cape Town for their expertise and help with these irradiations; and Mark Chadwick for the calculations made using MC-ALICE.

References: [1] Jull A. J. T. et al. (1998) *Geochim. Cosmochim. Acta, 62*, 3025-3036. [2] Welton K.C. et al. (2003) *Meteoritics and Planet. Sci., 38,* 157-172. [3] Reedy R. C. and Arnold J. R. (1972) *J. Geophys. Res., 77*, 537-555. [4] Reedy R. C. (1985) *J. Geophys. Res., 90 Suppl*. C722-728. [5] Reedy R. C. and Nishiizumi K (1998) *LPS XXIX*, Abstract #1689. [6] Sisterson J. M. et al. (2001) *LPS XXXII*, Abstract #1302. [7] Reedy R. C. et al. (1994) *Nucl. Instr. Meth., B92,* 335-339. [8] Sisterson J. M. (2003) *LPS XXXIV*, Abstract #1326. [9] Sisterson J. M. et al. (2005) *Nucl. Instr. Meth., B240*, 617-624. [10] Sisterson J. M. and Chadwick M.B. (2006) *Nucl. Instr. Meth., B*, in press. [11] Sisterson J. M. and Ullmann J. (2005) *Nucl. Instr. Meth., B234*, 419-432. [12] Kim E. J. et al. (1999) J. of *Nucl. Sci. and Tech., 36*, 29-40.