REVISED PRODUCTION RATES FOR ^{22}NA AND ^{54}MN IN METEORITES USING CROSS SECTIONS MEASURED FOR NEUTRON-INDUCED REACTIONS.

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Introduction: The interactions of galactic cosmic rays (GCR) with extraterrestrial bodies produce small amounts of radionuclides and stable isotopes [e.g., 1]. The production rates of many relatively short-lived radionuclides, including 2.6-year ^{22}Na and 312-day ^{54}Mn, have been measured in several meteorites collected very soon after they fell [e.g., 2,3]. Theoretical models used to calculate production rates for comparison with the measured values rely on input data containing good cross section measurements for all relevant reactions. Most GCR particles are protons, but secondary neutrons make most cosmogenic nuclides. Calculated production rates using only cross sections for proton-induced reactions do not agree well with measurements [e.g., 4,5]. One possible explanation is that the contribution to the production rate from reactions initiated by secondary neutrons produced in primary GCR interactions should be included explicitly. This, however, is difficult to do because so few of the relevant cross sections for neutron-induced reactions have been measured [6,7].

A systematic study is underway to measure as many of the relevant cross sections for neutron-induced reactions as possible [7] using both quasi-monoenergetic neutron beams and 'white' neutron beams. Using the cross sections for neutron-induced reactions available in 2001, we showed that better agreement could be obtained between the calculated ^{22}Na production rate and the measurements when some relevant cross sections were included explicitly in the calculation [8] made using the Reedy and Arnold model [9,10].

New cross section measurements are now available and these have been used to create new data sets to use as input to the theoretical calculations. Production rates have been calculated using GCR fluxes determined using the Monte Carlo code MCNPX and several different cross section databases as input.

Measuring cross sections for neutron-induced reactions: Cross sections for neutron-induced reactions are measured using two different techniques. The first uses quasi-monoenergetic neutron beams generated by 80, 120 or 160 MeV proton beams on a Be target at iThemba LABS (iTL), Somerset West, South Africa. In the second technique, an 'average' cross section is measured using a 'white' neutron beam, which has an energy range of ~0.1 – 750 MeV at the Los Alamos Neutron Science Center (LANSCE), Los Alamos, New Mexico [7]. The cosmogenic nuclides produced are measured using several techniques including non-destructive gamma-ray spectroscopy for relatively short-lived radionuclides, accelerator mass spectrometry (AMS) for the long-lived radionuclides and mass spectrometry for stable isotopes.

The cross section measurements for the production of short-lived radionuclides are now almost complete. Replicate measurements are available for many of these reactions leading to short-lived radionuclides, and the agreement is generally good.

Production rate calculations: The production of ^{22}Na and ^{54}Mn at depth in L-chondrite bodies was calculated for three GCR flux conditions and with several different cross section databases as input.

GCR flux calculations. Three different primary GCR flux conditions, solar minimum, solar maximum and solar-cycle average [11], were used to calculate GCR fluxes at various depths in L-chondrites of 20 and 40 cm radii. The effective proton flux >10 MeV adopted for these spectra, based on those determined from MCNPX calculations for other nuclides, are, for solar maximum, average, and minimum, 2.29, 4.00, and 5.99 protons/cm^2/s, respectively.

Cross section databases. Several different cross section databases were used as input to the production rate calculations. These databases were generated using the cross section measurements available at the time of generation. Most GCR particles are protons, so good cross section measurements for proton-induced reactions are essential. Most of the relevant cross sections now have been measured. The most recently generated data sets include as many cross section measurements for neutron-induced reactions as possible. Data bases generated in the past used several strategies if the needed cross sections for neutron-induced reactions had not been measured. The cross section for the corresponding proton-induced reaction might be used, a cross section estimated from thick target experiments made with proton beams [12] or a cross section calculated from theoretical models, e.g., MC-Alice [13]. None of these are ideal solutions, but they were often used previously.

^{22}Na production rate calculations. ^{22}Na is produced mainly from Mg, Al and Si, with Mg and Si accounting for most of the production. For these calculations, three different cross section databases were used. In all three, good cross sections for proton-induced reactions were used plus any cross sections for neutron-induced reactions found in the literature, which were mainly for energies <30 MeV. In the first (S6N), estimates were used for the unmeasured cross sections for the neutron-induced reactions. In the second (S0N), measured cross sections were used for Al(n,x)^{22}Na and Si(n,x)^{22}Na, which included both 'average' cross sections and measurements made at two quasi-monoenergetic neutron energies >70 MeV. In the third database, complied at the end of 2003, the cross sections for these two neutron induced reactions plus the 'average' cross section measured for Mg(n,x)^{22}Na were included.

^{54}Mn production rate calculations. For a L-chondritic composition, ^{54}Mn is produced mainly from Fe. Ni contributes ~1% to the total production, and Mn contributes even less. Two cross section databases were used in the calculations, the existing one (S6N) based on estimates and the second using measured values that we recently had obtained for the cross section Fe(n,x)^{54}Mn including both the 'average' cross section and measurements made at two quasi-monoenergetic neutron energies >70 MeV (S3N).

Figure 1 shows the data sets used for both neutron-induced reactions for both ^{22}Na and ^{54}Mn.

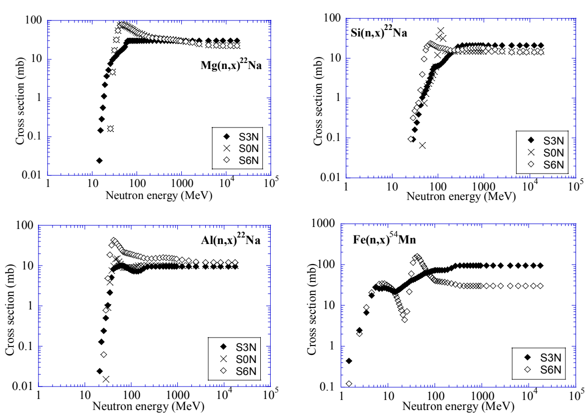

Fig. 1. Cross sections used for neutron reactions.

Results and Discussion: The calculated production rates for ^{22}Na and ^{54}Mn using the new neutron cross sections for the 3 GCR spectra during a typical 11-year solar cycle are shown in Fig. 2. The ranges are similar to but a little lower than those reported by [2,3], probably because of the adopted effective fluxes. The new production rates for ^{22}Na are similar to those using the S0N set based on initial cross sections for some neutron-induced reactions. Those for ^{54}Mn now are higher than those with the earlier estimates, mainly because of the higher neutron cross sections above ~100 MeV. The range in production rates over a solar cycle is similar to those estimated using simpler calculations [11].

The calculated production rates show that the effects of shielding (the meteoroids pre-atmospheric size and the sample's depth) are important. One method to reduce the spread in activities due to shielding is to ratio the measured activity of the short-lived radionuclide to that of a similar long-lived radionuclide, such as ^{26}Al and ^{53}Mn.

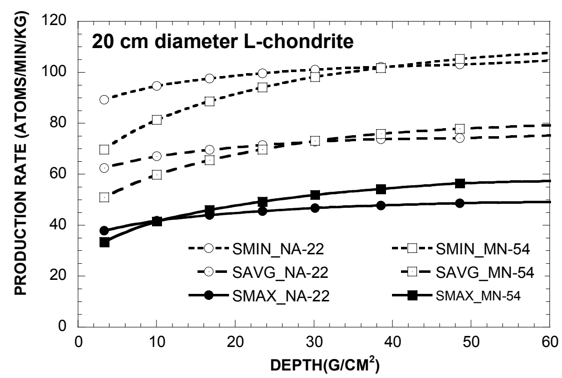

Fig. 2. Production rates calculated for a 20 cm radius L-chondrite for the average and ranges of a solar cycle.

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