MEASUREMENT OF RECOIL LOSSES AND RANGES FOR SPALLATION PRODUCTS PRODUCED IN PROTON INTERACTIONS WITH AL, SI, MG AT 200 AND 500 MEV. J. M. Sisterson, Northeast Proton Therapy Center, Massachusetts General Hospital, 30 Fruit Street, Boston MA 02114. jsisterson@partners.org

Introduction: Cosmic rays interact with extraterrestrial materials to produce a variety of spallation products. If these cosmogenic nuclides are produced within an inclusion in such material, then an important consideration is the loss of the product nuclei, which recoil out of the inclusion. Of course, at the same time, some atoms of the product nuclei under study may be knocked into the inclusion from the surrounding material, which is likely to have a different composition to that of the inclusion [1]. For example, ^{21}Ne would be produced in presolar grains, such as SiC, when irradiated in interstellar space. However, to calculate a presolar age, one needs to know how much ^{21}Ne is retained in the grain. For small grains, the recoil losses might be large [2, 3] To study this effect under laboratory conditions, recoil measurements were made using protons with energies from 66 – 1600 MeV on Si, Al and Ba targets [3, 4, 5].

Similarly, when measuring cross sections for both proton- and neutron-reactions an important consideration is the loss of the product nuclei, which recoil out of the target mainly in the forward (KON) and backward (KOB) directions. In these cross section measurements, the ideal experimental geometry to minimize the effect of these losses is to include ‘catcher’ foils of the same material either side of the target foil, so that approximately the same number of nuclei are knocked into the target as are knocked out of the target.

This good geometry was used in all our measurements of cross sections for proton-induced reactions from 20 – 500 MeV [6] but frequently one of the ‘catcher’ foils was also used for cross section measurements. As the materials on either side of the ‘catcher’ foil are likely to be different, there is in all probability an imbalance in the number of atoms of the spallation product under study knocked into the ‘catcher’ foil compared to those knocked out. The question is, how big is this effect?

This is also the question in our cross section measurements for neutron-induced reactions from 70 – 750 MeV [7, 8]. In these measurements we could not use ‘catcher’ foils because we wanted to keep the neutron attenuation through the entire target stack to <~10% for almost all neutron energies and relatively thick targets were required to produce the optimum number of product atoms.

Experiments using 200 and 500 MeV proton beams were designed to measure these recoil effects because few measurements for energies <500 MeV have been reported. While the motivation was to estimate the additional error (if any) that should be included in our cross section measurements, these experiments also provide insight into the problems associated with cosmogenic nuclide production in inclusions in meteoritic material. Our new measurements which are intermediate between the extreme energies used in the earlier experiments [3, 4, 5] will provide additional insight into these recoil losses.

Experimental method: Three target stacks were irradiated at the Tri-Universities Meson Facility (TRIUMF) at the University of British Columbia in 1997. Two of these stacks were irradiated using 200 MeV protons and the third using 500 MeV protons.

Experimental parameters: The proton fluence was directly measured in each irradiation by an upstream ion chamber, which had been previously calibrated using a Faraday cup for each proton energy. The total number of protons through the target stacks for the three runs ranged from 1E+15 to 5E+15 protons. The diameter of the proton beam was always smaller than that of the target stacks so that the entire beam was captured.

Target materials: All targets and ‘catcher’ foils were 15 mm in diameter. Carbon foils, ~22 mg/cm^2 thick were used as the ‘catcher’ foils. The target foils were Al (~35 mg/cm^2 thick), Si (~184 mg/cm^2 thick), Mg (~22 mg/cm^2) and Fe (~99 mg/cm^2).

Target stack composition: An example of a typical stack configuration might be Al (upstream monitor foil) – C (Al forward ‘catcher”) – C (neutral ‘buffer’) – C (Mg backward ‘catcher) – Mg – C (Mg forward ‘catcher’) – C (neutral ‘buffer’) – C (Al backward ‘catcher’) – Al (downstream monitor). In one of the stacks irradiated at 200 MeV, the forward ‘catcher’ foils for the Si and Fe targets were replaced by stacks of 10 Mylar foils (each 0.0009 mm thick) mounted on 0.762 mm thick Al annular holders. The total target stack thickness was designed to minimize the loss of protons scattering out of the stack and the production of neutrons within it. The total energy lost in the entire target stack was ~3.5 MeV for the stack irradiated at 200 MeV containing the stacked mylar foils and <1.5 MeV for the other two stacks

Gamma ray spectroscopy: The product nuclei were measured in the targets and ‘catcher’ foils using non-destructive gamma ray spectroscopy. High purity Ge detectors were used and spectra collected starting soon after irradiation and continuing for several months. Background levels for the ‘catcher’ foils were measured in the carbon ‘buffer’ foils.

Results and Discussion: The measured recoil losses for ^{22}Na and ^{24}Na in the forward (KON) and backward (KOB) directions for targets of Mg, Al, Si and Fe are summarized in Tables 1 and 2. The error associated with the activity measurement in the target foils was generally ~7-8% but for the 'catcher foils' the error in the activity measurement ranged from 7-25%. Higher errors were always associated with measuring the KOB activity and in some cases, the signal for ^{22}Na in the 'catcher' foils was too small to be detected. The recoil ranges were calculated using the formalism given in references [9, 10].

Table1: recoil losses and ranges at 200 MeV

Product	target	%KON (F)	%KOB (B)	Ratio F/B	Range μm
^{24}Na	Mg	0.57	0.04	13.3	1.2
	Al	0.77	0.1	7.4	1.9
	Si	0.22	0.02	10.3	2.9
^{22}Na	Mg	?	0.1	-	-
	Al	0.93	0.13	7.1	2.3
	Si	0.17	0.0	-	-

Table 2: Recoil losses and ranges at 500 MeV

Product	target	%KON (F)	%KOB (B)	Ratio F/B	Range μm
^{24}Na	Mg	0.52	0.09	5.8	1.3
	Al	0.71	0.14	5.0	1.9
	Si	0.17	0.03	5.5	2.7
^{22}Na	Mg	0.58	0.13	4.4	1.6
	Al	0.82	0.23	3.6	2.5
	Si	0.18	0.04	4.1	3.2

It should be noted that the data presented in Tables 1 and 2 for the fractions and ratios of particles recoiling out of the target nucleus are actual measurements while the recoil ranges are calculated using a formalism, which is dependent on the exact model assumed for the type of interaction taking place. At these energies and within the measurement errors, the recoil losses for ^{22}Na and ^{24}Na nuclides from Mg, Al and Si targets were <1%. Similarly for ^{46}Sc, ^{48}V, ^{51}Cr, ^{52}Mn and ^{54}Mn produced from Fe, most of the recoil losses were <1%. These small losses show that for the cross section measurements no additional error need be included even when a 'catcher' foil is used for the cross section measurements.

Our estimated recoil ranges calculated using the formalism in [9] are consistent with those measured in Si and Al at 66 MeV by Ott et al. [5] and at 3 – 300 GeV in ref. [10]. These measurements show that there is little chance in recoil range over a wide range of input projectile energies.

Conclusions: Recoil losses and ranges have been measured for several materials and the results are generally consistent with reported measurements most of which were made at much higher energies. Recoil ranges calculated by the same method as used in [5] provide additional confirmation that the recoil range is relatively independent of the energy of the incoming projectile under our irradiation conditions.

In particular, at 200 and 500 MeV, the recoil losses were small for all studied radionuclides from Mg, Al, Si and Fe targets and no additional error has to be included in the cross section measurements for these reactions.

The measured percentage recoil losses for ^{22}Na and ^{24}Na produced in Mg, Al and Si targets are very similar, so no significant additional error is added to a cross section measurement made using one of the 'catcher' foils with our target stack configurations.

This observation also implies that for the case of inclusions in extraterrestrial material, the net loss/gain of product nuclei might be small if the surrounding matrix is composed of elements that are close in the periodic table to those found in the inclusion.

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References: [1] Vogt S. et al. (1990) *Rev. of Geophys.*, *28*, 253-275. [2] Ray J. and Volk H. J. (1983) *Icarus*, *54*, 406-416. [3] Ott U. and Begemann F. (2000) *Meteoritics and Planet. Sci., 35*, 53-63. [4] Mohapatra R. et al. (2001) *LPS XXXII* Abstract #1296. [5] Ott U. et al. (2001) *Meteoritics and Planet. Sci.*, *36 Suppl.*, A155. [6] Sisterson J. M. and Caffee M. W. (1998) *LPS XXIX* Abstract #1234. [7] Sisterson J. M. and J. Ullmann (2005) submitted to *Nucl. Instr. Meth.* [8] Sisterson J. M. (2003) *LPS XXXI* Abstract #1326. [9] Sugarman N. et al. (1956) *Phys. Rev. 101*, 388-397. [10] Steinberg E. P. and Winsberg L. (1974) *Phys. Rev. 10*, 1925-1927.