DETERMINATION OF SOLAR-PROTON FLUXES USING CARBON-14 IN LUNAR ROCKS; Janet M. Sisterson, Harvard Cyclotron Lab., Harvard University, Cambridge, MA 02138; Herminia Román, John S. Vogel†, and John R. Southon†, McMaster University, Hamilton, Ontario L8S 4L8; Robert C. Reedy‡, SST-8, MS-D438, Los Alamos National Lab., Los Alamos, NM 87545.

Radioactivities produced in the top ~1 cm of lunar samples by solar cosmic rays (SCR) can be used to determine SCR-particle fluxes over various time periods. The solar-proton fluxes determined by direct energetic-particle measurements or using lunar radioactivities are given in Table 1, which is modified slightly from (*1*). This table has many blanks or large uncertainties because of the lack of cross sections with which to unfold the lunar radioactivity-*vs.*-depth profiles (*1*). A few cross sections have been measured recently for the production by low-energy protons of the radionuclides listed in Table 1, such as for ^{41}Ca (*2*,*3*) and for ^{10}Be and ^{26}Al (*4*). The measured ^{10}Be cross sections of (*4*) for E_p<135 MeV are higher than those estimated by (*5*), and the SCR ^{10}Be production rates calculated with them are ≈10% higher than those using the old set (*6*). Here we discuss new experimental cross sections for unfolding the lunar ^{14}C record.

The lunar ^{14}C profile of (*7*) was unfolded with cross sections in (*8*), which for the dominant, ≳90% of production (*9*), ^{16}O(p,3p)^{14}C reaction used the cross sections of (*10*). The cross sections of (*10*) were revised by (*11*) using better cross sections for the ^{27}Al(p,3pn)^{24}Na monitor reaction. The solar-proton fluxes from the ^{14}C data are interesting as they are much higher than those from longer-lived radionuclides (Table 1), although some fluxes might move upwards, e.g., for 1–5 Ma (*6*). Until recently, the ^{14}C production cross sections of (*10*) had not been independently checked.

Using an irregular-shaped piece of the Bruderheim meteorite as a target, (*12*) reported a cross section for the ^{16}O(p,3p)^{14}C reaction at 150 MeV of 6.0±0.1 mb, which was ~3 times higher than that of (*10*). They assumed that all the ^{14}C was made from oxygen. Their cross section suggested that the high solar-proton fluxes inferred from the lunar ^{14}C measurements were due to the cross sections used for ^{14}C. These results have been re-analyzed using ^{24}Na activities measured in aluminum foils attached to the target's upstream and downstream faces. The ^{24}Na activities corresponded to cross sections that differ by ~2 with those of (*13*). Re-examination of the irradiation conditions showed that an incorrect parameter had been used in calibrating the monitor chamber used to determine the total number of protons incident on the target. Using the correct parameter, the beam intensity increased by a factor of 2.31, and the measured ^{27}Al(p,3pn)^{24}Na cross sections were those expected. Scaling the ^{16}O(p,3p)^{14}C cross section of (*12*) by the inverse of 2.31 yields a cross section of 2.6 mb, much closer to that of (*10*) and to a value reported verbally by Ed Fireman at *LPSC-20* in 1989 for a CO_2 target of 1.5 mb. The beam energy was also found to have been 148 MeV, not the value of 150 MeV in (*12*). The uncertainty of this revised cross section should also include ~5% each for beam intensity and the fraction made from oxygen plus

Table 1. Solar-proton integral fluxes averaged over various time periods.

Time Period	Data Source	Flux References	R_o[a] (MV)	---- E>10	Integral E>30	Fluxes[b] E>60	----- E>100
1976–1986	IMP-8	(Goswami *et al.*, 1988)[14]	40	63	5	0.6	~0.2[c]
1965–1975	SPME	(Reedy, 1977)[15]	90	92	30	8	–[c]
1954–1964	^{22}Na, ^{55}Fe	(Reedy, 1977)[15]	100	378	136	59	26
$\sim 10^4$ y	^{14}C	(Boeckl, 1972)[7]	100	–[d]	~72[e]	~26[e]	~9[e]
$\sim 2\times10^5$ y	^{41}Ca	(Klein *et al.*, 1990)[2]	~70	–[d]	~28[e]	~7[e]	~1.5[e]
$\sim 3\times10^5$ y	^{81}Kr	(Reedy and Marti, 1991)[1]	~85	–[d]	–[d]	–[e]	–[e]
$\sim 5\times10^5$ y	^{36}Cl	(Nishiizumi *et al.*, 1989)[16]	–	–[d]	–[e]	–[e]	–[e]
$\sim 10^6$ y	^{26}Al	(Kohl *et al.*, 1978)[17]	100	70	25	9	3
$\sim 2\times10^6$ y	^{10}Be	(Nishiizumi *et al.*, 1988)[6]	≳70	–[d]	~35[e]	~8[e]	~2[e]
$\sim 5\times10^6$ y	^{53}Mn	(Kohl *et al.*, 1978)[17]	100	70	25	9	3

a. Spectral shape in rigidity, usually 10–30 MeV. b. Omnidirectional fluxes in protons/(cm^2 s); energies in MeV. c. Not measured (1965–1973) or sometimes not reported (1973–1986). d. Energy is below main reaction thresholds. e. Few or no cross sections available, see text.

unknown amounts due to the irregular target geometry and the extraction. Further refinement of the cross section for the CO_2 target (J. Sisterson, priv. comm.) gives 1.6 (± ~0.1) mb at 158 MeV.

A new measurement of the $^{16}O(p,3p)^{14}C$ cross section was carried out using stacks of quartz plates irradiated with a beam of 63-MeV protons from the Crocker Nuclear Laboratory cyclotron at the University of California at Davis. The ^{14}C produced was extracted by crushing the quartz under argon and heating the powder to 1000° C with an oxidizer in an evacuated sealed quartz tube and was measured by accelerator mass spectrometry (*18*). The proton beam stopped in the stacks and out-scattering from the sides was negligible (*19*). In view of the relatively low proton energy, ^{14}C production from secondary neutron reactions could be safely neglected, and the final plates in the stacks were used as blanks to determine sample processing backgrounds. Tests showed that the extraction technique was essentially 100% efficient, and that the effects of ^{14}C losses during crushing and the adsorption of modern CO_2 during sample processing were both small (*18*). The results (Table 2 and Fig. 1) show fair agreement with the data of (*10*).

Production rates for ^{14}C by solar protons from oxygen were calculated using the cross sections of (*10*) as shown in (*8*) and the new ones presented here. Rigidity spectral shapes with R_o of 70 and 100 MV were used. The total ^{14}C production rates were ~10–20% lower with the new cross sections than with those of (*10*), with the higher new cross sections below 42 MeV being less important than the lower ones at higher energies. From 0 to 1 cm, protons above 100 MeV contributed ~10% to ~25% of the total ^{14}C production. These calculations show that the high ^{14}C-derived fluxes in Table 1 are probably not due to the cross sections used to unfold the measurements of (*7*). Measurements of additional cross sections for the production of ^{14}C are planned for these and other energies from oxygen and at a few energies from silicon.

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Table 2. $^{16}O(p,3p)^{14}C$ cross sections from quartz targets (*18*).

E_p (MeV)	σ (mb)
61 ± 2	1.8 ± 0.3
58 ± 2	1.2 ± 0.2
54 ± 2	1.4 ± 0.2
50 ± 2	1.4 ± 0.3
46 ± 2	1.2 ± 0.2
36 ± 2	1.0 ± 0.2
25 ± 3	0.19 ± 0.04

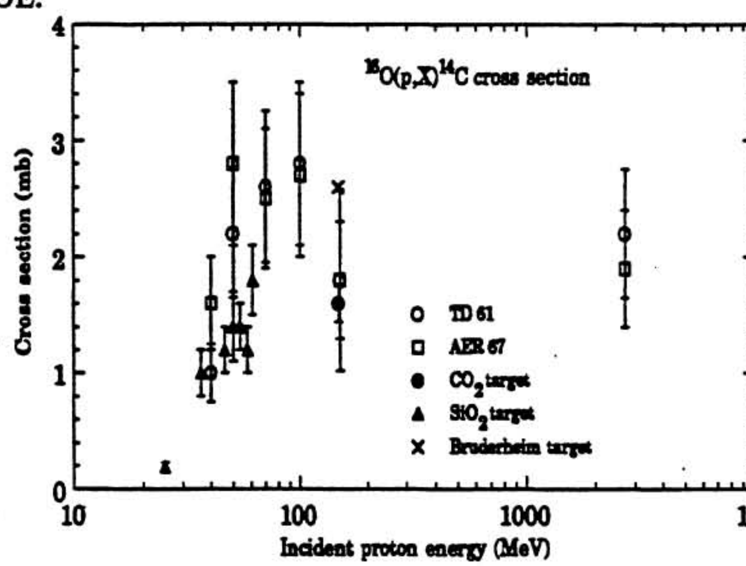

Fig. 1. $^{16}O(p,3p)^{14}C$ cross sections reported by (*10*) (open circles) and as revised by (*11*) (open squares) and as measured for CO_2 (filled circle), Bruderheim (×), and quartz (filled triangles) targets. Energy spreads are not indicated.