REVISED SOLAR COSMIC RAY FLUXES ESTIMATED USING MEASURED
DEPTH PROFILES OF 14C IN LUNAR ROCKS; THE IMPORTANCE OF GOOD 14C
CROSS SECTION DETERMINATIONS. J. M. Sisterson1, R. J. Schneider IV1,
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Long-lived radionuclides produced in lunar rocks by solar cosmic rays (SCR) preserve an
historical record of the Sun's activity (1). SCR flux estimates over different time intervals can be
made by using radionuclides with different half-lives. Knowing the solar proton flux in the past
combined with modern direct measurements made with satellites results in better estimates of
hazards that might be met in space missions (2). The SCR flux estimated over the time period
characterized by the 14C half life (5730 years) does not agree with those calculated using other
radionuclides, and one possible explanation might be that the cross sections used in the calculation
were incorrect (3). We present new values for the cross sections 16O(p,3p)14C, Mg(p,x)14C, and
Fe(p,x)14C at selected energies to add to those that we have reported before (4, 5). Lunar rocks are
usually 41-46% (by weight) oxygen, so it is very important to have good values for the cross
section for the reaction 16O(p,3p)14C, particularly near threshold. We present new values for this
cross section and revised estimates for the SCR flux over the past 10,000 years.

Theoretical production rates for SCR, usually using the model of Reedy and Arnold (6), are
used to analyze measured depth profiles for the production of these cosmogenic nuclides in well
documented lunar rocks (7). A good estimate for the SCR flux can be made IF the cross section
values for all interactions of all cosmic ray particles with all elements in the lunar rock are known
e.g. (3). In practice, proton production cross sections are the most important because most solar
and galactic cosmic ray (GCR) particles are protons (98% and ~87%) in the lunar environment.
Values for the cross sections are needed at energies greater than those typically found in SCR to
allow good GCR corrections to be made. The solar proton spectral shape is usually expressed as
an exponential in rigidity, $dJ/dR = \text{constant*exp}(-R/R_0)$. The model predictions can then be
compared to measured depth profiles and the best estimates for the parameters $J$ (the integral
omnidirectional proton flux above 10 MeV) and $R_0$ (the rigidity) determined.

Over the past decade, many of these needed cross sections have been measured (4, 5, 8, 9, 10)
with the required accuracy and precision, but still more measurements are needed. Measuring
cross sections of long-lived radionuclides became easier with the development of Accelerator
Mass Spectroscopy (AMS), but for many cross sections there are only single determinations.
When SCR fluxes are estimated using these cross section values in the data analysis and the SCR
estimates differ from what was expected, the reliability of the cross section data is again questioned -
this is the case for solar proton fluxes calculated over the time period characterized by the 14C half
life (3).

Our collaboration is making relevant cross section measurements over the proton energy range
of ~25 - 500 MeV. Three accelerators are used and in all cases thin targets are used to minimize
the loss of protons scattering out of the target stack and production of secondary neutrons within
the target stack. The maximum energy loss in any target is about 2 MeV and in a whole stack
about 10 MeV. After irradiation, chemistry and AMS analysis of the target foils for 14C are done at
the NSF-Arizona AMS Facility using the techniques described in earlier papers (11).
Figure 1 shows all published cross section measurements (4, 5, 9, 12, 13) for the reaction $^{16}$O(p,3p)$^{14}$C including the new measurements reported here. Cross section values for Si(p,x)$^{14}$C, Mg(p,x)$^{14}$C, Fe(p,x)$^{14}$C and $^{27}$Al(p,x)$^{14}$C have been reported before (4, 5), but work is in progress on additional measurements at selected proton energies. Figure 2 shows the predicted $^{14}$C production rates at depth in rock 68815 calculated using three cross section data bases; the latest data, those from (5) used by Rao et al. (3), and the original set of (6).

The new cross section values for $^{16}$O(p,3p)$^{14}$C are at energies from 50 MeV down to threshold and are lower than those we reported before (5). The new data points were obtained under carefully controlled irradiation conditions which gave the optimum number of $^{14}$C atoms for AMS determination; this should result in an accurate measurement of the cross section. The earlier irradiations had resulted in too many $^{14}$C atoms being produced, so the samples required considerable dilution before an AMS determination was possible. The dilution introduced an unknown error into the system; for this reason, the measurements were repeated under better irradiation conditions.

Using all the available cross section data for all elements in lunar rock 68815 and the lower cross section values for $^{16}$O(p,3p)$^{14}$C reported here, the model of Reedy and Arnold predicts that the $^{14}$C production rates at depths up to 3.36 g/cm$^2$ in 68815 range from 0.65 - 0.8 of those estimated before (3). The contribution to the $^{14}$C production rate from the reactions Mg(p,x)$^{14}$C, Al(p,x)$^{14}$C, Si(p,x)$^{14}$C and Fe(p,x)$^{14}$C was estimated to be< 2%, so the change in $^{14}$C production rate is due to the change in the cross section values for $^{16}$O(p,3p)$^{14}$C at low energies. This decrease in predicted $^{14}$C production rate implies an increase of 25 -30% in the SCR flux over this time period. Once good GCR corrections to the production rate have been calculated using all cross section data, final estimates for the SCR flux over this time period will be made.


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