TITANIUM SPALLATION CROSS SECTIONS BETWEEN 30 AND 584 MeV AND Ar^{39} ACTIVITIES ON THE MOON

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(NASA-CR-134251) TITANIUM SPALLATION CROSS SECTIONS BETWEEN 30 AND 584 MeV AND Ar-39 ACTIVITIES ON THE MOON (Smithsonian Astrophysical Observatory) 11 p HC $4.00 CSCL 03B
N74-27336
Unclas
G3/30 41077

April 1974

404-068

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Abstract – The production cross sections of Ar^{39} for Ti spallation at 45-, 319-, 433-, and 584-MeV proton energies were measured to be 0.37 ± 0.09, 12.4 ± 3.7, 9.1 ± 2.7, and 17.8 ± 6.2 mb, respectively. Normalized Ar^{39} production rates and activities are also derived for protons above 40 MeV and for three differential proton spectra of the type $\sim E^{-\alpha}$. It is concluded that, even for samples of high-Ti content, Ti spallation by solar protons below 200-MeV energy does not contribute significantly to their Ar^{39} radioactivity.

INTRODUCTION

The Ar^{39} activities were measured in lunar surface and drill-core samples from all Apollo missions (Fireman et al., 1970, 1972, 1973; D'Amico et al., 1970, 1971; Stoenner et al., 1970, 1971). The Ar^{39} activity in near-surface samples is produced by solar- and cosmic-ray-proton spallation of Ti and Fe; therefore, it should be possible to obtain information on the average proton intensity and rigidity over the past ~1000 yr from Ar^{39} data. If cross sections extrapolated to low energies are used, an unusually high solar-proton intensity is indicated by Ar^{39} data (Fireman, 1973). The Ti content of some samples at the Apollo 11 and 17 sites is quite high and can reach about 50% of the Fe content (Rose et al., 1974). It is necessary to know the Ti spallation cross sections produced by 45- to 600-MeV protons in order to calculate the contribution of Ti to the production of Ar^{39} by solar protons. The Ar^{39} activity

This work was supported in part by grant NGR 09-015-145 from the National Aeronautics and Space Administration.

in six proton-irradiated Ti foils was measured (Steinbrunn and Fireman, 1974), and the cross sections are reported together with Ar^{39} production rates for Ti bombarded by solar protons of $E^{-\alpha}$ differential energy spectra.

EXPERIMENTAL PROCEDURE

Table 1 summarizes data on the six Ti foils including proton fluxes and energies obtained by R. Perkins (private communication, 1973). Previously, a number of other radioisotopes were measured in the same foils by nondestructive γ-spectrometry (Brodzinski et al., 1971). Since it is nearly 5 yr since the irradiation, no interference from the Ar^{37} activity ($T_{1/2}$ = 35 days) was observed.

The Ar^{39} extraction procedure was the same as that used earlier in our laboratory for the extraction of Ar from magnetic fractions of meteorites (Fireman and Spannagel, 1971). The Ar was released by dissolving the foils in hot sulfuric acid of 9n concentration. The Ti foils were cut in ~100 pieces and placed inside a three-neck flask of the extraction system. Under vacuum conditions, 400 cm^3 of sulfuric acid was dripped onto the Ti chips. Air had been removed from the acid by bubbling He through it for 15 min. The system was filled with He at a pressure of ~90 mm Hg above atmospheric, and the He flow was started at an estimated rate of 80–100 cm^3/min. The He bubbled through the solution and then passed through a condenser, a silica-gel trap, a charcoal trap at liquid-nitrogen temperature, and, finally, through a flow meter in the room. Argon carrier of 0.5-cm^3 volume was mixed into the He flow. The flow was continued (4–14 hr) until the Ti was completely dissolved. The Ar yield was 100 ± 5% of the initial carrier. The Ar, together with 10% methane, was placed into a small proportional counter at 1.4-atm pressure for counting.

RESULTS

The 15-MeV-proton energy is below the threshold of any nuclear reaction of protons with any of the stable Ti isotopes leading to Ar^{39}. For protons of 30 MeV, only the reaction $Ti^{47}(p; 2\,He^4, p)\,Ar^{39}$ contributes, if a Coulomb barrier of 5.5 MeV is added. The Ar^{39} activities in both 15- and 30-MeV foils were within the counter background activity. The cross sections derived for these energies are smaller than ~5 μb. The

Ar^{39} activities of the remaining four foils were corrected for counter efficiency and carrier yield. The derived cross sections are the following:

Proton energy (MeV)	45	319	433	584
Cross section (mb)	0.37 ± 0.09	12.4 ± 3.7	9.1 ± 2.7	17.8 ± 6.2

The errors include the statistical counting error (less than 5% at 2σ throughout), 5% for the extraction efficiency, and 10% for the counter efficiency. Errors assumed for the proton fluxes are 5% at 45 MeV, 10% at 319 and 433 MeV, and 15% at 584 MeV, according to Brodzinski et al. (1971) and Perkins (private communication, 1973).

In Fig. 1, the measured cross sections are shown together with a yield curve calculated after Rudstam's (1966) CDMD formula. At high energies, the cross sections agree well with the semiempirical formula; however, at 45 MeV, the cross section does not agree, because it was deduced from data at higher energies.

Ar^{39} PRODUCTION RATES AND ACTIVITIES

In order to estimate the Ar^{39} production from Ti by solar-flare-proton bombardment, three differential proton spectra of the form $\sim E^{-2}$, $\sim E^{-2.5}$, and $\sim E^{-3}$ were assumed. Normalized production rates,

$$Ar^{39} = \int_{40}^{\infty} F(E) x\ \sigma(E)\ dE \quad ,$$

were calculated in 17 steps for each proton spectrum. The cross sections as a function of energy listed in Table 2 were taken graphically from a yield curve similar in shape to the Rudstam curve in Fig. 1, but the curve connected our measured data points.

The calculated production rates and activities, normalized to an integrated flux of 1 proton/cm^2 and a target of 1 Ti atom/cm^2 and to 1% by weight Ti content, are given in Table 3. The data represent a "thin target" case and apply only to surface samples of ~1-mm thickness.

For a sample with a 10% Ti content, only 0.1 dis/min kg of Ar^{39} activity is produced by a flux of 100 protons/cm^2 sec above 40 MeV with an E^{-2} differential spectrum. From the Ar^{39} activities calculated with our cross sections, we conclude that solar protons of relatively low energies and of the assumed spectral distribution do not contribute significantly to lunar Ar^{39} activities via Ti spallation.

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Table 1. Target and irradiation summary

Target	Area (cm^2)	Weight (g)	Proton dose ($\times 10^{13}$)	Proton energy (MeV)	Date of irradiation
8600-40-Ti	23 (round)	2.600	304.6	15	3/13/69
8600-41-Ti	23 (round)	2.588	448.9	30	3/13/69
8600-42-Ti	23 (round)	2.583	333.9	45	3/13/69
Ti-A (front foil)	40.3 (square)	13.9	7.582	319	7/12/68
8600-8-Ti	40.3 (square)	14.05	1.983	433	7/12/68
8600-9-Ti	41.5 (square)	14.4	5.405	584	7/12/68

Table 2. Cross sections used for the calculation of Ar^{39} production rates in Table 3

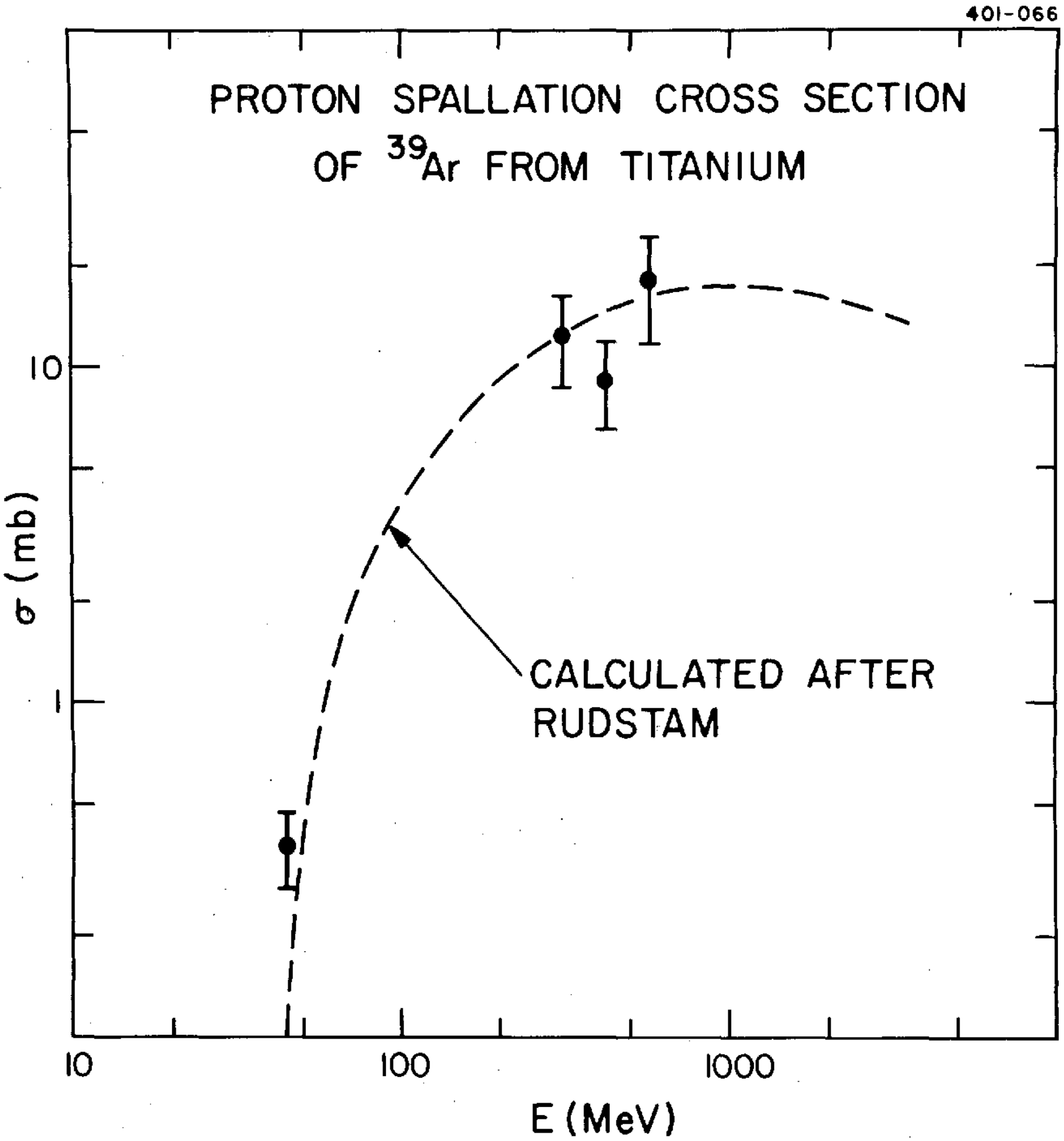
Energy interval (MeV)	σ (mb)	Energy interval (MeV)	σ (mb)
40–50	0.37	130–140	6.25
50–60	1.25	140–150	6.7
60–70	2.1	150–160	7.15
70–80	2.8	160–170	7.6
80–90	3.4	170–180	8.05
90–100	4.1	180–190	8.45
100–110	4.65	190–200	8.9
110–120	5.2	200–∞	12.5
120–130	5.75		

Table 3. Normalized production rates and equilibrium activities of Ar^{39} for three differential proton spectra

Differential proton spectrum (E > 40 MeV)	Ar^{39} production* (10^{-27} Ar^{39} atoms)	Ar^{39} activity† (10^{-4} dis/min kg)
$\sim E^{-2}$	4.8 ± 1.2	1.0 ± 0.25
$\sim E^{-2.5}$	3.3 ± 0.8	0.69 ± 0.17
$\sim E^{-3}$	2.4 ± 0.6	0.50 ± 0.12

*Ar^{39} production normalized to an integral proton flux of 1 proton/cm^2 above 40 MeV and to a target of 1 Ti atom/cm^2.

†Ar^{39} activity normalized to an integral proton flux of 1 proton/cm^2 sec above 40 MeV and 1% by weight Ti content.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PROTON SPALLATION CROSS SECTION
OF 39Ar FROM TITANIUM
CALCULATED AFTER
RUDSTAM
σ (mb)
10
1
10
100
1000
E (MeV)

Fig. 1.