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Cross sections of ^{10}Be and ^{26}Al by 30 to 500 MeV protons on thin targets of C, Mg, Al, Si, and SiO_2

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**CROSS SECTIONS OF ^{10}Be AND ^{26}Al BY 30 TO 500 MeV PROTONS
ON THIN TARGETS OF C, Mg, Al, Si, AND SiO_2**

A Thesis

Presented to

The Faculty of the Radiological Health Physics Program

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Kyeong J. Kim

August 1997

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ABSTRACT

CROSS SECTIONS OF ^{10}Be AND ^{26}Al BY 30 TO 500 MEV PROTONS ON THIN TARGETS OF C, Mg, Al, Si, AND SiO_2

By Kyeong J. Kim

Cross sections for production of long-lived radionuclides ^{10}Be and ^{26}Al by cosmic-ray-energy range of protons were measured for Al, C, Mg, Si, and SiO_2 targets. Yields of ^{10}Be and ^{26}Al were determined by the new technique of accelerator mass spectrometry. Results fill in large gaps over the cosmic-ray energy range and are useful for model calculations of cosmogenic nuclide production in extended bodies. These data are important for interpretation of ^{10}Be and ^{26}Al concentrations in terrestrial, planetary, and meteoritic materials.

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I. INTRODUCTION

Proton production cross sections for radionuclides are important in the fields of astro- and cosmophysics, and space technology. Cosmogenic nuclides allow investigation of geo- and cosmochemical processes and the cosmic ray exposure history of rock samples in space and meteorites. Cross sections are also essential for radiation protection assessment. Data interpretation requires knowledge of integral excitation functions for proton-induced reactions.

Solar-cosmic-rays (SCR) and galactic-cosmic-rays (GCR) are mostly protons. Solar-cosmic-rays (SCR) produced cosmogenic nuclides have been investigated in lunar surface material and meteorites[1, 2]. The relevant energies for the SCR proton production of cosmogenic nuclides are ≤ 200 MeV. Due to their relatively low energies, SCR particle interactions are restricted to the outermost surface of the irradiated material. However, the average GCR energy is several GeV, and the relevant energies for GCR proton production of cosmogenic nuclides are between 0.1 and 1 GeV. GCR protons can penetrate a few meters of a matter and produce numerous secondary particles. Production rates of cosmogenic nuclides can be calculated as a function of depth inside the irradiated material using integral excitation functions for the production of the respective nuclides from all contributing target elements:[3]

$$P(d, R, N, t) = \sum_j N_j \sum_k \int_0^{\infty} \sigma_{j,k}(E) \varphi_k(E, d, R, N_j, t) dE$$

Here $P(d, R, N, t)$ is a production rate that depends on the geometric conditions of irradiation or shielding and the abundances, N_j , of the target elements in the exposed object; d is a depth in a spherical body with radius R ; $\sigma_{j,k}(E)$ is the

energy-dependent cross section for the production of the nuclide of interest from nucleus j by particle k ; $\phi_k(E, d, R, N_j, t)$ is the local flux of particles of type k ; t is the time of exposure to radiation.

The half-lives of ^{10}Be and ^{26}Al are 1.5×10^6 years and 7.20×10^5 years respectively, and encompass geologically and cosmologically interesting and significant time periods. The main target elements for the production of ^{10}Be and ^{26}Al in lunar surface materials, meteorites, and the atmosphere of the earth are C, O, Si, Mg, and Al. Reliable cross sections for ^{10}Be and ^{26}Al spanning a wide proton energy range are needed, but there is a scarcity of experimental data on the relevant target/product combinations over the cosmic ray energy range from threshold energy to 0.1 GeV.

Development in the past decade of accelerator mass spectrometry (AMS) for trace-isotope assays offers significant improvement in accuracy of cross section measurements over traditional decay counting techniques. Most previous publications provide proton cross section data for only a small proton energy range. Using AMS, this work provides necessary excitation functions of ^{10}Be and ^{26}Al for the energy range from threshold to 500 MeV for the elements C, O, Al, Mg, and Si. This work provides experimental excitation functions and confirms previous cross section measurements which available.

Appropriate proton beams were available at U.C. Davis, Crocker Nuclear Laboratory (thresholds < E_p < 67.5), Harvard University, Harvard Cyclotron Laboratory (HCL) ($55 < E_p < 160$), and Tri-Universities Meson Facility (TRIUMF) in Vancouver, Canada ($200 < E_p < 500$).

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II. EXPERIMENTAL METHODS AND CALCULATIONS

Proton cross section measurements require determination of the number of radionuclides produced from the nuclear reaction, the flux of incoming protons, and the concentration or number of target atoms. Accurate determination for all three parameters is critical to the success of the experiment.

The probability of production of a radionuclide, x , by a bombarding proton is specified by a “cross section”, σ [area/target] defined by the following relation between yield, $Y(x)$ [particles/second], proton current, I [protons/second] and target density, n [target nuclei/area]

$$Y(x) = I \cdot n \cdot \sigma$$

In this accelerator-based experiment, proton currents were evaluated by dividing the beam current (in amperes) by the proton charge [1]. Targets were thin films of known density and thickness. The very small yields were measured by accelerator mass spectrometry. Proton irradiation and target information are discussed in Chapter II, 1. and chemistry to separate the radionuclides produced in each target is discussed in Chapter II, 2., and measurement of the radionuclide yield by accelerator mass spectrometry is described in Chapter II, 3..

1. PROTON IRRADIATION OF TARGETS

Proton bombardments were performed at the Crocker Nuclear Laboratory (CNL) for proton energies from 30 to 67.5 MeV, at Harvard Cyclotron Laboratory (HCL) for energies from 55 to 160 MeV, and at Tri-Universities Meson Facility

(TRIUMF) for energies from 200 MeV to 500 MeV. Dependent on cyclotron design, the proton energy ranges of each of the irradiation facilities differed. At all three facilities, irradiation procedures were similar, with minor differences in details.

Target disks were 10 or 15 mm in diameter. Thicknesses of Al, C, Mg, Si, and SiO₂ targets (SJSU targets) were 0.055, 0.125, 0.125, 0.5, and 0.5 mm, respectively. Most targets were certified by the supplier (Goodfellow, Malvern PA 19355) to be at least 99.999% pure. Some target disks were weighed to the nearest 0.2 mg with a standard analytical balance (Sartorius, Type 2463, S/N 141408), and the majority were weighed to the nearest 0.02 mg with a digital torsion balance (Cahn Instrument Co. Model 29. 0-250 mg range, ID 010077). These measurements reduced the uncertainties associated with target weight to less than or equal to 1 % [2]. Contamination of targets by handling was minimized by using gloves and forceps.

For a typical proton irradiation at CNL, target stacks were composed of three disks of high purity carbon, magnesium, silicon, or silicon dioxide with aluminum foil separators upbeam and downbeam (Fig1).

Figure 1. Target sequence and incident proton energies. There is no spacing between targets during irradiation.

To confirm the accuracy of the beam current measurement, ^{22}Na production in aluminum foils was used to back-calculate the proton flux using the well known cross-section for this reaction. The proton currents determined by these two methods agreed to within 5 %. The proton bombardments were performed in the north cave beam line at CNL for proton energies from 30 to 67.5 MeV (Figure 2). We used an Ortec, Model 2800, S/N 1 scattering chamber which contains a remote controlled turntable (Figure 3). A television camera was used to confirm the position of the target stacks during irradiation. Target stack holders were machined from aluminum. A tantalum collimator confines the proton beam to a 12.9 mm diameter to match the target diameter. Two target stacks were loaded in the scattering chambers for each run.

After evacuation of the scattering chamber and beam pipe in the north cave, this section was opened to the evacuated interior of the cyclotron. The cross mark on the phosphor screen (Figure 4) was used as a vertical and horizontal reference for tuning the proton beam to the center position of the target stack. A phosphor screen for beam diagnosis was mounted between the target stacks. The shape of the beam spot was a 5- by 9-mm ellipse with the longer axis in the horizontal position. Collimation of the beam was done with 1/4-inch diameter carbon and two 1/8-inch ID tantalum collimators upstream of the scattering chamber. Upon completion of tuning, the beam was blocked and a target stack was rotated into position. The duration of proton bombardment was carefully noted and recorded.

A calibrated brass Faraday cup downstream of the target stack was used to integrate the proton current that passed through the stack during bombardment. A secondary-electron-emission monitor located between the target stack and the

Figure 2. Plan of North Cave Beam Line at Crocker Nuclear Laboratory.

Figure 3. Scattering Chamber Interior with Carbon Beam Stop in Chamber Lid.

Figure 4. Assembled Target Holder (L) and Phosphor Screen Holder (R).

Faraday cup was used to monitor the beam current during bombardment. When the readout from the Faraday cup indicated that the designed integrated fluence had been received by the target stack, the beam stop was replaced and the time recorded. The same procedure was repeated for the second target stack. Proton irradiations at HCL and TRIUMF were performed by Dr. Janet Sisterson and others in a similar manner.

To obtain the incident proton energy in each single target foil irradiated at CNL, proton energy losses in each target stack were calculated using Monte Carlo techniques. Incident proton energies for HCL and TRIUMF bombardments were determined using Janni's table and interpolation techniques [3]. For those targets from CNL, TRIM-91 was used for the calculations of proton energy loss [4].

Table 1 shows proton energy loss for different target elements.

Table 1. Entering proton energy in each target stack at 67.5 MeV incident energy.

Run 1	Al1	Si1	Si2	Si3	Al2
incident energy(MeV)	(67.5)	67.4	(66.5)	(65.6)	(64.7)
Run 2	Al3	SiO ₂ 1	SiO ₂ 2	SiO ₂ 3	Al4
incident energy(MeV)	(67.5)	67.4	(66.3)	(65.2)	(64.1)
Run 8	AlB	Mg1	Mg2	Mg3	AlC
incident energy(MeV)	67.5	67.4	(67.2)	(67)	(66.8)
Run 9	AlF	C5	C6	C7	AlG
incident energy(MeV)	(67.5)	67.4	(67.1)	(66.9)	(66.7)
element	Al	Si	SiO ₂	Mg	C
density (g/cm ³)	2.283	2.230	2.230	1.787	2.10
thickness (cm)	0.0055	0.05	0.05	0.125	0.125

2. CHEMISTRY

The most challenging part of this proton cross section measurement is the determination of the small number of ^{10}Be and ^{26}Al atoms produced in each target. The long half-lives (1.6×10^6 years for ^{10}Be and 7.1×10^5 years for ^{26}Al) which make these radioisotopes important geologic tracers, mean that they have very small decay probabilities. Therefore, counting radioactive decays to assay the targets is impractical, the background from short-lived activities produced in the targets overwhelms the signal from the isotopes of interest. The recently-developed technique of accelerator-mass spectrometry (AMS) can assay isotopic composition at ratios in the range $1:10^{15}$ for milligram-sized samples [5].

Chemical separation of Be and Al for most targets in this study was performed approximately three years after the date of the irradiations. The short-lived radionuclides, ^7Be and ^{24}Na , had decayed. Some residual ^{22}Na remained, but was separated from the Be or Al fraction in the beginning of the elution process [6]. The separations were done by ion exchange chromatography. Elution schemes for Be and Al were developed and calibrated with natural Be and Al using atomic absorption spectrometry.

Carefully measured amounts of stable ^9Be and ^{27}Al to serve as carriers were added before the target dissolving process. Each target was dissolved by heating with appropriate acids. Subsequent to ion chromatographic separation, the Be and Al containing fractions were evaporated to dryness. The dried residue of Be or Al fraction was dissolved with nitric acid solution, and then ammonia solution was added dropwise to precipitate $\text{Be}(\text{OH})_2$ or $\text{Al}(\text{OH})_3$. Beryllium hydroxides were purified from the isobaric boron interferences by fuming with HF and HClO_4 . After reprecipitation, both beryllium hydroxides and aluminum hydroxides were cleaned with high-purity water and then dried [7]. The beryllium sample or aluminum sample was then transformed to the oxide by firing with a

flame for three minutes. Finally, the oxide samples were mixed with powdered silver and packed in a target holder for AMS measurements. In the case of Be, repetition of the purification procedure ensured the reduction of isobaric interference from ^{10}B in the AMS measurements. All chemical steps were designed to avoid any undesired chemical contamination. Figure 5 shows the general chemistry scheme in this work. The following sections describe in detail the chemical procedures for each different type of target. The chemical separation scheme for each target is shown in Appendix A.

2.1. SAMPLE PREPARATION FOR CARBON TARGETS

A carbon target and 1 mg of stable Be carrier were dissolved by heating for several hours with concentrated HClO_4 and a catalytic amount of K_2CrO_4 [8]. After all the carbon was dissolved, concentrated HNO_3 was used to complete the oxidation. Then 1 ml HF was added to reduce isobaric interference of boron in the sample by volatilizing BF_3 . Several drops of concentrated HClO_4 were added at the sample heated to remove HF [9]. The dried residue was dissolved in 50% HNO_3 , then 50% NH_4OH was added [10]. The pH of the solution was then adjusted to 8. The $\text{Be}(\text{OH})_2$ precipitate was washed with high-purity water, dried at 90 °C in a quartz vial, and fired in a flame for three minutes. The samples were prepared as previously described.

2.2. SAMPLE PREPARATION FOR SILICON AND SILICON DIOXIDE TARGETS

After the addition of Be and Al carrier, the Si or SiO_2 target was dissolved with concentrated HF and concentrated HNO_3 (1:1). The dried residue was

purified with concentrated HF and concentrated HClO_4 [11]. This purification was repeated three times. The evaporated dried residue was then dissolved with 1N HCl and transferred to a cation exchange column. The column was conditioned by eluting with 200 ml of 6N HCl, 100 ml H_2O , and 60 ml 1N HCl consecutively [10]. The Be fraction was collected by elution with 160 ml of 1N HCl; then 100 ml of 1N HCl was added to clean the column. Then 100 ml of 4.5N HCl was added to collect the Al fraction [12]. The Al and Be fractions were evaporated to dryness. The dried Be fraction was purified by fuming with 1 ml conc HF at least three times. Then several drops of HClO_4 was added and the dry residue was dissolved with 50% HNO_3 . $\text{Be}(\text{OH})_2$ was precipitated by adding 50% NH_4OH . This precipitation procedure was repeated. The $\text{Be}(\text{OH})_2$ precipitate was washed with high-purity water, dried, and fired with a flame of natural gas. The Al fraction was also dissolved with 50% HNO_3 and then precipitated by adding 50% NH_4OH , which was added until the pH was approximately 8. $\text{Al}(\text{OH})_3$ was washed with high purity water at least two times, then dried at 90°C , fired with a flame, prior to packing into a stainless steel AMS target holder.

2.3. SAMPLE PREPARATION FOR AL TARGETS

Only Be carrier was added and the target was dissolved with 6N HCl by heating [13]. The dried sample was purified by fuming with HF and HClO_4 . The remaining chemistry followed the Si targets' treatment.

2.4. SAMPLE PREPARATION FOR MG TARGETS

Be and Al carriers were added before the Mg target was dissolved with 6N HCl. 25 % NH_4OH was added to neutralize the solution [10]. NH_4Cl was added

to 5 % by weight. Precipitating Be and Al hydroxides, Mg remained in solution. Separation of Mg from Be and Al was completed by centrifugation. The precipitates, the mixture of $\text{Be}(\text{OH})_2$ and $\text{Al}(\text{OH})_3$ were dried. Adding 65 % HNO_3 , ammonium in the dried residue was removed by heating. The separation of Be from Al followed the method for Si targets.

Figure 5. General Chemistry Scheme in this work.

3. ACCELERATOR MASS SPECTROMETRY

3.1. INTRODUCTION

Accelerator mass spectrometry (AMS) has become an increasingly important tool in physics, environmental, and geo-sciences, archaeology, cosmology, and as well as in biomolecular tracing. AMS allows the efficient detection of long-lived radionuclides, such as ^{10}Be , ^{26}Al , ^{36}Cl , ^{41}Ca , ^{14}C , and ^{129}I , etc. AMS can be used for efficient detection of long lived isotopes at part-per-quadrillion sensitivities with good precision [14].

Accelerator mass spectrometry is based on the fact that accelerated ions with the same energy are deflected more or less in a magnetic field according to their masses. This behavior provides the tool for collecting quantitative information on different isotopes in a sample. In accelerator mass spectrometry, particle accelerators are used to accelerate the sought-after nuclide to a high energy, at which molecules can be easily destroyed and isobars and neighboring masses can be identified by nuclear detection techniques.

3.2. INSTRUMENTATION

Most accelerator mass spectrometry systems include ion source, injector, tandem accelerator, electrostatic deflector, magnetic spectrometer, and ΔE -E gas counter. Figure 6 shows the schematic diagram of an AMS facility [14].

The prepared sample is loaded into the ion source. Then, a negative ion beam is generated from the target material. Cs-sputter sources are most often used for this stage. In a Cs-sputter source the target is bombarded with positive

Cs-ions. In the sputtering process a fraction of the emitted atoms and molecules becomes negatively charged and is extracted and focused by an appropriated electric field configuration. Cs deposited on the sample enhances the formation of negative ions. It is known that it is important that the source be simultaneously optimized for high negative ion yield, high current and small beam emittance. Also stability is essential, especially for high precision measurements. Various geometries are in use for focusing the Cs ions on the target: symmetric injection from the front and asymmetric injection from the side or from the back by reflecting the Cs beam. The Cs-energies are typically 10-40 kV and the Cs⁺-currents are in the 100 μ A range for these designs.

After extraction from the ion source, the ions are normally analyzed with a first magnetic spectrometer to select the masses of interest. Although all the ions are accelerated in the ion source by the same electric field, the beam formed is not quite monoenergetic. In some cases a larger portion of the Cs-ion energy is transferred to the negative target ions, leading to a tail toward higher energies. Sputtered molecules can be in excited states which break up during or after the acceleration in the ion source. The fragments will then have to share the acceleration energy and will thus have a lower energy. Tails toward lower and higher energy can cause interference to appear from neighboring masses. By adding an electrostatic filter these tails can be significantly reduced.

In tandem accelerators, particles are accelerated in a static electric field. In order to reach ion energies in the MeV range, Megavolt (MV) potentials are needed. To obtain these high voltages without arcing, the accelerator is mounted in a tank filled with insulation gas. Most tandem accelerators use SF₆-gas at pressures of 3-8 bars. In tandem accelerator systems, negative ions are injected and are then accelerated to the positive high voltage terminal. The advantage of

this type of accelerator is that the ion source can be outside the tank and is therefore easy to maintain. The beam intensity is constant in time and high optical transmission can be maintained. In the high voltage terminal, carbon foil stripper is used. Due to the polarity change of the ions in the terminal the high potential can be used twice for acceleration.

After the accelerator, the ion beam consists of various components having different charge states and different energies. Because molecular fragments beside the main components, are also found, due to charge changing processes in the acceleration tubes, a small continuous background of species with various energy and charge state combinations is present. Therefore, a magnetic spectrometer alone is not sufficient to perform the final mass separation. In most cases an electrostatic deflector which sorts by energy/charge or a velocity filter, perpendicular electron and magnetic fields are also included. The same beam path is taken by rare and stable isotopes up to the final spectrometer. This design provides monitoring transmission and stability of the system by repetitively measuring the abundant isotopes. A time-of flight detector allows measurement of the ion velocity. Together with the total energy measurement this velocity measurement allows an additional mass determination to be performed which is independent of the previous analyzing steps.

The final analysis is performed by a ΔE -E gas-filled particle counter which gives electrical signals identifying the total energy deposited and the specific energy loss of the ion, dE/dx . This additional information makes possible a determination of the atomic number. The rate of energy loss, which depends on the atomic number of the ion, can be calculated from stopping power data. This allows the identification of ions according to element. By splitting the anode in two or more parts both energy loss signals (ΔE) and the total energy (E) can be

derived. The difference of the ΔE signals between two neighboring elements becomes smaller for heavier elements but increases with increasing energy. By the appropriate choice of electrode length and gas pressure the difference in ΔE signals between isobars can be optimized.

3.3. AMS MEASUREMENT FOR ^{10}Be AND ^{26}Al SAMPLES

For ^{26}Al measurement, a thin mylar window, $220\ \mu\text{g}/\text{cm}^2$ was used as the entrance for the gas counter [15]. For ^{10}Be , an $11\text{ mg}/\text{cm}^2$ Havar window is used for “ranging out” ^{10}B . This window is thick enough to stop the contaminant ^{10}B beam, while allowing the lower Z ^{10}Be beam to enter the detector. The initial energy of a ^{10}Be beam is 23 MeV and the residual beam energy in the detector is 10 MeV. In case of the ^{26}Al beam, the initial energy of ^{26}Al is about 56 MeV and the its residual energy is about 50 MeV. A reaction between boron ions and hydrogen in the Havar foil or on the foil can produce alpha particles and ^7Be (See Figure 9). Below the ^{10}Be peak, an interfering peak can be formed. In order to obtain the $^{10}\text{Be}/^9\text{Be}$ ratio for a sample, several ^{10}Be standards are measured with the Be sample for the normalization of the ratio for the sample to be measured.

The boron correction can be very important in Be measurements. Serious boron contamination in Be samples can usually be avoided by the chemical purification procedure. However, the remaining small amount of boron present in a Be sample can be corrected. By running samples containing considerable boron contamination, correction to $^{10}\text{Be}/^9\text{Be}$ is obtained. The boron figure of merit of most samples in this work were above 0.9, which means <10% of counts occurring in the ^{10}Be region are attributed to boron.

Figure 6. Schematic Diagram of the AMS Facility at Lawrence Livermore National Laboratory.

Figure 7. Schematic Diagram of a Tandem Accelerator.

Figure 8. Gas Counter with 4 ΔE Electrodes.

Figure 9. Figure of Software Program for ¹⁰Be Measurement of a Dirty Blank. ⁷Be Stripe is shown.

4. CALCULATION OF CROSS SECTIONS

The calculation of experimental proton cross sections for long-lived radionuclides and total error is expressed in the following equations [16, 17]

$$\text{Cross Section } (\sigma) = R_i/N \cdot I_p$$

$$\text{Total Error } (\pm \sigma) = R_i/N \cdot I_p \sqrt{\{(r/R)^2 + (i/I)^2 + (n/N)^2\}}$$

where

R = No. of reactions/sec

I_p = No. of protons/sec

N = No. of target atoms/cm²

r, i, and n = the uncertainty in R, I, and N respectively

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III. RESULTS AND DISCUSSION

The results of proton cross section measurement of ^{10}Be and ^{26}Al are shown in Tables 7 through 15 and Figures 10 through 18. In the tables the cross sections are shown along with target names, irradiation locations, and uncertainties in each measurement. Previously published other cross sections are also listed in each table. The sources of targets were indicated as SJSU for proton energies below 67.5 MeV, HCL for proton energies between 55 and 160 MeV, and TRIUMF for proton energies between 200 and 500 MeV. The following discussion of nuclear reaction applies to the isotopes present in each target element.

Table 2. List of Nuclear Reactions for ^{10}Be and ^{26}Al on selected targets. Most ejected particles form clusters.

Reaction type to produce ^{10}Be	Reaction type to produce ^{26}Al	abundance of target isotope (%)
$^{12}\text{C}(\text{p},3\text{p})^{10}\text{Be}$	no reaction	98.9
$^{13}\text{C}(\text{p},3\text{p}1\text{n})^{10}\text{Be}$	no reaction	1.1
$^{16}\text{O}(\text{p}, 5\text{p}2\text{n})^{10}\text{Be}$	no reaction	99.76
$^{17}\text{O}(\text{p}, 5\text{p}3\text{n})^{10}\text{Be}$	no reaction	0.04
$^{18}\text{O}(\text{p}, 5\text{p}4\text{n})^{10}\text{Be}$	no reaction	0.20
$^{24}\text{Mg}(\text{p},9\text{p}3\text{n})^{10}\text{Be}$	no reaction	78.99
$^{25}\text{Mg}(\text{p},9\text{p}4\text{n})^{10}\text{Be}$	$^{25}\text{Mg}(\text{p},0)^{26}\text{Al}$	10.00
$^{26}\text{Mg}(\text{p},9\text{p}5\text{n})^{10}\text{Be}$	$^{26}\text{Mg}(\text{p},\text{n})^{26}\text{Al}$	11.01
$^{27}\text{Al}(\text{p}, 10\text{p}8\text{n})^{10}\text{Be}$	$^{27}\text{Al}(\text{p},1\text{p}1\text{n})^{26}\text{Al}$	100
$^{28}\text{Si}(\text{p},11\text{p}8\text{n})^{10}\text{Be}$	$^{28}\text{Si}(\text{p},2\text{p}1\text{n})^{26}\text{Al}$	92.23
$^{29}\text{Si}(\text{p},11\text{p}9\text{n})^{10}\text{Be}$	$^{29}\text{Si}(\text{p},2\text{p}2\text{n})^{26}\text{Al}$	4.67
$^{30}\text{Si}(\text{p},11\text{p}10\text{n})^{10}\text{Be}$	$^{30}\text{Si}(\text{p},2\text{p}3\text{n})^{26}\text{Al}$	3.10

In this work, 67 different targets were used for ^{10}Be and ^{26}Al cross section measurements. The total errors for Be and Al measurements were usually less than 10%. Those Be samples from targets associated with low proton energies have higher errors since their ratios are close to background level. The new cross section data in this study provide accurate ^{10}Be and ^{26}Al excitation functions for each target element from threshold up to 500 MeV. The measurements are in agreement with previous work where available. Table 3 shows the range of isotopic ratios for Be and Al samples and blanks.

Table 3. Be and Al isotopic ratios for blanks and samples.

sample	blank	minmum	maximum	carrier (mg)
$^{10}\text{Be}/^9\text{Be}$	$\sim 1 \times 10^{-14}$	$\sim 4.3 \times 10^{-15}$	$\sim 5.8 \times 10^{-12}$	0.1 ~ 2
$^{26}\text{Al}/^{27}\text{Al}$	$\sim 2 \times 10^{-14}$	$\sim 5.8 \times 10^{-13}$	$\sim 3.4 \times 10^{-9}$	1 ~ 7

Cross contamination of samples in the ion source or chemistry laboratory was found to be a serious problem when the activity of a sample exceeded that of low activity sample by a factor of 300 unexpectedly. Five magnesium targets whose isotopic ratios were about 10×10^{-12} were loaded with SiO_2 targets whose isotopic ratio were ranged between 10×10^{-9} and 10×10^{-10} . The ratio of Al blank in this run was measured as 10×10^{-12} , which confirmed cross contamination of both blank and other low level samples. Subsequent to this incident low level samples were isolated at all stages from high level samples. In order to resolve this contamination problem, the chemistry procedures for all Mg targets were performed after all other targets were completely finished. Only Mg targets were measured in the last AMS run and there was no contamination problem observed (Figure 15).

Figure 12 and 15 show the proton cross sections of ^{10}Be and ^{26}Al on Mg targets. The new results provide a complete proton excitation functions for both ^{10}Be and ^{26}Al on Mg targets from threshold energy up to 500 MeV.

Table 4. Q-values for the production of ^{10}Be in oxygen.

Reaction Type	Q-value (MeV)
$^{16}\text{O}(p, 3p1\alpha)^{10}\text{Be}$	-21.74
$^{16}\text{O}(p, 3p2d)^{10}\text{Be}$	-45.59
$^{16}\text{O}(p, 4p1n1d)^{10}\text{Be}$	-47.81
$^{17}\text{O}(p, 3p1n1\alpha)^{10}\text{Be}$	-25.88
$^{17}\text{O}(p, 2p1\alpha1d)^{10}\text{Be}$	-23.66
$^{18}\text{O}(p, 1p2\alpha)^{10}\text{Be}$	-5.63
$^{18}\text{O}(p, 3p2n1\alpha)^{10}\text{Be}$	-33.93
$^{18}\text{O}(p, 2p1n1\alpha1d)^{10}\text{Be}$	-31.7

Figure 10 shows the results from this work to have higher accuracy between 100 and 200 MeV proton energy range when compared to other reference values. In addition, the gap between 200 and 500 MeV energy range is satisfactorily filled with new cross sections by this work.

Cross section values for ^{10}Be production from silicon dioxide are shown in Table 6 and Figure 11. Figure 11 shows that above 40 MeV all cross section values measured here are agree with previous data and fill in the gap between 200 and 400 MeV. Table 4 shows the Q values for ^{10}Be production from oxygen. This data show the feasibility of ^{10}Be production below 40 MeV. The cross section values in this region were carefully checked for the flux of incoming protons, the total number of the target atoms, and the isotopic ratio in AMS

measurement. Cross sections for ^{26}Al production on SiO_2 targets in Figure 18 show that below 40 MeV, cross section data points lie on the excitation function curve very smoothly without having any unusual peak. It is concluded that there is no significant error in either proton flux or energy of protons in the low energy region. According to this fact and all investigations in AMS results, it is concluded that there might be real ^{10}Be production in the low energy range.

$^{\text{nat}}\text{Mg}(\text{p},9\text{pxn})^{10}\text{Be}$

Cross section values for $^{\text{nat}}\text{Mg}(\text{p},9\text{pxn})^{10}\text{Be}$ are shown in Figure 12. The new cross section values cover the entire energy range; hence this study contributed a new excitation function for $^{\text{nat}}\text{Mg}(\text{p},9\text{pxn})^{10}\text{Be}$. Higher precision at low energies (<100 MeV) is shown in comparison to previous measurements.

$^{\text{nat}}\text{Al}(\text{p},10\text{p8n})^{10}\text{Be}$

Higher precision and accuracy of this measurement is shown in comparison to previous measurements below 200 MeV (Fig. 13). Also, new cross section values complete the excitation function between 200 and 500 MeV.

$^{\text{nat}}\text{Si}(\text{p},11\text{pxn})^{10}\text{Be}$

Consistent and more accurate results at energies below 100 MeV are shown in Figure 14. New cross section values complete the excitation function between 100 and 500 MeV.

Consistent and more accurate data of ^{26}Al from Mg targets between 30 and 500 MeV are shown in Figure 15. The reference values from M. Furukawa et al. [8] were obtained from coincident gamma ray spectrometry in 1971; the values from R. Reedy are semi-empirical estimates.

A consistent and more accurate set of data between 19 and 200 MeV are shown in Figure 16, and expand into an accurate excitation function between 200 and 500 MeV. The data agree with those from B. Dittrich et al. [2] rather than with those of Schneider et al. [6].

In figure 17 a consistent and more accurate set of data between 30 and 500 MeV is shown. The new data fill gaps between 100 and 500 MeV.

In Figure 18 consistent and accurate new data between 26 and 43 MeV are shown. This data set was obtained from the irradiation runs in 1995 at U.C., Davis (indicated as SJSU 95). The cross section values from the irradiation runs in 1993 at U.C., Davis (indicated as SJSU) are higher than those values from 1995 irradiation runs. There is a systematic error in 1993 irradiation runs with SiO_2 . Further investigation is required toward the correction of the cross section values. The data between 100 and 400 MeV are filled the gap in the excitation function.

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IV. CONCLUSION

Using thin targets, precise determinations of cross sections for cosmogenic nuclide production were obtained by careful attention to proton flux monitoring, reduction of isobaric interference through chemical purification, and avoidance of sample cross contamination. Using accelerator mass spectrometry for counting ^{10}Be atoms, reliable measurements were made on samples having $\sim 10,000$ atoms of ^{10}Be .

This study provides ^{10}Be and ^{26}Al cross sections for proton energies from threshold up to 500 MeV for five elements: C, O, Mg, Al, and Si. Most of the new cross section values reported here provide new data of high precision and accuracy. Where previous measurements were available, our data provide higher precision and accuracy when in disagreement or agreement with previously published results. These accurate cross section measurements provide a good foundation for applications of high energy particle radiation with extended bodies as well as cosmogenic nuclides in extraterrestrial and terrestrial materials. In addition, the new experimental excitation functions given here provide a better estimate for the solar proton flux over a time period characterized by the half-lives of ^{10}Be and ^{26}Al .

Table 5. Experimental cross sections for the production of ^{10}Be from natural carbon.

name	energy (MeV)	x-section (mb)	error (mb)	references
	30.5	0.0045	0.0016	[1]
	35.7	0.0382	0.003	[1]
	40.3	0.138	0.013	[1]
CAA	40.6	0.164	0.026	SJSU
	48	0.241	0.019	[1]
C9	49.6	0.439	0.019	SJSU
	52.5	0.408	0.035	[1]
	56.7	0.522	0.042	[1]
C2	59.6	0.668	0.016	SJSU
	60.8	0.569	0.045	[1]
	64.6	0.719	0.054	[1]
C6	67.1	0.759	0.019	SJSU
	71.8	0.756	0.061	[1]
	78.4	0.846	0.066	[1]
	84.7	0.85	0.067	[1]
	90.6	0.904	0.07	[1]
	96.3	0.939	0.072	[1]
	150	1.1	0.1	[4]
	150	1	0.3	[3]
C19	160	1.39	0.078	HCL
C4	200	1.47	0.082	TRIUMF
	220	1.9	0.6	[3]
C16	300	1.89	0.11	TRIUMF
C10	400	2.29	0.13	TRIUMF
C13	500	2.75	0.15	TRIUMF
	600	2.8	0.4	[4]
	600	2.8	0.3	[3]

Table 6. Experimental cross sections for the production of ^{10}Be from natural oxygen in silicon dioxide.

name	energy (MeV)	x-section (mb)	error (mb)	references
Q6	25.9	0.00036	0.00014	SJSU
SiO ₂ 14	30.9	0.00495	0.00038	SJSU
Q9	31.4	0.00358	0.00056	SJSU
Q12	36.6	0.00720	0.00096	SJSU
SiO ₂ 11	41.8	0.00743	0.00069	SJSU
Q17	43	0.00695	0.00081	SJSU
	43.5	0.0113	0.0009	[1]
	49	0.039	0.0029	[1]
SiO ₂ 4	49.9	0.0362	0.0026	SJSU
	51.5	0.073	0.005	[1]
	54	0.111	0.009	[1]
	60.8	0.241	0.02	[1]
	67.4	0.34	0.02	[1]
SiO ₂ 1	67.4	0.309	0.019	SJSU
	69.6	0.372	0.03	[1]
	79.2	0.445	0.036	[1]
	86.3	0.475	0.038	[1]
	91.3	0.52	0.03	[1]
	91.5	0.495	0.04	[1]
	94.9	0.505	0.0041	[1]
	96.6	0.52	0.03	[1]
Qu15	200	0.764	0.044	TRIUMF
Qu6	300	1.07	0.060	TRIUMF
Qu9	400	1.37	0.15	TRIUMF
	600	1.85	0.15	[2]
	800	2.45	0.15	[2]
	1200	3.05	0.19	[2]
	1600	2.26	0.14	[2]

Table 7. Experimental cross sections for the production of ^{10}Be from natural magnesium.

name	energy (MeV)	x-section (mb)	error (mb)	references
MgAC	29.8	0.00055	0.00017	SJSU
MgAB	42.1	0.00509	0.00064	SJSU
Mg10	49.5	0.0106	0.0013	SJSU
Mg5	59.5	0.0222	0.0015	SJSU
Mg4	59.7	0.0246	0.0019	SJSU
	62.3	0.017	0.006	[1]
	66	0.016	0.006	[2]
Mg2	67.2	0.0341	0.0031	SJSU
	95	0.078	0.009	[1]
	95	0.075	0.009	[2]
Mg15	100	0.110	0.012	HCL
Mg22	130	0.190	0.012	HCL
Mg18	160	0.256	0.016	HCL
Mg3	200	0.306	0.019	TRIUMF
Mg6	300	0.524	0.034	TRIUMF
Mg9	400	0.756	0.048	TRIUMF
Mg12	500	0.955	0.060	TRIUMF
	600	0.98	0.04	[5]
	800	1.74	0.12	[5]
	1200	2.17	0.14	[5]
	2600	2.56	0.16	[5]

Table 8. Experimental cross sections for the production of ^{10}Be from aluminum.

name	energy (MeV)	x-section (mb)	error (mb)	references
AlAB	40.2	0.0029	0.0013	SJSU
AlR	50	0.0078	0.0021	SJSU
	57.1	0.008	0.0014	[1]
AlH	60	0.0141	0.0019	SJSU
	64.3	0.0179	0.0023	[1]
	66.7	0.014	0.004	[2]
AlF	67.5	0.0401	0.005	SJSU
	68.6	0.0361	0.0042	[1]
	74.9	0.0395	0.0037	[1]
	78.7	0.0422	0.0039	[1]
	80	0.041	0.003	[2]
	85	0.0571	0.0053	[1]
	90.9	0.0571	0.0053	[1]
	95.5	0.081	0.007	[2]
	96.6	0.0747	0.0065	[1]
Al19	100	0.112	0.011	HCL
	115	0.105	0.009	[1]
Al16	130	0.163	0.020	HCL
	132	0.127	0.011	[1]
	147.6	0.15	0.013	[1]
	155.3	0.143	0.007	[2]
TA17	160	0.248	0.021	HCL
	160.6	0.162	0.014	[1]
	172.3	0.2	0.017	[1]
	183.6	0.203	0.017	[1]
	199.5	0.244	0.02	[1]
Al1	200	0.298	0.022	TRIUMF
	202	0.25	0.002	[2]
Al13*	300	0.489	0.048	TRIUMF
Al7	400	0.774	0.050	TRIUMF
Al10	500	1.02	0.065	TRIUMF
	600	1.18	0.005	[2]
	800	1.86	0.016	[5]
	1200	2.67	0.017	[5]
	2600	2.68	0.017	[5]

Table 9. Experimental cross sections for the production of ^{10}Be from natural silicon.

name	energy (MeV)	X-section (mb)	error (mb)	references
Si10D	29.8	4.92E-05	8.00E-06	SJSU
Si11D	44.5	0.000551	0.0007	SJSU
Si6D	50.2	0.0009	0.00015	SJSU
	51.2	0.009	0.003	[1]
Si19	55.8	0.00261	0.00045	HCL
	57.8	0.0007	0.00035	[1]
Si23	61.1	0.00580	0.00052	HCL
	62.7	0.00139	0.00045	[1]
Si3D	65.6	0.0047	0.00043	SJSU
Si26	66.3	0.00981	0.00055	HCL
	66.5	0.00221	0.00034	[1]
	68.8	0.02	0.003	[1]
	70	0.00394	0.00045	[1]
	73.5	0.0079	0.001	[1]
Si16	76.7	0.0107	0.0006	HCL
	80.1	0.0092	0.0011	[1]
	86.2	0.0178	0.0017	[1]
Si13	86.9	0.0193	0.0020	HCL
	92.1	0.0193	0.0017	[1]
	92.9	0.023	0.0021	[1]
	96.8	0.029	0.004	[1]
	97	0.0182	0.0019	[1]
Si10	97.2	0.0226	0.0026	HCL
	97.7	0.0231	0.0021	[1]
Si7	127.7	0.0453	0.0018	HCL
Tsi9	130	0.0475	0.035	HCL
Si4	147.9	0.0619	0.0051	HCL
Si1	157	0.0662	0.0027	HCL
Si15	200	0.114	0.0070	TRIUMF
Si6	300	0.245	0.029	TRIUMF
Si9	400	0.398	0.044	TRIUMF
Si12	500	0.554	0.064	TRIUMF
	600	0.57	0.04	[5]

Table 10. Experimental cross sections for the production of ^{26}Al from magnesium. R. Reedy are adopted values made a decade ago.

name	energy (MeV)	X-section (mb)	error (mb)	references
	5	0.1		R. Reedy
	6	4		R. Reedy
	9	12		R. Reedy
	12	14		R. Reedy
	15	10		R. Reedy
	25	2.5		R. Reedy
MgAC	29.8	2.84	0.16	SJSU
	40	0.8		R. Reedy
MgAA	42.3	1.74	0.12	SJSU
Mg8D	49.9	1.22	0.093	SJSU
Mg1D	67.4	0.828	0.069	SJSU
Mg 15	100	0.33	0.031	HCL
Mg22	130	0.245	0.017	HCL
Mg18	160	0.19	0.028	HCL
Mg3	200	0.165	0.013	TRIUMF
	220	0.1		R. Reedy
Mg6	300	0.126	0.011	TRIUMF
Mg9	400	0.096	0.0072	TRIUMF
	450	0.07		R. Reedy
Mg12	500	0.092	0.0063	TRIUMF

Table 11. Experimental cross sections for the production of ^{26}Al from aluminum.

name	energy (MeV)	x-section (mb)	error (mb)	references
Al14D	16.1	78.1	5.6	[1]
	18	124	9	[1]
	18.8	115	6.1	SJSU
	23.8	181	13	[1]
AlAJ	28	169	8.7	SJSU
Al4D	29.1	138	8.8	SJSU
Al3D	29.9	140	10	[1]
	31.1	135	10	[1]
	35	107	6.5	SJSU
	35.2	106	8	[1]
AlAB	39.8	96.7	7.1	[1]
	40.2	98.2	5.4	SJSU
	47.5	78.1	6.2	[1]
	50	74	5.9	[6]
AlR	50	68.8	3.8	SJSU
AlH	52.1	78.3	6	[1]
	60	66.4	6.6	[6]
	60	63.4	3.4	SJSU
	60.4	69.1	5.3	[1]
Alf	66.7	71.2	3.3	[2]
	67.5	57.9	3.2	SJSU
	80	70.8	4.4	[2]
	88	50	3.8	[1]
Al19	90	59.3	6.5	[6]
	93.8	48.6	3.8	[1]
	95.5	54.4	4	[2]
	98.8	45.5	3.5	[1]
Al16	100	46.4	2.6	HCL
	115	39.6	3	[1]
	120	50	4.5	[6]
	130	37.9	2.2	HCL
TA17	132	37.8	2.9	[1]
	147.6	32.1	2.5	[1]
	155.3	29.4	1.5	[2]
	159	43.9	4	[6]
Al1	160	36	1.8	HCL
	160.6	31.5	3.3	[1]
	172.3	28.2	2.2	[1]
	183.6	27.8	2.1	[1]
Al13*	200	27.7	1.5	[2]
	200	30.2	2.0	TRIUMF
	300	22	1.3	TRIUMF
	400	22.3	1.3	TRIUMF
Al10	500	20.8	1.3	TRIUMF
		22.6	1	[2]

Table 12. Experimental cross sections for the production of ^{26}Al from natural silicon.

name	energy (MeV)	x-section (mb)	error (mb)	references
Si10	29.8	5.8	0.4	SJSU
	44.3	66	7.3	[1]
Si11	44.5	67.2	4.9	SJSU
	50.2	59.1	6.5	[1]
	51.2	74.1	8.2	[1]
Si6D	51.3	70.5	5.0	SJSU
	54.6	57.9	6.4	[1]
Si19	55.8	55.4	5.3	HCL
	57.8	61.2	6.7	[1]
Si23	61.1	53.5	3.9	HCL
	62.7	41.3	4.5	[1]
	65.5	41.6	5.0	[1]
Si3D	66.3	50.7	3.6	SJSU
Si26	66.3	47.4	3.5	HCL
Si2	66.5	47.4	3.4	SJSU
	68.8	53.7	5.9	[1]
	70	43.6	5.2	[1]
	73.5	34.4	4.1	[1]
Si16	76.7	44.3	3.2	HCL
	80.1	36.9	4.2	[1]
	86.2	37.1	4.5	[1]
Si13	86.9	39.1	2.9	HCL
	92.1	37.8	4.5	[1]
	92.9	46.1	5.1	[1]
	96.8	42.3	5.1	[1]
	97	32.0	3.5	[1]
Si10	97.2	36.7	2.7	HCL
	97.7	33.1	3.6	[1]
Si7	128	34.9	2.5	HCL
TSi9	130	32.3	1.7	HCL
Si4	148	30.4	2.2	HCL
Si1	157	32.9	2.4	HCL
Si15	200	24.8	1.3	TRIUMF
Si6	300	22.0	1.2	TRIUMF
	400	18.3	1.0	TRIUMF
	500	18.7	1.0	TRIUMF
Si12	600	13.0	0.8	[5]

Table 13. Experimental cross sections for the production of ^{26}Al from natural silicon dioxide. R. Reedy are adopted values.

name	energy (MeV)	x-sections (mb)	error (mb)	references
	13	1		R. Reedy
	21	2.84	0.34	[1]
	25	1.5		R. Reedy
	25.7	5.58	0.67	[1]
O6	25.9	2.19	0.12	SJSU 95
	29.8	17.3	2	[1]
	30	7		R. Reedy
SiO ₂ 14	30.9	36.1	4.8	SJSU 93
O9	31.4	17.8	0.95	SJSU 95
	33	20		R. Reedy
	36	40		R. Reedy
O12	36.6	45.1	2.4	SJSU 95
	37.1	63.5	7.6	[1]
	39	55		R. Reedy
	40.4	69.9	8.4	[1]
SiO ₂ 11	41.8	85.9	6.8	SJSU 93
O17	43	68.6	3.6	SJSU 95
	46.4	78.2	9.4	[1]
SiO ₂ 4	49.9	76.4	3.4	SJSU 93
	56.3	53.5	5.9	[1]
	60	60		R. Reedy
	60.8	43.5	4.8	[1]
SiO ₂ 1	67.4	47.6	3.4	SJSU 93
	73.6	34.9	4.2	[1]
	79.2	38.5	4.6	[1]
	80	32		R. Reedy
	91.5	32.5	3.6	[1]
	94.9	41.9	5	[1]
TQu9	130	28.0	1.5	HCL
Qu15	200	26.2	1.4	TRIUMF
Qu6	300	21.6	1.2	TRIUMF
Qu9	400	19.8	1.3	TRIUMF
	3000	10		R. Reedy

Figure 10. Experimental Cross Sections of ^{10}Be in Carbon.

Figure 11. Experimental Cross Sections of ^{10}Be in Oxygen.

Figure 12. Experimental Cross Sections of ^{10}Be in Magnesium

Figure 13. Experimental Cross Sections of ^{10}Be in Aluminum.

Figure 14. Experimental Cross Sections of ^{10}Be in Silicon.

Figure 15. Experimental Cross Sections of ²⁶Al in Magnesium.

Figure 16. Experimental Cross Sections of ^{26}Al in Aluminum

Figure 17. Experimental Cross Sections of ²⁶Al in Silicon.

Figure 18. Experimental Cross Sections of ²⁶Al in Silicon Dioxide.

Appendix A-1. Separation Scheme for Carbon Targets.

Appendix A-2. Separation Scheme for Magnesium Targets.

Appendix A-3. Separation Scheme for Aluminum Targets.

Appendix A-4. Separation Scheme for Silicon or Silicon Dioxide Targets.

Anode 1 vs E Tot. Gated: 882

Anode 1 Gated: 0

- ☒ 1
- ☐ 2
- ☐ 3
- ☐ None

☒ Autoscale

LyFr	173.40	0.9979	LyFr
Analyzed	8021	882	Gated
Cum 1 (nC)	5904.23	2.0120	(uA)
Ratio(s)			
(cts/nC) =	0.002489739	+0.00	Sc 1
		6.67	Sc 2
		+100.00	Sc 3
Count Limits	-400	3000	Max Time 300

Appendix B. Figure of Software Program for ¹⁰Be Measurement.