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Cross sections for production of ^7Be , ^{22}Na , and ^{24}Na in thin targets of C, Mg, Al, Si, and SiO_2 by bombardment with monoenergetic protons at 30 to 67.5 MeV

Clinton Dexter Gans
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Gans, Clinton Dexter, M.S.

San Jose State University, 1994

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**CROSS SECTIONS FOR PRODUCTION OF
 ^7Be , ^{22}Na , AND ^{24}Na
IN THIN TARGETS OF C, Mg, Al, Si, AND SiO_2
BY BOMBARDMENT WITH MONOENERGETIC PROTONS
AT 30 TO 67.5 MeV**

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
Clinton Dexter Gans

May, 1994

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A handwritten signature in cursive script, appearing to read "Peter Englert", written over a horizontal line.

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A handwritten signature in cursive script, appearing to read "Carlos Castaneda", written over a horizontal line.

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ABSTRACT

CROSS SECTIONS FOR PRODUCTION OF ^7Be , ^{22}Na , AND ^{24}Na IN THIN TARGETS OF C, Mg, Al, Si, AND SiO_2 BY BOMBARDMENT WITH MONOENERGETIC PROTONS AT 30 TO 67.5 MeV

by Clinton D. Gans

This thesis describes measurements of cross sections for the proton-induced production of ^7Be , ^{22}Na , and ^{24}Na from carbon, magnesium, aluminum, silicon, and silicon dioxide. The cyclotron of the Crocker Nuclear Laboratory at the University of California at Davis was used to bombard small stacks of thin, high purity target foils with protons at discrete energies between 30 and 67.5 MeV. Following bombardments, pulse-height spectroscopy was used to count the radionuclides produced in the target foils. The cross sections measured agree with prior studies where thin targets were used. Applications for the results of this work may include: dose-component calculations for radiation buildup due to cosmic-ray bombardment in the hulls of air- and spacecraft; shielding and dosimetry calculations to support the application of proton accelerators in medical radiation therapy; or interpretation of the history of meteorites and the processes that shape planetary surfaces.

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This work was accomplished through the cooperation of Mr. Anthony Beverding and Miss Kyeong Kim with me. Tony and I worked together to prepare for and perform the target bombardments and subsequent spectroscopic analyses. Kyeong took over collection of the target spectra when Tony and I could no longer pursue it. Without them, this thesis would not exist. Mr. Norman McElroy, the Radiation Safety Officer at San Jose State University, graciously answered my unending questions and provided technical writing assistance. Finally, I thank my wife, Claudia, for her patience while I have continued my formal education.

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I. Introduction

The probability for the occurrence of a nuclear reaction between an accelerated particle and a stationary target nucleus is expressed as a quantity called the reaction cross section. A cross section is the effective target area presented by the stationary nucleus from the perspective of the incident particle. A reaction cross section may be several orders of magnitude greater than the geometric cross section of a nucleus, depending on the nucleus and particle involved. Two main components contribute to the reaction cross section for *uncharged* particles like neutrons. These are the particle's angular momentum and the centrifugal barrier for the reaction. Both of these components are related to the quantum level of the incident particle and the radius of the target nucleus. The Coulombic force (V_c in (1) below) that occurs at close range between a target nucleus and an accelerated *charged* particle (such as a proton) is an additional component that contributes to the magnitude of the reaction cross section when charged particles are used as the medium of bombardment.¹

From a classical nuclear chemistry perspective, the upper limit of the cross section for a reaction (σ_r) between an accelerated charged particle (having Z_1 protons and radius R_1) and a target nucleus (Z_2, R_2) can be estimated (1).¹

$$(1) \quad \sigma_r = \pi R^2 \left(1 - \frac{V_c}{\mathcal{E}} \right)$$

where R = the radius of the target nucleus plus the radius of the accelerated particle,

$$V_c = 1.44 \frac{Z_1 Z_2}{(R_1 + R_2)}, \text{ where } R_1 \text{ and } R_2 \text{ are expressed in fermis (10}^{-15} \text{ m),}$$

and $\mathcal{E}$ = the incident proton energy.

The purpose of the study described in this thesis was the characterization of the cross sections for production of one to three specific radionuclides (^7Be , ^{22}Na , and ^{24}Na) generated by proton bombardment of thin target foils made from very pure natural materials (C, Mg, Al, Si, and SiO_2). The materials used were natural in that they had been refined from natural sources and thus had normal isotopic abundances. Thin foils were used so that the accelerated protons used for

bombardments would remain practically monoenergetic within any target foil. Many cross section measurements for the same reactions we studied have been previously made. In some of these measurements, the cross sections reported may have been influenced by the control of incident proton energy through degradation of a high energy beam using layered absorbers or bombarding many targets in a single stack. Due to the use of proton energies that actually ranged over a few MeV in some of the bombardments, these historical cross sections may have been "smoothed" to varying degrees. Our aim in this work was to measure the cross sections by bombarding small stacks of thin targets with monoenergetic protons and then measuring the resulting activation by quantitative gamma ray spectroscopy.

Results from the work described here will be compared (where appropriate) with those that were made previously to validate our methods. This work will set a foundation for accurate measurement of cross sections for proton-induced radionuclide production at San Jose State University that we hope will contribute to both the nuclear science and health physics communities. Later work will include accurate measurements of cross sections for proton-induced reactions in less-well-characterized materials.

Energetic protons are quite common at very high altitudes and in outer space, though not of primary concern to pilots and astronauts.² Accurate cross section measurements for proton-induced reactions in materials used for construction of air- and spacecraft may be increasingly useful as humanity's knowledge and reach expands. Terrestrial applications of energetic protons include bombardment of targets to generate neutrons for the study of gamma ray emissions resulting from neutron capture.³ The use of accelerated MeV-range protons in medical radiation therapy may also add value to our results (and those that follow). In this context, the cross sections we report may be of use in treatment planning or shielding and dosimetry considerations.

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¹ G. Friedlander, J. Kennedy, E. Macias, and J. Miller, *Nuclear and Radiochemistry*, 3rd Edition, John Wiley and Sons, New York, New York, USA (1981) pps. 110-152.

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- ² *Radiation Exposure of Civil Aircrew, Proceedings of a Workshop, Luxembourg, June 25-27, 1991*, G. Reitz, K. Schnuer, and K. Shaw, editors, *Radiation Protection Dosimetry*, Nuclear Technology Publishing, Ashford, Kent, England (1993) 48, 1.
- ³ K. Krane, *Introductory Nuclear Physics*, John Wiley and Sons, New York, New York, USA (1988) pps. 462-465.

II. Experimental and Mathematical Methods

Proton Bombardment of Target Stacks

Stacks of thin targets were bombarded with protons accelerated by the isochronous cyclotron at the Crocker Nuclear Laboratory (CNL) located on the University of California's Davis campus. Sixteen bombardments were performed on nine days from February to June of 1993. Bombardments were done at discrete proton energies from 30 to 67.5 MeV. Target stacks were composed of three disks of high purity carbon, magnesium, silicon, or silicon dioxide with aluminum foils upbeam and downbeam. The aluminum foils would have been used to back-calculate the integrated proton flux using the previously-determined cross sections for ^{24}Na and ^{22}Na production from aluminum if the Faraday cup had failed. The Faraday cup operated satisfactorily during the bombardments and we redetermined these cross sections. Target disks were 15 mm in diameter and thicknesses were chosen to minimize beam degradation in the stack and make handling practical (Table 1). All target materials for bombardment to measure production cross sections were certified by the suppliers to be of at least 99.999% purity. The arrangement of targets in the stacks and data for the bombardments are listed (Table 2).

Table 1. Description of Target Disk Materials

<u>Target Material</u>	<u>Thickness</u>	<u>Supplier</u>
Aluminum	0.055 mm	Goodfellow Corporation
Carbon	0.125 mm	Goodfellow Corporation
Magnesium	0.125 mm	Goodfellow Corporation
Silicon	0.500 mm	Goodfellow Corporation
Silicon Dioxide	0.500 mm	Heraeus Optics Corporation

For bombardments from February to May, target disks were weighed to the nearest 0.1 mg with a standard analytical balance (Sartorius, Type 2463, S/N 141408). For the remainder of the bombardments, a digital torsion balance (Cahn Instrument Co., Model 29, 0-250 mg range, ID 010077) was used to weigh targets to the nearest 1 μg at the Pacific Gas & Electric Company's Technical and Ecological Services Air Quality Laboratory in San Ramon, California. This

Table 2. Bombardment Data and Arrangement of Target Stacks.

Date	19-Feb-93	19-Feb-93	25-Feb-93	26-Feb-93	26-Feb-93	4-Mar-93	26-Mar-93	26-Mar-93
Run	1	2	3	4	5	6	7	8
E_{protons} (MeV)	67.5	67.5	50	52.5	45	35	67.5	67.5
Targets	Al	Al	Al	Al	Al	Al	Al	Al
(upbeam)	Si	SiO ₂	SiO ₂	Si	SiO ₂	SiO ₂	Mg	C
	Si	SiO ₂	SiO ₂	Si	SiO ₂	SiO ₂	Mg	C
	Si	SiO ₂	SiO ₂	Si	SiO ₂	SiO ₂	Mg	C
(downbeam)	Al	Al	Al	Al	Al	Al	Al	Al
N_{protons} (x 10¹⁴)	4.37	4.37	6.18	8.74	8.74	8.74	4.99	4.99
Date	2-Apr-93	2-Apr-93	6-May-93	6-May-93	20-May-93	20-May-93	21-Jun-93	21-Jun-93
Run	9	10	11	12	13	14	15	16
E_{protons} (MeV)	50	50	42.5	42.5	60	60	30	30
Targets	Al	Al	Al	Al	Al	Al	Al	Al
(upbeam)	C	Mg	C	Mg	Mg	C	Si	Mg
	C	Mg	C	Mg	Mg	C	C	SiO ₂
	C	Mg	Si	SiO ₂	Si	C	Al	Al
(downbeam)	Al	Al	Al	Al	Al	Al		
N_{protons} (x 10¹⁴)	4.37	4.99	8.74	8.74	8.74	8.74	15.8	15.8

allowed reduction of the uncertainties associated with target weights from up to 1.5% to less than 0.1%. The latter balance was calibrated with a 200 mg standard weight (Fisher Scientific, Permas Class S, Set S/N 651). Calibration weights previously used at SJSU with the analytical balance were standardized with this system. After weighing, the targets were packaged in polystyrene Petri dishes for storage or transportation to the CNL for bombardment. Laboratory gloves and forceps were used at all times in handling the targets to minimize contamination. In weighing all targets except carbon, control of static charge on the targets was critical for obtaining a stable weight with the digital torsion balance. Static charge dissipation was done by using two encapsulated ²¹⁰Po sources (Nuclear Products Co., Staticmaster Model 2U500) that were attached to the walls of the torsion balance's weighing chamber.

At the CNL, the proton bombardments for this study were done in the concrete cave enclosing the branches of the northern beam line (Figure 1). Shielded doors isolated the area during bombardment and were interlocked to the beam-stop that allowed energizing of the beam

FIGURE 1. Plan of North Cave Beam Line at Crocker Nuclear Laboratory.

line. An evacuable scattering chamber (Ortec, Model 2800, S/N 1) was located in the beam line used for our work (Figure 2). This scattering chamber contained a turntable that was operated from the cave during setup or from the cyclotron control room between bombardments. Precise positioning of the target stacks was confirmed with a remote camera trained on the turntable's index marks and monitored in the control room.

Two identical target stack holders were machined from aluminum to ensure reproducible bombardment geometry and allow rapid unloading of the targets after irradiation. In addition to the removable target holder (Figure 3, right side), a tantalum collimator (12.9-mm inside diameter (ID)) in a brass support (Figure 3, center) was made for each target stack holder base (Figure 3, left). Prior to the bombardments, a stack of the prepared targets was placed in the target holder which was in turn mounted to its base (shown assembled in Figure 4, left) that had been secured to the scattering chamber turntable (Figure 5) along with the collimator. The second target holder assembly was similarly loaded and placed.

Between the target holders was mounted a phosphor screen supported in a similar holder (Figure 4, right). After evacuation of the scattering chamber and beam pipe in the north cave, this section was opened to the evacuated interior of the cyclotron. Following equalization of the system's vacuum pressure and energizing the beam line, the crosshairs marked on the phosphor screen were used as vertical and horizontal references for tuning the proton beam to the position where the target stack centers were located when rotated into the beam line (Figure 5). Collimation of the beam was done with 1/4-inch ID carbon and two 1/8-inch ID tantalum collimators upbeam of the scattering chamber (Figure 1). The shape of the beam spot on the surface of the phosphor was a 5 by 9 mm ellipse with the longer axis horizontal. The actual size and location of the beam was observed on a second video monitor that was trained on the phosphor screen during tuning for each bombardment and confirmed using radiation-sensitive film (Kodak, Radiochromic) during one session.

Figure 2. Exterior of Open Scattering Chamber with Video Monitor in Foreground.

Figure 3. (L-R) Target Stack Holder Base, Collimator, and Holder with Retainer. Holder base, collimator holder, and target holder are ~2-inch squares with thicknesses at the mating surfaces of 0.8, 0.5, and 0.3 inches, respectively.

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

Figure 5. Interior of Scattering Chamber with Phosphor Screen and Target Holders Placed.

Pre- and post-bombardment checks of the cyclotron's beam current were done by measuring the charge collected in a carbon block lowered by remote control in front of the phosphor screen (Figure 6). Upon completion of tuning, the beam was blocked and a target stack was rotated into position. When the proton bombardment of the target stack was begun, the time was recorded. A calibrated brass Faraday cup downbeam of the target stack was used to integrate the proton current that passed through the stack during bombardment. Between the target stack and the Faraday cup, an experimental secondary-electron-emission monitor was used to monitor the instantaneous beam current at the last bombardment session (Figure 5). Between 70 and 140 μC beam current was collected in the target bombardments for this study. When the readout from the Faraday cup indicated that the predetermined current had been received through the stack, the beam stop was replaced and the time again recorded. The second target stack to be bombarded at that session's proton energy was then rotated into position and the sequence repeated. On completion of this process, the beam current was rechecked in the carbon block and the beam stop replaced.

Figure 6. Scattering Chamber Interior with Carbon Block Visible in Chamber Lid.

About an hour after completion of the second bombardment, the cave isolation doors were opened and a dosimetric survey of the scattering chamber area was made. Based on the results of this dose survey, the beam operator would either grant permission for the researchers to re-enter the cave or require more time for the decay of apparatus activated by the bombardment. This activity appeared mainly in the upbeam collimators and the Faraday cup (Figures 1, 7, and 8). When the researchers were allowed to re-enter the cave, the scattering chamber was vented to atmosphere and the target stacks removed in their holders. The stacks were then disassembled and each target was replaced in its original container. These containers were then placed in a lead-shielded carrier. The steps taken following re-entry of the cave area were performed as rapidly as was practical in order to minimize dose to the researchers from the targets and beam line components. Film badges worn by the researchers during the study recorded no more than background dose. Four to six hours was generally required from set-up to removal of the targets.

Figure 7. Access Box for Collimators Upbeam of Scattering Chamber.

Figure 8. Scattering Chamber Exterior with Faraday Cup (arrow) at End of Beam Line.

Gamma Ray Photon Spectroscopy of Radionuclides Produced in Targets by Proton Bombardment

Quantitative measurement by pulse height spectroscopy of the ^{24}Na ($t_{1/2} = 14.959$ h) generated in the aluminum, magnesium, silicon, and silicon dioxide targets was performed first at the CNL and then at San Jose State University (SJSU) immediately following each bombardment session. Each of the target counts took about fifteen minutes for collection of enough pulses from the ^{24}Na 1368.6 keV gamma ray so that the uncertainty in the peak area was approximately 1%. These targets were later recounted at SJSU for longer periods to obtain peak areas for ^{22}Na at 1274.5 keV ($t_{1/2} = 2.602$ y). When carbon and silicon dioxide targets had been bombarded, these were also counted for the ^7Be ($t_{1/2} = 53.284$ d) gamma-ray at 477.6 keV after the ^{24}Na counts had been made. Counts made for ^7Be , ^{22}Na , or both generally required twenty-four hours to obtain 1% uncertainty in the peaks of interest.

Peak-fitting of the gamma-ray spectra from the targets was done manually using a multi-channel analyzer (MCA) software.¹ Peak area was determined with this software by manually

choosing the beginnings of the baseline on either side of the peak at the first count-versus-energy minimum. This method required the analyst to visually confirm the fitting of the peak to the baseline. It was used instead of the program's automatic fitting function because visual validation of each peak's fit was desired. Previous experience had shown no peak-fitting algorithm can be completely trusted to provide a consistent fit to a baseline that is generated by a random phenomenon such as radioactivity. Alternately, the spectral files from the target counts were downloaded to the *Ganymede* peak-fitting program² as done by our counterparts at the Harvard Cyclotron Laboratory. *Ganymede*'s ability to fit complex baselines with accuracy was not needed for the relatively simple spectra from our targets and took more than twice the amount of time required for the manual fitting described.

With *Ganymede*, a spectral file is first converted to a format compatible with the program. The converted file is then read into a larger "pool" file which contains the spectra to be analyzed. From the pooled spectra, the main program is used to bring up the individual spectrum for analysis. After the energy range of interest is chosen, the characteristics of the background in the peak region are specified by the number of inflection points and the a fitting routine initiated. The resultant fit is displayed and the process repeated with different parameters if a poor fit is obtained. Three or more such iterations were normally required to validate the fit. Peak fitting with the *Ganymede* algorithm gave results that agreed within 1% of the results obtained by manual fitting with the MCA software. After the peaks in more than thirty spectra had been fitted using both methods and the difference between the results was shown to be insignificant, the less-time-consuming manual MCA method was consistently used.

The gamma ray detectors used at both the CNL and SJSU were made of high purity germanium (Table 3). Target-detector geometry at the CNL was fixed at 4.65 cm by means of a target holder bolted to a monorail within the detector shield. Shielding of this detector was done by surrounding the detector and monorail with 2-inch-thick lead bricks on four sides. The SJSU detector and its integral liquid nitrogen reservoir were held within a rigid aluminum frame fabricated for the study described here. Target-detector distance in this

Table 3. Description of Gamma Ray Detectors

<u>Location</u>	CNL	SJSU
<u>Supplier</u>	EG&G Ortec	EG&G Ortec
<u>Model</u>	GEM-10175	GMX-30190-P
<u>S/N</u>	24P-47RB	31-TN10318
<u>Crystal Dimensions</u>	43.4 mm diam. 46.6 mm length	54.8 mm diam. 74.0 mm length
<u>End Cap to Crystal</u>	3 mm	4 mm
<u>Absorbing Layer</u>	1.27 mm Al	0.5 mm Be
<u>Inactive Germanium</u>	0.7 mm	none
Actual Resolution of 1.33 MeV ^{60}Co γ ray:		
<u>FWHM</u>	1.75 keV	1.74 keV
<u>Ratio of Peak Height to Background</u>	45.2	66.0
<u>Measured Detector Efficiency</u>	12.2%	34.9%

geometry was maintained with a fixture bolted to the detector frame and aligned with the detector's central axis (Figure 9). Slots had been milled in this fixture at 5-cm increments to 30 cm from the detector face and at 10-cm increments to a distance of 1 meter. These slots were used to hold removable 5-1/4 inch squares of 1/8-inch-thick polycarbonate so that the center of the square was located on the detector's central axis. A single target was attached to each such square with a small piece of cellophane tape for counting. The detector and target-holding apparatus was shielded on all sides except the top with 2-inch-thick lead bricks. The tops of the detector and target-holding fixture were shielded along their full lengths with 1/8-inch thick copper sheet and 3/8-inch thick steel plates (Figure 10).

The lower efficiency of the CNL detector allowed counts to be made at 4.65 cm source-detector distance. Because this detector was used mainly for counting the 1368.6 keV ^{24}Na gamma ray, its efficiency at this energy was indirectly determined using a standard mixed-gamma point source (National Institute of Standards and Technology (NIST), Standard Reference Material 4275C-56) in the same geometry used for target counts. This NIST standard

Figure 9. SJSU Detector; Shielding Partially Removed with Target-Holding Fixture (R).

Figure 10. SJSU Detector with Side Shielding In Place and Top Opened to Change Source.

source emits photons from 150 to 1600 keV at certified rates³ that are traceable to international standards. The indirect determination of the detector's efficiency at 1368.6 keV was accomplished by the sequence described below.

The efficiency of the CNL detector for detection of the 1368.6 keV ^{24}Na gamma ray was calculated using a multiple-step process that allowed subsequent compilation of the uncertainties associated with each step. After collection of the gamma ray spectrum of the NIST source (described above), the peak areas at this source's standard photon energies between 247.7 and 1596.4 keV were determined by manually fitting them with the MCA program as previously described. Parameters for the collection of the spectrum (date, time, count duration, etc.) and these peak areas were input to a spreadsheet template (Appendix A-1). The first section of this spreadsheet was made to calculate the decay-corrected photon emission rates of the NIST standard source. The detected emission rates at each gamma ray energy were determined in this spreadsheet by dividing the appropriate peak area by the duration of the count of the standard source. The detector's efficiency at each energy was calculated in the spreadsheet by dividing the detected count rate at each energy by the respective decay-corrected emission rate for the standard.

The second phase in determining the efficiency for the 1368.6 keV ^{24}Na gamma ray (or other gamma ray energy for which the standard had no emission of equal energy) involved use of a curve-fitting program.⁴ To this program were entered energies of the standard photon-emissions and the respective calculated detector efficiencies from the spreadsheet (Appendix A-1) described above. The 1368.6 keV ^{24}Na photon energy was added to these data, but excluded from processing for determination of a curve to fit the input array. The program then executed an iterative comparison of the input data to its resident library of curves. The result of this comparison was a list of functions (and their plots) that fit the data. The functions were arranged by decreasing correlation coefficients (r^2 ; where $r^2=1.000$ indicates a "perfect" fit of the data). These best-fit plots were scanned for functions with discontinuities that could not represent detector efficiency as a function of gamma ray energy. From the remainder of the listing, the function with the highest correlation coefficient was selected. Output from the curve-fitting program (Appendix

A-2) included predicted detection efficiencies and confidence intervals for the energies of both the standard and the 1368.6 keV ^{24}Na gamma rays.

The detection efficiency interpolated by the curve-fitting program at 1368.6 keV was used in calculating ^{24}Na activity in targets counted before the next collection of a spectrum from the NIST standard. The uncertainty used for interpolated detector efficiencies was calculated by summing: (1) the uncertainty of the interpolated efficiency from the curve-fitting program output; (2) the greater of the uncertainties associated with the certified photon emission rates at the standard energies adjacent to the energy for which detector efficiency was interpolated; and (3) the uncertainty from the experimentally-determined efficiency at this latter energy.

At SJSU, target and standard counts were made mainly at 15 cm source-detector distance. The efficiency of that detector for the 1274.5 keV ^{24}Na gamma was calculated directly from the ^{154}Eu gamma ray emitted at the same energy from the standard source. A positive interference in the peak at 1596.4 keV (the highest emission energy of the NIST standard) was observed in the spectra collected with the SJSU detector to determine its efficiency. This interference raised the calculated efficiency for this energy about 4% above the value from fitting a curve to the energy vs. efficiency data set without including the 1596.4 keV datum. The source of the interference was the summing of pulses from the 591.8 and the 1004.7 keV photons emitted by the standard as described in the notes issued with the NIST source. The magnitude of this interference decreased when the distance from the source to the detector was increased. The 15-cm source-detector distance was chosen as a compromise between longer count times and increased summing in the 1596.4 keV peak. Due to the presence of the summing interference in this peak, it was eventually deleted from those used to calculate the SJSU detector's efficiency.

To provide calibrated activities at gamma ray energies above 1274.5 keV (the highest energy emission from the NIST source that did not show summing effects), a ^{56}Co secondary standard was made by bombarding a single iron target foil (Goodfellow Corp., 99.99+% purity, 0.125-mm thickness) at the CNL. The activity of this source was calibrated by first obtaining the SJSU detector's efficiency for the 846.8 keV ^{56}Co gamma. This was done by collecting a spectrum of

the NIST standard and calculating the detector efficiency at the energies of that source's photon emissions with the spreadsheet previously described (Appendix A-1). The calculated efficiencies were input to the curve-fitting program described above, with the exception of the 1596.4 keV datum. An interpolated efficiency and associated uncertainty were obtained by the same process described for the CNL detector efficiency at 1368.6 keV. The ^{56}Co source's activity was then calculated by dividing the peak area at this energy by the product of the estimated efficiency and the 99.99% abundance of this gamma. The ^{56}Co source's activity was calculated to have been $38525 \text{ Bq} \pm 3.87\%$ (95% CL) at the end of bombardment on June 11, 1993 (Appendix A-3). Efficiencies were obtained using the secondary source's photon emissions at 846.8, 1037.8, 1238.3, 1771.3, and 2598.5 keV in combination with those of the NIST standard as described below.

During the period when targets were counted for this study at SJSU (February to September of 1993), detector efficiencies were calculated from counts of the NIST standard when ^{24}Na counts were made and weekly when counting ^7Be or ^{22}Na . After the secondary standard was made, it too was counted on this schedule. This frequent measurement of detector efficiency allowed the researchers to monitor the performance of the spectroscopy system over time. An average deviation of the mean efficiencies over the period of 1.4% with a maximum of 3.5% (95% CL) was calculated and only random variations were observed. Counts of background activity were made monthly to identify potential interferences in the spectra collected to measure ^7Be or ^{22}Na activity in the targets because these counts often took more than 24 hours.

After the final target bombardment at the CNL in late June, the detector efficiencies from six counts of the primary source taken up to that time (at 15 cm source-detector distance) were assembled and adjusted for variations in background activity. These efficiencies were averaged at each of the NIST standard's emission energies from 176.3 to 1596.4 keV (the latter was deleted from final efficiency calculations). The uncertainties of these means, the standard emission rates, the averaged individual efficiencies, and the half-lives of the respective radionuclide sources (all at 95% CL) in the standard were summed to give overall uncertainties for each mean detector efficiency. Due to variations in count times used for the primary standard (from 5713 to 13769 s

over this period), the averages described were weighted according to the length of the individual counts (Appendix A-4). It was the SJSU detector's efficiency at 1274.5 keV from these calculations ($0.0010069 \pm 2.294\%$ at 95% CL) that was used in determining ^{22}Na cross sections (as described below) from spectra collected from the beginning of the study until early July of 1993.

The efficiencies of the SJSU detector for the 477.6 keV ^7Be and 1368.6 keV ^{24}Na gamma rays from February to the end of June were determined by combining the time-weighted average efficiencies from the NIST standard described above (less the 1596.4 keV datum) with the average efficiencies from three counts of the ^{56}Co secondary standard. The combined data thus included detector efficiencies at gamma ray energies from 176.3 to 2598.5 keV. This data set was read into the curve-fitting routine described previously to obtain estimates for the SJSU detector efficiencies at 477.6 keV of $0.0021563 \pm 5.90\%$ (95% CL) and $0.0009508 \pm 3.06\%$ (95% CL) at 1368.6 keV. The uncertainties of these detector efficiencies reflect addition of the uncertainty associated with the curve fit to those previously described.

Between July and September of 1993, six counts of about 2 hours each were made of both standard sources in succession. After adjustment of these counts for variations in the background that occurred as a result of relocating the SJSU detector, the efficiencies calculated from the individual counts were combined as done previously to yield new average efficiencies at the energies of interest for this period (Appendix A-5). These later efficiencies differed less than 1% from those given above.

Calculation of Production Cross Sections at Respective Proton Energies

Production cross sections for the radionuclides generated in the targets by proton bombardment were calculated by use of a spreadsheet template (Appendix A-6) for each target and radionuclide produced by the bombardment. The bombardment parameters were first entered in the template (Appendix A-6; Proton Bombardment Data Section) to give the proton current (I_p in Equation 3 below). The energy of the proton beam as it entered each target was calculated using the modified Bethe-Bloch formula (2) to obtain the mass collision stopping power, $(dT/\rho dx)_c$ in units of (MeVcm²/g), for combined soft and hard collisions by protons in the targets as described by Attix.⁵

$$(2) \quad \left(\frac{dT}{\rho dx} \right)_c = 0.3071 \frac{Zz^2}{A\beta^2} \left[13.8373 + \ln \left(\frac{\beta^2}{1-\beta^2} \right) - \beta^2 - \ln I \right]$$

where

T = kinetic energy of incident protons (MeV),

Z = number of protons / atom of absorber,

z = charge of proton,

A = atomic number of absorber,

$\beta = [1 - ((T/M_0c^2) + 1)^{-2}]^{1/2}$,

M_0c^2 = rest mass of proton (938.28 MeV), and

I = mean excitation potential of absorber (eV).

With solution of the expression (2) above, the kinetic energy lost by the proton beam in each target of the stack was calculated and used as the incident energy for the next target. The resulting values (Appendix A-7) were in agreement with similar, though more lengthy, calculations made with the TRIM-90 algorithm.⁶ The uncertainty in the initial proton beam energy of the CNL cyclotron was given by Dr. Carlos Castaneda to be ± 150 keV. He also stated that the charge (μC) integrated from the Faraday cup during the bombardments had an uncertainty of 1%. Output values from TRIM-90 for the angle of beam spreading in the target stacks were less than 1° for all runs. Calculation of the size of the beam at the Faraday cup from these results indicated that it fell within the cup in all cases, confirming Dr. Castaneda's statement. The densities of target materials

for Equation 2 were calculated from their masses and size measurements made with a precision caliper (Mitutoyo, Type 505-633 D-15).

The data specifying the target parameter of interest (diameter, thickness, mass, and atomic or molecular weight of the target substance) were next entered in the cross section template for calculation of the number of target atoms per cm² (N in Equation 3 below). These entries were followed by the parameters and results of counting (Appendix A-6). This section included specification of the half-life of the radionuclide of interest (in that spreadsheet) for back-calculation of its activity at the end of the target's bombardment. The final section of the template (Appendix A-6) was used to calculate the production cross-section (σ) for the radionuclide of interest using the relation described by Fink, Sisterson, Vogt, *et al.* ⁷:

$$(3) \quad \sigma = \frac{N_c g(t_0) f(t_1, t_2)}{NAETI_p}$$

where

N_c = number of counts in the photopeak,

$g(t) = [1 - e^{(-t/T)}]^{-1}$ where

$g(t_0)$ = buildup factor and t_0 = bombardment time,

$f(t_1, t_2) = e^{(t_1/T)} g(t_2)$ where

t_1 = time from end of bombardment to beginning of count;

T = mean life of the radionuclide of interest ($t_{1/2}$ from NCRP 58⁸ divided by $\ln 2$), and

t_2 = count length,

N = number of atoms/cm² in target,

A = abundance of the gamma ray of interest,

E = detector efficiency at the gamma ray energy of interest, and

I_p = proton current (protons/s).

The percent uncertainty (95% CL) of each calculated cross-section value was determined by summing the squares of the percent uncertainties of the values used in the numerical components of Equation 3 and then taking the square root of this sum. The uncertainties included those (95% CL) of the charge collected, target diameter and mass, the detector efficiency for the appropriate gamma ray energy, the gamma ray intensity,⁸ the peak area from the target spectrum, and the half-life of the radionuclide of interest.⁸

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- ¹ *Accuspec*, Canberra Nuclear Products Group, Meriden, Connecticut, USA (1989).
- ² H. Kruse and J. Brueckner, "Documentation on the Program Package Ganymede, V3.3," Max Planck Institut fuer Chemie, Mainz, Germany (1991).
- ³ Certificate (for) Standard Reference Material 4275C Radioactivity Standard, National Institute of Standards and Technology, Gaithersburg, Maryland, USA (1988).
- ⁴ *Tablecurve*, version 2.10, Jandel Scientific, Inc., San Rafael, California, USA (1990).
- ⁵ F. Attix, *Introduction to Radiological Physics and Radiation Dosimetry*, John Wiley & Sons, New York, New York, USA, (1986) pps. 165-180.
- ⁶ J. Ziegler, "TRIM-90, The TRansport of Ions in Matter (Version 6.0)," International Business Machines Corporation, Yorktown, New York, USA (1990).
- ⁷ D. Fink, J. Sisterson, S Vogt, G. Herzog, J. Klein, R. Middleton, A. Koehler, and A. Magliss, "Production of ⁴¹Ca and K, Sc, and V short-lived isotopes by the irradiation of Ti with 35 to 150 MeV protons; applications to solar cosmic ray studies," *Nuclear Instruments and Methods in Physics Research*, Elsevier Science Publishers, North Holland, Amsterdam, Netherlands, **B52** (1990), pps. 601-607.
- ⁸ *NCRP Report No. 58, Second Edition, A Handbook of Radioactivity Measurements Procedures*, National Council on Radiation Protection and Measurements, Bethesda, Maryland, USA (1989).

III. Results of Production Cross Section Measurements for Reactions in Targets

The results of our measurements of production cross sections for the reactions below have been collected in Tables 4 through 8 and plotted in Figures 11 through 15. Included in the tables were proton energies incident on each target, the production cross section measured for the radionuclide named, the percent uncertainty (95% CL) in the cross section, the target name, the location of counting for the respective radionuclide, and the counting (source-detector) distance.

The results of our study are discussed below under the reaction (or set of reactions) that applies to the isotopes present in the target materials. This format emphasizes (especially in the plots) the commonalities between proton-induced reactions in a given material.

$^{27}\text{Al}(p,3p\text{n})^{24}\text{Na}$

The cross sections measured for production of ^{24}Na in the aluminum target foils (Table 4 and Figure 11A) were at or below 0.1 mb for energies below 30 MeV. Measurements above 35 MeV showed a linear increase from 0.9 to 12.2 mb over the region from 30 to 65 MeV. A recent compilation of cross sections for ^{24}Na production in aluminum¹ showed values that agreed with those reported here up to 50 MeV (Figure 16). Between 50 and 100 MeV incident proton energy, a maximum was plotted in this compilation that showed variations from 9 to 14 mb and had relatively wide scatter between the values of different researchers. The cross sections values we measured showed a maximum ^{24}Na production cross section of 12 mb at 64 MeV. This is at the upper side of the cross sectional maximum for this reaction in aluminum from Reference 1. The 64 MeV proton energy for our study's largest ^{24}Na production cross section was in very close agreement with the value from the compilation of results described above.¹ Our results also agreed within 0.9 mb at 50 and 60 MeV with those reported² by Dr. Janet Sisterson who used a similar thin-foil bombardment geometry at the Harvard Cyclotron Laboratory.

$^{27}\text{Al}(p,3p3n)^{22}\text{Na}$

The results of the study described here showed a proton energy threshold for increased ^{22}Na production in aluminum at approximately 30 MeV (Figure 11B). The data plotted in Figure 11B were also listed in Table 4. We measured a maximum cross section of 50.1 mb at 45.1 MeV. Close agreement was observed (Figure 17) between our cross section values and those previously reported.¹

$^{12}\text{C}(p,3p3n)^7\text{Be}$ and $^{13}\text{C}(p,3p4n)^7\text{Be}$

Our measurements of the cross section for production of ^7Be from carbon targets spanned proton energies from about 42 to 67 MeV (Table 5 and Figure 12). This range did not include the production energy threshold nor the maximum of the excitation function. However, within the proton energy interval of our bombardments, cross section values were measured that showed little scatter. These results were very consistent in their agreement with a -0.3 mb/MeV slope in this region. The results of an earlier study³ showed a -0.15 mb/MeV slope in the energy interval from 41 to 71 MeV with cross section values shifted from 5 to 10 mb lower.

$^{25}\text{Mg}(p,2p)^{24}\text{Na}$ and $^{26}\text{Mg}(p,2pn)^{24}\text{Na}$

Cross sections measured for production of ^{24}Na in magnesium targets from our data between 30 and 67.5 MeV did not include the reaction's threshold energy (Table 6 and Figure 13A). At the lowest incident proton energy (30 MeV) used in our bombardments, we measured 5.5 mb for the production cross section of this reaction. We were unable to define the local maximum of the ^{24}Na excitation function for magnesium with the data gathered. The highest values (8.3 to 8.7 mb) obtained from our data set corresponded to a proton beam energy of 42 MeV while the maximum cross section probably occurred between 35 and 40 MeV. The cross sections we measured for this reaction declined linearly with energy to 6.6 mb at 67.4 MeV with a local minimum of 6.8 mb at 49.6 MeV (Figure 13A).

$^{24}\text{Mg}(p,2p\text{n})^{22}\text{Na}$, $^{25}\text{Mg}(p,2p2\text{n})^{22}\text{Na}$, and $^{26}\text{Mg}(p,2p3\text{n})^{22}\text{Na}$

Of the radionuclide-producing reactions we observed in this study, the production of ^{22}Na from magnesium had the largest cross sections. These results are shown in Table 6 and plotted in Figure 13B. Over the proton energy range between 42 and 67 MeV in magnesium, we saw a close-to-linear decrease of the ^{22}Na production cross section from 83 to 62 mb. Scattering in these results was at most 4 mb (49.3 to 49.8 MeV incident proton energies). Uncertainties (95% CL) for these cross section values were about 3 mb.

$^{28}\text{Si}(p,4p\text{n})^{24}\text{Na}$, $^{29}\text{Si}(p,4p2\text{n})^{24}\text{Na}$, $^{30}\text{Si}(p,4p3\text{n})^{24}\text{Na}$

^{24}Na production in both silicon and silicon dioxide in our plots of cross section versus proton energy (Figures 14A and 15A, respectively) began increasing gradually at approximately 40 MeV from less than 0.1 mb to about 0.6 mb at 50 MeV. In silicon, a maximum for ^{24}Na production cross section (1.2 mb) was obtained from our data set at 59 MeV (Table 7 and Figure 14A). Cross sections for ^{24}Na production in silicon dioxide were also tabulated (Table 8). The major difference for the ^{24}Na and ^{22}Na production cross sections in silicon and silicon dioxide was exhibited above 65 MeV incident proton energy (Figures 14A and 15A). In silicon, the ^{24}Na production cross section at this energy decreased to 0.8 mb, while in silicon dioxide the cross section at 66 MeV was slightly greater than 2 mb. We did not measure cross sections for ^{24}Na production from silicon dioxide in the range from 50 to 65 MeV and therefore have no data to support the latter value. However, Dr. John Young previously measured cross sections of 1.8 to 2.1 mb at 63 to 65 MeV that were in general agreement with this result.⁴

$^{28}\text{Si}(p,11p11n)^7\text{Be}$, $^{29}\text{Si}(p,11p12n)^7\text{Be}$, and $^{30}\text{Si}(p,11p13n)^7\text{Be}$

$^{16}\text{O}(p,5p5n)^7\text{Be}$, $^{17}\text{O}(p,5p6n)^7\text{Be}$, and $^{18}\text{O}(p,5p7n)^7\text{Be}$

Values for the ^7Be cross sections we measured in silicon targets ranged from below detection at 30 MeV to a maximum of 1.5 mb at 59 MeV (Table 7 and Figure 14B). In silicon dioxide we calculated a baseline cross section for ^7Be production of approximately 2 mb at 34.8 MeV (Table 8 and Figure 15B). Our results showed an energy threshold for increased ^7Be production around 41 MeV due to the $^{16}\text{O}(p,x)^7\text{Be}$ reaction in silicon dioxide. Between this energy and 50 MeV, the cross section rose by 0.6 mb/MeV to 7.7 mb. The maximum of this excitation function did not fall within the incident proton energies of the bombardments performed, but can be estimated to occur at about 55 MeV. The maximum values that we did calculate were 8.9 and 8.7 mb at 65 and 66 MeV, respectively.

$^{28}\text{Si}(p,4p3n)^{22}\text{Na}$, $^{29}\text{Si}(p,4p4n)^{22}\text{Na}$, and $^{30}\text{Si}(p,4p5n)^{22}\text{Na}$

In silicon and silicon dioxide, production cross sections for ^{22}Na differed by relatively small margins (Table 7 and Figure 14C for silicon, Table 8 and Figure 15C for silicon dioxide). In both materials the production had a threshold energy between 40 and 50 MeV. Increased production of ^{22}Na in silicon dioxide was observed beginning at 45 MeV versus 50 MeV in silicon. This was in agreement with values reported by Walton.¹ Our results showed a rapid increase of the ^{22}Na production cross section in silicon with proton energy that began at about 50 MeV and rose to a peak value of 20.5 mb at 65 MeV. In contrast, Furukawa, *et al.*, reported⁵ an energy threshold for ^{22}Na production in silicon at 41.5 MeV with a more linear increase (to 9 mb at 52 MeV) than exhibited by our results. The cross section reported by Furukawa, *et al.*, was less than ours (9 mb and 14 mb, respectively) at the maximum proton energy used in their study.

¹ Personal communication to Dr. John Young from Dr. Janet Sisterson (Harvard Cyclotron Laboratory) on September 24, 1992 of historical results compiled by Dr. Rolf Michel (University of Hannover, Germany).

² R. Schneider, J. Sisterson, A. Koehler, J. Klein, and R. Middleton, "Measurement of Cross Sections for Aluminum-26 and Sodium-24 Induced by Protons in Aluminum," *Nuclear Instruments and Methods in*

Physics Research, Elsevier Science Publishers, North-Holland, Amsterdam, Netherlands (1987), B29, pps.271-274.

³ I. Williams and C. Fulmer, "Cross Section for Formation of ^7Be by 20-155-meV Proton-Induced Reactions in Carbon," *Physical Review*, (February 20, 1967) 154, 4, pps. 1005-1007.

⁴ Personal communication, April 17, 1994.

⁵ M. Furukawa, S. Kume, and M. Ogawa, "Excitation Functions for the Formation of ^7Be and ^{22}Na in Proton Induced Reactions on ^{27}Al ," *Nuclear Physics*, North-Holland Publishing Company, Amsterdam, Netherlands (1965), 69, pps. 362-368.

IV. Discussion of Results.

The results of our spectral analyses of the target foils after bombardment showed production of ^7Be in the magnesium and aluminum foils. We also observed ^{28}Mg ($t_{1/2} = 20.91$ h) in our counts for ^{24}Na . Cross sections for these radionuclides were not reported because the associated uncertainties (when calculated) were more than 25%. We chose to limit reported cross section values to those with uncertainties less than 25% because of the abundance of previously-obtained results. Exceptions to this criterion were made in cases where these cross section(s) were needed for comparison with other results, i.e., ^7Be production in silicon (Table 7 and Figure 14B) for comparison to ^7Be production in silicon dioxide (Table 8 and figure 15B).

We have attempted to eliminate sources of systematic error in our measurements by calibrating with independent standards whenever appropriate. The agreement between our results for ^{24}Na and ^{22}Na production cross sections in aluminum and previously-reported values confirms that we have been successful with respect to values pertaining to this material. Fink, *et al.*¹ reported the use of an ion chamber to measure the proton flux upbeam of the target stacks. That chamber had been previously calibrated against the Faraday cup used in their study by taking measurements of the charge collected in both devices when targets were absent. In the presence of the target stack, the measurements made with these devices allowed calculation of the energy lost by the proton beam in traversing the stack. In our study, we relied on the beam current measured at the Faraday cup during the actual bombardments and assumed the number of protons that passed through the target stack without being registered at the cup to be negligible. This assumption was based on our calculation of the beam spreading angle in the stacks as previously described (Section II., Experimental and Mathematical Methods, Calculation of Production Cross Sections at Respective Proton Energies) and our routine comparisons between the proton current at the beam stop and the Faraday cup before and after the target bombardments.

Protons with kinetic energies from 100 MeV to 10 GeV make up 87% of the galactic cosmic ray (GCR) flux. Protons at energies from 10 to 300 MeV are trapped in the earth's

magnetosphere. The latter have a flux density of 10^2 to more than 10^4 per cm^2 per day at 450 km altitude and 28.5° latitude during solar minimum. During a solar flare, the flux of solar cosmic ray (SCR) protons (at less than 100 MeV kinetic energy) may rise to more than 10^6 per cm^2 per day.² With the increased use of carbon-composite materials in air and spacecraft, the results of our study are potentially valuable in the calculation of the component dose to the crew from the GCR/SCR-induced buildup of radiation in the hulls of these vehicles, if manned. Aluminum and magnesium are now commonly used as materials of construction in these applications. Our results may help to clarify the proton excitation functions that would be considered as part of the radiological health assessment for long term workers in a prospective near-earth space station. These data are also applicable to measurements of radioactivity generated by the interaction of solar cosmic rays with extraterrestrial soils and meteorites.

Some of the targets bombarded for the study described here have been given to the accelerator mass spectrometry (AMS) laboratory at the University of Arizona for quantitation of the radionuclides (^{10}Be , ^{14}C , ^{26}Al , etc.) generated in smaller amounts during the bombardments we performed. The results of the AMS analyses will be used to calculate cross sections for proton-induced reactions (Table 9) that have been less completely characterized than those we have reported and could be of use in studies of SCR-proton-induced reactions in extraterrestrial materials. Disks of the same target materials with which we have worked have also been bombarded at the Harvard Cyclotron Laboratory (HCL) for similar gamma-ray spectroscopy at the HCL and AMS analyses at the University of Philadelphia. The HCL bombardments were made at proton energies from 55 to 160 MeV, complementing those made at the CNL and described here.

The excitation functions for the reactions listed (Table 9) were generally in the first half of a list of twenty compiled at the 54th Annual Meeting of the Meteoritic Society in 1991.³ This

Table 9. List of Nuclear Reactions for which Cross Sections May Be Defined by AMS

Measurement of Radionuclides Produced in Targets from This Study.

$^{12}\text{C}(\text{p},3\text{p})^{10}\text{Be}$	$^{24}\text{Mg}(\text{p},9\text{p}6\text{n})^{10}\text{Be}$
$^{24}\text{Mg}(\text{p},7\text{p}4\text{n})^{14}\text{C}$	$^{27}\text{Al}(\text{p},10\text{p}8\text{n})^{10}\text{Be}$
$^{27}\text{Al}(\text{p},8\text{p}6\text{n})^{14}\text{C}$	$^{27}\text{Al}(\text{p},\text{pn})^{26}\text{Al}$

compilation was made to prioritize the excitation functions needed for research on radionuclides generated in extraterrestrial materials by exposure to GCR and SCR fluxes. Measurements of this type have several uses that include enhancing our knowledge of, "(1) the variation of the cosmic ray fluxes in the past, (2) the nature of the cosmic ray interactions, (3) the history of the meteorite, (4) terrestrial residence times of meteorites, (5) complex irradiation histories of materials exposed to cosmic rays, (6) sample shielding due to depth and location, and (7) estimates of the size and shape of the pre-atmospheric meteoritic body." ⁴

The production rate (P) of a cosmogenic radionuclide at a depth (d) in a meteorite of radius (R) may be mathematically expressed ⁴ as

$$(4) \quad P(d, R) = \sum_j N_j \sum_k \int_0^\infty \sigma_{j,k}(E) F_k(E, d, R) dE$$

where N_j = abundance of the target element (j),

k = primary or secondary particles that can induce nuclear reactions,

$\sigma_{j,k}(E)$ = cross section as a function of energy (E) for particle (k) making the product from element (j), and

$F_k(E, d, R)$ = flux of particle (k) as a function of energy (E), meteoritic radius (R), and sample depth (d).

Expression (4) is also suitable for calculating buildup of radionuclides in the hull of a spacecraft or space station. In either case, the excitation functions describing production of radionuclides in specific materials, knowledge of the target composition, and the composition and flux of the appropriate cosmic rays are required for solution.

The results of our study of cross sections could also be of value in choosing materials for use in construction of patient-locating fixtures for the proton-beam treatment of ocular melanoma (or other cancers). This type of treatment will be begun at the CNL later in 1994. In that context, the production cross sections for ^7Be , ^{22}Na , and ^{24}Na in silicon and silicon dioxide (described below) may be useful in predicting the radioactivity induced in concrete used as shielding around the cyclotron at the CNL and other proton accelerators.

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¹ D. Fink, J. Sisterson, *et al.*, "Production of ^{41}Ca and K, Sc, and V short-lived isotopes by the irradiation of Ti with 35 to 150 MeV protons: applications to solar cosmic ray studies," *ibid.*

² *NCRP Report No. 98, Guidance on Radiation Received in Space Activities*, National Council on Radiation Protection and Measurements, Bethesda, Maryland, USA (1989).

³ *Workshop on Cosmogenic Nuclide Production Rates*, P. Englert, R. Reedy, R. Michel, eds., LPI Technical Report Number 90-05, Lunar and Planetary Institute, Houston, Texas, USA (1990).

⁴ Personal communication from Dr. Peter Englert.

V. Conclusion.

High purity, thin target foils of carbon, magnesium, aluminum, silicon, and silicon dioxide were bombarded with protons at discrete energies from 30 to 67.5 MeV. The ^7Be , ^{22}Na , and ^{24}Na produced in the foils were measured by pulse-height spectroscopy. Experimental cross sections for the production of these radionuclides in the target foils were calculated using the results of the spectroscopic analyses and the target and bombardment parameters. The cross sections agree with previously-reported values except where the thickness of the foils used in earlier research may have caused the protons to lose significant energy by Coulombic interactions within the target stacks.

The proton-induced production cross sections reported here may be useful in nuclear science and health physics applications. This work has established a basis for future research at San Jose State University into the production cross sections of other materials that are less well characterized than those that are its subject.

TABLE 4. Measured Cross Sections in Aluminum.

Radionuclide Produced:	E(protons) (MeV)	Cross Section (mbarns)	Unc'ty @95% CL in Cross Section	Target (Al-)	Site of Spectroscopy	Counting Distance (cm)
SODIUM-24	27.04	0.01	11.4%	AJ	SJSU	15
	28.14	0.10	10.2%	12	CNL	4.65
	30.00	0.01	18.3%	AK	SJSU	15
	35.00	0.92	7.9%	11	CNL	4.65
	39.62	2.15	8.8%	10	SJSU	2.5
	39.96	1.40	4.3%	AB	SJSU	15
	40.01	1.34	5.1%	AD	SJSU	15
	42.50	1.94	3.9%	AA	SJSU	15
	42.50	1.97	4.0%	AC	SJSU	15
	45.00	4.43	8.8%	9	SJSU	2.5
	45.11	4.23	7.8%	6	CNL	4.65
	48.25	6.30	7.8%	8	CNL	4.65
	48.91	5.70	8.0%	Q	CNL	4.65
	49.03	6.24	4.0%	S	SJSU	15
	50.00	6.45	4.2%	P	SJSU	15
	50.00	6.57	3.9%	R	SJSU	15
	50.00	6.89	7.8%	5	CNL	4.65
	52.50	7.81	7.7%	7	CNL	4.65
	58.12	10.48	3.8%	K	SJSU	15
	58.19	10.53	4.2%	I	SJSU	15
	60.00	10.86	4.1%	H	SJSU	15
	60.00	10.92	4.1%	J	SJSU	15
	63.75	11.73	7.8%	4	SJSU	5
	64.09	12.25	7.8%	2	SJSU	5
	66.66	10.95	4.2%	G	SJSU	15
	66.75	11.14	4.1%	C	SJSU	15
	67.50	11.08	4.3%	F	SJSU	15
	67.50	11.29	4.2%	B	SJSU	15
	67.50	12.01	7.7%	3	SJSU	5
	67.50	12.07	7.8%	1	SJSU	5
SODIUM-22	27.04	0.00	N/A	AJ	SJSU	15
	30.00	0.71	68.7%	AK	SJSU	15
	39.96	41.69	4.6%	AB	SJSU	15
	40.01	42.16	4.2%	AD	SJSU	15
	42.50	46.09	4.7%	AC	SJSU	15
	42.50	46.49	5.0%	AA	SJSU	15
	45.11	50.08	5.9%	6	SJSU	15
	48.25	43.57	4.6%	8	SJSU	15
	48.91	37.12	7.2%	Q	SJSU	15
	49.03	37.88	5.4%	S	SJSU	15
	50.00	34.81	8.6%	R	SJSU	15
	50.00	37.42	7.2%	P	SJSU	15
	52.50	36.88	7.2%	7	SJSU	4.65
	58.12	29.58	5.5%	K	SJSU	15
	58.19	29.11	6.6%	I	SJSU	15
	60.00	26.01	6.0%	H	SJSU	15
	60.00	28.41	5.8%	J	SJSU	15
	63.75	22.39	9.7%	4	SJSU	15
	64.09	26.59	9.4%	2	SJSU	15
	67.50	26.65	7.9%	3	SJSU	15

TABLE 5. Measured Cross Sections in Carbon.

Radionuclide Produced:	E(protons) (MeV)	Cross Section (mbarns)	Unc'ty @95% CL in Cross Section	Target (C-)	Site of Spectroscopy	Counting Distance (cm)
BERYLLIUM-7	41.97	28.38	6.2%	AB	SJSU	15
	42.33	27.13	6.7%	AA	SJSU	15
	49.54	25.23	6.5%	9	SJSU	15
	49.85	23.95	6.6%	8	SJSU	15
	59.34	23.00	5.6%	3	CNL	4.65
	59.61	22.62	6.4%	2	SJSU	15
	59.87	21.50	6.3%	1	SJSU	15
	66.90	19.89	6.8%	7	SJSU	15
	67.14	20.24	6.5%	6	SJSU	15
	67.39	19.09	6.9%	5	SJSU	15

TABLE 6. Measured Cross Sections in Magnesium.

Radionuclide Produced:	E(protons) (MeV)	Cross Section (mbarns)	Unc'ty @95% CL in Cross Section	Target (Mg-)	Site of Spectroscopy	Counting Distance (cm)
SODIUM-24	29.77	5.57	3.7%	AC	SJSU	15
	42.02	8.67	3.8%	AB	SJSU	15
	42.33	8.35	3.8%	AA	SJSU	15
	49.31	7.57	4.0%	10	SJSU	15
	49.58	6.85	7.9%	9	CNL	4.65
	49.85	7.59	4.0%	8	SJSU	15
	59.41	7.43	4.0%	5	SJSU	15
	59.64	7.15	4.0%	4	SJSU	15
	59.87	7.17	4.0%	7	SJSU	15
	66.96	6.61	4.2%	3	SJSU	15
	67.17	6.57	4.2%	2	SJSU	15
	67.39	6.76	4.2%	1	SJSU	15
SODIUM-22	42.02	82.85	3.2%	AB	SJSU	15
	49.31	73.52	4.8%	10	SJSU	15
	49.58	74.48	4.3%	9	SJSU	15
	49.85	77.42	5.7%	8	SJSU	15
	59.41	67.52	3.7%	5	SJSU	15
	59.64	68.59	3.8%	4	SJSU	15
	66.96	61.92	4.6%	3	SJSU	15
	67.17	61.97	4.0%	2	SJSU	15

TABLE 7. Measured Cross Sections in Silicon.

Radionuclide Produced:	E(protons) (MeV)	Cross Section (mbarns)	Unc'ty @95% CL in Cross Section	Target (Si-)	Site of Spectroscopy	Counting Distance (cm)
SODIUM-24	29.77	N/D*	N/A	10	SJSU	15
	41.61	0.29	3.6%	8	SJSU	15
	49.65	0.68	7.7%	6	CNL	4.65
	51.02	0.74	7.7%	5	CNL	4.65
	52.36	0.82	7.7%	4	CNL	4.65
	59.07	1.24	3.4%	B	SJSU	15
	59.17	1.21	3.3%	A	SJSU	15
	66.30	0.83	6.5%	2	SJSU	5
BERYLLIUM-7 **	29.77	N/D	N/A	10	SJSU	15
	41.61	0.62	18.0%	8	SJSU	15
	49.65	0.22	26.1%	6	SJSU	15
	51.02	0.48	22.7%	5	SJSU	15
	52.36	0.50	21.0%	4	SJSU	15
	59.07	1.51	44.3%	B	SJSU	15
	59.17	0.64	32.4%	A	SJSU	15
	65.20	0.88	23.1%	3	SJSU	15
	66.30	0.70	33.8%	2	SJSU	15
	67.39	0.66	35.8%	1	SJSU	15
SODIUM-22	29.77	0.38	35.9%	10	SJSU	15
	41.61	1.19	15.3%	8	SJSU	15
	49.65	3.14	3.9%	6	SJSU	15
	51.02	12.04	3.8%	5	SJSU	15
	52.36	14.12	3.5%	4	SJSU	15
	59.17	21.94	2.8%	A	SJSU	15
	65.20	24.40	3.8%	3	SJSU	15
	66.30	24.25	3.6%	2	SJSU	15
	67.39	24.35	3.8%	1	SJSU	15

* No peak detectable above background.

** Values included (despite high uncertainties) for comparison to Be-7 production in silicon dioxide targets.

TABLE 8. Measured Cross Sections in Silicon Dioxide.

Radionuclide Produced:	E(protons) (MeV)	Cross Section (mbarns)	Unc'ty @95% CL in Cross Section	Target (SiO ₂ -)	Site of Spectroscopy	Counting Distance (cm)
SODIUM-24	30.49	N/D	N/A	14	CNL	4.65
	32.70	0.01	13.7%	13	CNL	4.65
	34.80	0.001	9.7%	12	CNL	4.65
	41.42	0.48	8.5%	11	SJSU	2.5
	43.16	0.58	8.5%	10	SJSU	2.5
	44.84	0.69	8.5%	9	SJSU	2.5
	46.74	0.60	7.7%	6	CNL	4.65
	48.32	0.64	7.7%	5	CNL	4.65
	49.85	0.75	7.7%	4	CNL	4.65
	66.19	2.06	7.6%	2	SJSU	15
BERYLLIUM-7	34.80	1.87	8.9%	12	SJSU	15
	41.70	2.90	12.4%	8	SJSU	15
	44.84	5.28	6.8%	9	SJSU	15
	49.85	7.70	7.3%	4	SJSU	15
	64.98	8.91	9.1%	3	SJSU	15
	66.19	8.72	7.1%	2	SJSU	15
SODIUM-22	34.80	1.26	5.5%	12	SJSU	15
	41.70	1.35	12.4%	8	SJSU	15
	44.84	1.40	14.2%	9	SJSU	15
	46.74	4.57	46.2%	6	CNL	4.65
	48.32	7.54	36.0%	5	CNL	4.65
	49.85	8.82	6.1%	4	SJSU	15
	64.98	20.53	8.1%	3	SJSU	15
	66.19	19.50	5.0%	2	SJSU	15

Figure 11A. Sodium-24 Cross Sections (mb) in Aluminum vs. Proton Energy (MeV)

Figure 11B. Sodium-22 Cross Sections (mb) in Aluminum vs. Proton Energy (MeV).

Figure 12. Beryllium-7 Cross Sections (mb) in Carbon vs. Proton Energy (MeV).

Figure 13A. Sodium-24 Cross Sections (mb) in Magnesium vs. Proton Energy (MeV).

Figure 13B. Sodium-22 Cross Sections (mb) in Magnesium vs. Proton Energy (MeV).

Figure 14A. Sodium-24 Cross Sections (mb) in Silicon vs. Proton Energy (MeV).

Figure 14B. Beryllium-7 Cross Sections (mb) in Silicon vs. Proton Energy (MeV).

Figure 14C. Sodium-22 Cross Sections (mb) in Silicon vs. Proton Energy (MeV).

Figure 15A. Sodium-24 Cross Sections (mb) in Silicon Dioxide vs. Proton Energy (MeV).

Figure 15B. Beryllium-7 Cross Sections (mb) in Silicon Dioxide vs. Proton Energy (MeV).

Figure 15C. Sodium-22 Cross Sections (mb) in Silicon Dioxide vs. Proton Energy (MeV).

Figure 16. Plot of Sodium-24 Cross Sections in Aluminum from This Study and Previous Results as Compiled by Michel.

Figure 17. Plot of Sodium-22 Cross Sections in Aluminum from This Study and Previous Results as Compiled by Michel.

Appendix A. Table of Contents.

Appendix A-1. Example of Spreadsheet for Calculation of Detector Efficiency.

Appendix A-2. Example of Detector Efficiency vs. Gamma Ray Energy Curve Fit Output.

Appendix A-3. Spreadsheet for Calculation of Co-56 Secondary Standard Source Activity.

Appendix A-4. Spreadsheet for Calculation of Averaged SJSU Detector Efficiencies; March-June of 1993.

Appendix A-5. Spreadsheet for Calculation of Averaged SJSU Detector Efficiencies; July-August of 1993.

Appendix A-6. Example of Spreadsheet for Calculation of Radionuclide Production Cross Section.

Appendix A-7. Example of Spreadsheet for Calculation of Proton Beam Energy Losses in Target Stacks.

Notes on Appendix A-1.

To measure detector efficiency, the activity of the radionuclides in a calibration source must be adjusted for decay from the date of its certification to the date of use. This spreadsheet includes calculation of the decay-corrected activities for our calibration sources to the date on which a spectrum was collected to measure detector efficiency. The uncertainties of the half-lives of the radionuclides in these sources are listed with their confidence intervals (95% CL), as are the uncertainties of their calibrated gamma-ray emission rates. The decay-corrected, calibrated emission rates are compared to those detected. The uncertainty in peak areas from the spectrum are adjusted to the 95% CL and the detector efficiency calculated at each gamma-ray energy. Parallel calculations at the extrema of the confidence intervals are used to obtain an overall uncertainty at each gamma-ray energy.

Appendix A-1. Example of Spreadsheet for Calculation of Detector Efficiency.

TWO-SOURCE EFFICIENCY CALIBRATION OF HPG₀ DETECTOR AT SJSU

USING NIST SOURCE 4275C-56 @ 15 cm :

CERT TIME=	09:00:00 PST	HALF-LIFE OF Sb-125=	2.7597 years
CERT DATE=	01-Sep-88	HALF-LIFE OF Eu-154=	8.5994 years
COUNT START TIME=	14:35:23 PST	HALF-LIFE OF Eu-155=	4.7583 years
COUNT DATE=	14-Jul-93	Sb-125 LAMBDA=	0.2512 1/years
LIVE TIME=	01:38:32	Eu-154 LAMBDA=	0.0806 1/years
REAL TIME=	01:39:31	Eu-155 LAMBDA=	0.1457 1/years
MIDPOINT OF COUNT=	15:25:08 PST		
DAYS FROM CERT. TO COUNT	1777	for SRM-4275 LAMBDA=	95% UNC. (95% MAX) (95% MIN)
HOURS & MINUTES=	0.2675 decimal days	Sb-125	0.0107 0.2521 0.2502
E.T. FROM CERT. TO COUNT	4.866 years	Eu-154	0.0644 0.0812 0.0800
		Eu-155	0.0215 0.1463 0.1450

ALSO USING CO-56 SOURCE MADE AT UCD:

CAL TIME=	16:16:48 PST	HALF-LIFE OF Co-56=	77.9 days
CAL DATE=	14-Jul-93	MAX HALF-LIFE OF Co-56=	79.1 days
SOURCE ACTIVITY=	28739 Bq	MIN HALF-LIFE OF Co-56=	76.7 days
COUNT START TIME=	16:16:48 PST		
COUNT DATE=	14-Jul-93	Co-56 LAMBDA=	0.0088979
LIVE TIME=	01:03:04	(95% MAX)	0.0090371
REAL TIME=	01:03:52	(95% MIN)	0.0087629
MIDPOINT OF COUNT=	16:48:44 PST		
ELAPSED DAYS FROM CAL=	0 days		
HOURS & MINUTES	0.0222 decimal days		
E.T. FROM CAL TO COUNT=	0.0222 decimal days		

E-GAMMA (CERT.)(keV)	CERT. COUNT RATE (cps)	UNCERTY (PERCENT) 95% C.L.	CERT. COUNT RATE (cps) 95% MAX	CERT. COUNT RATE (cps) 95% MIN	14-Jul-93 CALC. RATE	14-Jul-93 CALC. RATE 95% MAX	14-Jul-93 CALC. RATE 95% MIN
247.7	5.386E+03	1.176	5.449E+03	5.323E+03	3.639E+03	3.692E+03	3.585E+03
427.9	1.650E+04	1.568	1.676E+04	1.624E+04	4.861E+03	4.960E+03	4.762E+03
463.4	5.800E+03	1.372	5.880E+03	5.720E+03	1.709E+03	1.740E+03	1.677E+03
591.8	3.855E+03	1.176	3.900E+03	3.810E+03	2.604E+03	2.643E+03	2.566E+03
600.6	9.801E+03	1.372	9.935E+03	9.667E+03	2.887E+03	2.941E+03	2.834E+03
635.9	6.263E+03	1.176	6.337E+03	6.189E+03	1.845E+03	1.876E+03	1.815E+03
723.3	1.564E+04	1.176	1.582E+04	1.546E+04	1.057E+04	1.072E+04	1.041E+04
846.8	2.874E+04	3.999	2.989E+04	2.759E+04	2.873E+04	2.988E+04	2.758E+04
873.2	9.464E+03	1.372	9.594E+03	9.334E+03	6.394E+03	6.500E+03	6.287E+03
996.3	8.128E+03	1.764	8.271E+03	7.985E+03	5.491E+03	5.604E+03	5.378E+03
1004.7	1.409E+04	1.372	1.428E+04	1.390E+04	9.519E+03	9.677E+03	9.360E+03
1037.8	4.041E+03	4.368	4.217E+03	3.864E+03	4.040E+03	4.216E+03	3.863E+03
1238.3	1.917E+04	4.778	2.008E+04	1.825E+04	1.917E+04	2.008E+04	1.825E+04
1274.5	2.716E+04	0.98	2.743E+04	2.689E+04	1.835E+04	1.858E+04	1.811E+04
1771.3	4.455E+03	4.468	4.654E+03	4.256E+03	4.454E+03	4.653E+03	4.255E+03
2598.5	4.880E+03	4.488	5.099E+03	4.661E+03	4.879E+03	5.098E+03	4.660E+03

E-GAMMA (CERT.)(keV)	MCA COUNTS UNDER PK.	ACTUAL COUNT RATE	95% C.L. FOR CT. RATE (DPS)	DETECTOR EFFIC'Y	DETECTOR EFFIC'Y 95% MAX	DETECTOR EFFIC'Y 95% MIN	% UNC. OF EFFICIENCY
247.7	78987	13.36	0.09	3.671893E-03	3.752332E-03	3.593661E-03	2.16%
427.9	68127	11.52	0.09	2.370696E-03	2.437938E-03	2.305834E-03	2.79%
463.4	22649	3.84	0.05	2.242134E-03	2.313618E-03	2.172986E-03	3.14%
591.8	28065	4.75	0.05	1.822810E-03	1.871398E-03	1.775569E-03	2.63%
600.6	30632	5.18	0.06	1.794509E-03	1.848418E-03	1.742349E-03	2.96%
635.9	18497	3.13	0.04	1.695741E-03	1.748703E-03	1.644335E-03	3.08%
723.3	95983	16.24	0.10	1.536591E-03	1.569253E-03	1.504824E-03	2.10%
846.8	147544	38.99	0.20	1.357150E-03	1.420812E-03	1.298384E-03	4.51%
873.2	49982	8.45	0.07	1.322329E-03	1.356370E-03	1.289345E-03	2.53%
996.3	39137	6.62	0.06	1.205604E-03	1.242964E-03	1.169669E-03	3.04%
1004.7	67146	11.36	0.09	1.193191E-03	1.222462E-03	1.164826E-03	2.42%
1037.8	18078	4.78	0.07	1.182573E-03	1.254390E-03	1.116767E-03	5.82%
1238.3	74302	19.64	0.14	1.024560E-03	1.083609E-03	9.708966E-04	5.50%
1274.5	108213	18.30	0.11	9.974498E-04	1.016268E-03	9.790831E-04	1.86%
1771.3	12594	3.33	0.06	7.472999E-04	7.957420E-04	7.030013E-04	6.21%
2598.5	10190	2.69	0.05	5.519496E-04	5.889670E-04	5.181123E-04	6.42%

-BACKGROUND

Notes on Appendix A-2.

In the three pages of this appendix is a sample of the output from the curve-fitting software used to calculate detector efficiencies at gamma-ray energies at which the standard sources had no emissions. The first page includes a plot of the best-fit curve chosen for the data and a summary of the curve's mathematical and statistical parameters. On the second page are detailed statistical analyses of the data and the fitted curve. The third page shows the (gamma-ray energy, measured efficiency) data from the input file and the detector efficiencies with uncertainties calculated from the curve fit. When non-standard gamma energies are input to the program, interpolations are made with the fit equation that include associated uncertainties. The uncertainties of these interpolated efficiencies were combined with those of the closest adjacent standard energy (from a spreadsheet of the type described in Appendix A-1) to give overall uncertainties for use with the interpolated detector efficiencies.

Efficiency Cal @SJSU on 4-3-93

May 30, 1994 9:18 PM

13 Active X-Y Points

X: E(gamma) (keV) Mean: 739.3846154 SD: 404.0571904
 Y: Detector Efficiency Mean: 0.001972754 SD: 0.001140343

7 Eqn 193 $y=1/(a+bx+cx^2+dx^3+ex^4)$ $r^2=0.999901826$

Coefficient	Std Error	T(Coef/Err)	95% Confidence Limits	
a 49.58482443	4.9784e-05	996005.3907	49.58470923	49.58493963
b 0.892065597	3.4992e-07	2549374.496	0.892064788	0.892066407
c 1.0885e-05	7.7373e-10	14068.7211	1.0884e-05	1.0887e-05
d -1.936e-07	6.6253e-13	-292190.344	-1.936e-07	-1.936e-07
e 7.1488e-11	1.907e-16	374864.9924	7.1488e-11	7.1489e-11

Curve-Fit Std Error: 1.38381799255e-05
 Curve-Fit F-Statistic: 20370.0315024

May 30, 1994 9:18 PM

Description: Efficiency Cal @SJSU on 4-3-93

X-Y Table Size: 15 Active Points: 13

X Variable: E(gamma) (keV)

Xmin: 176.3	Xmax: 1596.4	Xrange: 1420.1
Xmean: 739.3846154	Xstd: 404.0571904	Xmedian: 635.9
X@Ymin: 1596.4	X@Ymax: 176.3	X@Yrange: 1420.1
Xav@Ymax: 176.3	X@50Y: 330.6781137	Xlt@50Y: 0
Xrt@50Y: 0	X@25Y: 507.9011038	X@75Y: 231.1707394
Xwavemin: 1217.975	Xwavemax: 176.3	Xwaverng: 2083.35

Y Variable: Detector Efficiency

Ymin: 0.000849029	Ymax: 0.004842557	Yrange: 0.003993528
Ymean: 0.001972754	Ystd: 0.001140343	Ymedian: 0.001709601
Y@Xmin: 0.004842557	Y@Xmax: 0.000849029	Y@Xrange: 0.003993528

7 Eqn 193 $y=1/(a+bx+cx^2+dx^3+ex^4)$ $r^2=0.999901826$

	Coefficient	Std Error	T(Coef/Err)	95% Confidence Limits	
a	49.58482443	4.9784e-05	996005.3907	49.58470923	49.58493963
b	0.892065597	3.4992e-07	2549374.496	0.892064788	0.892066407
c	1.0885e-05	7.7373e-10	14068.7211	1.0884e-05	1.0887e-05
d	-1.936e-07	6.6253e-13	-292190.344	-1.936e-07	-1.936e-07
e	7.1488e-11	1.907e-16	374864.9924	7.1488e-11	7.1489e-11

Curve-Fit Std Error: 1.38381799255e-05

Source	Sum of Squares	DF	Mean Square	F
Regr	1.5603055e-05	4	3.9007637e-06	20370
Error	1.5319618e-09	8	1.9149522e-10	
Total	1.5604587e-05	12		

Efficiency Cal @SJSU on 4-3-93
Page 1

#	X-Value	Y-Value	Y-Predict	95% Confidence Intvl	
1	176.3	0.0048426	0.0048496	0.0048218	0.0048774
2	247.7	0.0037138	0.0037238	0.003705	0.0037426
3	427.9	0.0023806	0.002378	0.0023603	0.0023957
4	463.4	0.0022553	0.0022255	0.0022088	0.0022422
5*	477.6	0	0.0021704	0.0021542	0.0021866
6	591.8	0.0017988	0.0018183	0.0018051	0.0018315
7	600.6	0.0017945	0.0017965	0.0017833	0.0018096
8	635.9	0.0017096	0.0017148	0.0017017	0.0017279
9	723.3	0.0015498	0.001546	0.0015316	0.0015604
10	873.2	0.0013324	0.0013342	0.0013177	0.0013507
11	996.3	0.001215	0.0012075	0.001191	0.001224
12	1004.7	0.0011984	0.0012	0.0011834	0.0012165
13	1274.5	0.0010061	0.001008	0.0009789	0.0010371
14*	1368.6	0	0.0009566	0.0009239	0.0009892
15	1596.4	0.000849	0.0008488	0.0008168	0.0008807

Notes on Appendix A-3.

This spreadsheet was used to confirm the amount of Co-56 activity in our secondary standard source at the end of the bombardment in which it was created. This source's gamma emission rate at 846.8 keV was measured during a period when the detector efficiencies were especially well characterized. The curve-fitting software previously described was used to interpolate the detector's efficiency at that energy. The number of pulses collected in the 846.8 keV peak was divided by the product of this detector efficiency and the gamma-ray's intensity to obtain the activity of the Co-56 in the source at the time of counting. Parallel calculations were made at the extrema of the 95% CL to determine the overall uncertainty associated with this activity. The secondary source's activity was then back-calculated to the end of bombardment. The resulting value was compared to the activity previously measured by my co-worker.

GROSS dt=	33 DAYS	AT END OF BEAM:
LESS	0.064722222 DAYS	38525 Bq
NET dt=	32.93527778 DAYS	(+0.7% FROM TONY'S VALUE)

Notes on Appendix A-4.

This spreadsheet was used to compare the efficiencies of the SJSU detector that were measured from March to June of 1993. The detector efficiency at each emission energy of the NIST standard source was tabulated and plotted for each of six dates. When the individual deviations of these efficiencies from the count-time-weighted mean efficiencies were observed to be insignificant, we accepted the mean values as characteristic of the detector over the period. The mean efficiency of the detector at 1274.5 keV was used directly in ^{22}Na analyses of spectra collected for that radionuclide during this time. The overall uncertainty of each detector efficiency was obtained by summing the component uncertainties. Detector efficiency data obtained with the newly-made Co-56 source was later added to that shown here. This allowed deletion of the problematic detector efficiency at 1596.4 keV that was measured from the NIST standard in which summing at that energy caused a positive bias. From the final compilation, detector efficiencies for gamma-ray energies at which the standards had no emissions were interpolated using the curve-fitting program described in Appendix A-2.

Appendix A-4.

Spreadsheet for Calculation of Averaged SJSU Detector Efficiencies; March – June of 1993.

AVERAGING HPGe DETECTOR EFFICIENCIES FOR PROTONS-R-US CO.

GAMMA ENERGY	SPECTRUM NO. 1 (3-27-93)	2 (4-3-93)	3 (5-7-93)	4 (5-12-93)	5 (5-21-93)	6 (6-23-93)
176.3	4.8370E-03	4.8623E-03	4.7534E-03	4.8356E-03	4.7892E-03	4.7933E-03
247.7	3.7090E-03	3.7138E-03	3.7029E-03	3.7202E-03	3.7116E-03	3.7382E-03
427.9	2.3735E-03	2.3806E-03	2.3723E-03	2.3931E-03	2.3436E-03	2.3930E-03
463.4	2.2188E-03	2.2553E-03	2.2223E-03	2.2237E-03	2.2076E-03	2.2757E-03
591.8	1.8000E-03	1.7988E-03	1.8092E-03	1.8082E-03	1.8066E-03	1.7961E-03
600.6	1.8139E-03	1.7945E-03	1.8091E-03	1.7881E-03	1.7907E-03	1.8155E-03
635.9	1.7441E-03	1.7906E-03	1.7240E-03	1.6980E-03	1.7448E-03	1.7230E-03
723.3	1.5521E-03	1.5498E-03	1.5492E-03	1.5352E-03	1.5362E-03	1.5484E-03
873.2	1.3438E-03	1.3324E-03	1.3361E-03	1.3462E-03	1.3382E-03	1.3452E-03
996.3	1.2380E-03	1.2150E-03	1.2207E-03	1.2094E-03	1.2158E-03	1.2183E-03
1004.7	1.2005E-03	1.1984E-03	1.2017E-03	1.1998E-03	1.1964E-03	1.1998E-03
1274.5	1.0126E-03	1.0061E-03	1.0056E-03	1.0035E-03	1.0097E-03	1.0060E-03
1596.4	8.8425E-04	8.4903E-04	8.6966E-04	8.6648E-04	8.6179E-04	8.6882E-04

*SPECTRA 1 & 2 1274.5 EFFCY REFLECTS SUBTRACTION OF 0.036 CPS BACKGROUND

COUNT TIMES=	7200	6509	13769	6501	5713	10525
FRACT. TIME=	0.1434	0.1296	0.2742	0.1295	0.1138	0.2096
					SUM OF FRACTS	1.0000
					SUM OF ALL COUNT TIME=	50217
						SECONDS

Efficiency Curves for Protons-R-US HPGe Detector

GAMMA ENERGY	COUNT TIME-WEIGHTED AVERAGE EFFICIENCY	95% C.L. INTERVAL	% UNCOF AVG @ 95% C.L.	95% UNCTY OF SRM	95% UNCTY OF 1(1/2)'S	AVERAGE PK ERROR %	SUM OF % ERRORS 95% CL
176.3	4.8026E-03	7.8475E-05	1.634%	1.176%	0.388%	2.211%	5.409%
247.7	3.7158E-03	2.4089E-05	0.648%	1.176%	0.749%	0.985%	3.558%
427.9	2.3773E-03	3.5845E-05	1.508%	1.568%	0.388%	0.892%	4.356%
463.4	2.2358E-03	5.0835E-05	2.274%	1.372%	0.388%	1.998%	6.032%
591.8	1.8034E-03	1.0826E-05	0.600%	1.176%	0.749%	1.648%	4.173%
600.6	1.8044E-03	2.4028E-05	1.332%	1.372%	0.388%	1.564%	4.656%
635.9	1.7343E-03	6.1164E-05	3.527%	1.176%	0.388%	2.454%	7.544%
723.3	1.5462E-03	1.4562E-05	0.942%	1.176%	0.749%	0.698%	3.565%
873.2	1.3402E-03	1.0931E-05	0.816%	1.372%	0.749%	0.976%	3.912%
996.3	1.2199E-03	1.9225E-05	1.576%	1.764%	0.749%	1.176%	5.265%
1004.7	1.1999E-03	3.5942E-06	0.300%	1.372%	0.749%	0.753%	3.174%
1274.5	1.0069E-03	6.4588E-06	0.641%	0.980%	0.749%	0.553%	2.924%
1596.4	8.6759E-04	2.2478E-05	2.591%	1.372%	0.749%	3.015%	7.727%
				PER SRM DOCS	PER SRM DOCS	3-27 TO 5-27 SPECTRA ONLY	AS SPECIFIED

Notes on Appendix A-5.

This spreadsheet was used to determine the efficiency of the SJSU detector during the period from July to August of 1993. It includes six sets of efficiencies measured at the gamma-ray energies of both the NIST and Co-56 standard sources. Equal weight was given to each efficiency at a given energy when the average was calculated because a uniform, two-hour count time was used for collection of efficiency spectra during this period. The overall uncertainty for each average efficiency was calculated by adding together the uncertainty in the average value, the average of the uncertainties associated with the individual efficiencies, and the uncertainty of that average. As explained previously, detector efficiencies for gamma-ray energies at which the standards had no emissions were interpolated using the curve-fitting program described in Appendix A-2.

Appendix A-5. Spreadsheet for Calculation of Averaged SJSU Detector Efficiencies, July-August of 1993.

AVERAGING HPGe DETECTOR EFFICIENCIES FOR PROTONS-R-US CO.

GAMMA ENERGY	SPECTRUM NO. 1 (7-14-93)	2 (8-3-93)					3 (8-5-93)					4 (8-13-93)					5 (8-21-93)					6 (8-31-93)				
247.7	3.671893E-03	3.684710E-03	3.642069E-03	3.706937E-03	3.667918E-03	3.665021E-03	3.642069E-03	3.706937E-03	3.667918E-03	3.665021E-03	3.642069E-03	3.706937E-03	3.667918E-03	3.665021E-03	3.642069E-03	3.706937E-03	3.667918E-03	3.665021E-03	3.642069E-03	3.706937E-03	3.667918E-03	3.665021E-03	3.642069E-03			
427.9	2.370696E-03	2.354858E-03	2.340388E-03	2.360063E-03	2.348366E-03	2.367127E-03	2.370696E-03	2.354858E-03	2.340388E-03	2.360063E-03	2.348366E-03	2.370696E-03	2.354858E-03	2.340388E-03	2.360063E-03	2.348366E-03	2.370696E-03	2.354858E-03	2.340388E-03	2.360063E-03	2.348366E-03	2.367127E-03	2.370696E-03			
463.4	2.242134E-03	2.190502E-03	2.239614E-03	2.260082E-03	2.215162E-03	2.214184E-03	2.242134E-03	2.190502E-03	2.239614E-03	2.260082E-03	2.215162E-03	2.214184E-03	2.242134E-03	2.190502E-03	2.239614E-03	2.260082E-03	2.215162E-03	2.214184E-03	2.242134E-03	2.190502E-03	2.239614E-03	2.260082E-03	2.215162E-03			
591.8	1.822810E-03	1.803809E-03	1.776588E-03	1.809421E-03	1.769524E-03	1.790053E-03	1.822810E-03	1.803809E-03	1.776588E-03	1.809421E-03	1.769524E-03	1.790053E-03	1.822810E-03	1.803809E-03	1.776588E-03	1.809421E-03	1.769524E-03	1.790053E-03	1.822810E-03	1.803809E-03	1.776588E-03	1.809421E-03	1.769524E-03			
600.6	1.794509E-03	1.787760E-03	1.756176E-03	1.787112E-03	1.799524E-03	1.800244E-03	1.794509E-03	1.787760E-03	1.756176E-03	1.787112E-03	1.799524E-03	1.800244E-03	1.794509E-03	1.787760E-03	1.756176E-03	1.787112E-03	1.799524E-03	1.800244E-03	1.794509E-03	1.787760E-03	1.756176E-03	1.787112E-03	1.799524E-03			
635.9	1.695741E-03	1.701000E-03	1.680158E-03	1.722838E-03	1.711646E-03	1.710893E-03	1.695741E-03	1.701000E-03	1.680158E-03	1.722838E-03	1.711646E-03	1.710893E-03	1.695741E-03	1.701000E-03	1.680158E-03	1.722838E-03	1.711646E-03	1.710893E-03	1.695741E-03	1.701000E-03	1.680158E-03	1.722838E-03	1.711646E-03			
723.3	1.536591E-03	1.536216E-03	1.517207E-03	1.536589E-03	1.528137E-03	1.536131E-03	1.536591E-03	1.536216E-03	1.517207E-03	1.536589E-03	1.528137E-03	1.536131E-03	1.536591E-03	1.536216E-03	1.517207E-03	1.536589E-03	1.528137E-03	1.536131E-03	1.536591E-03	1.536216E-03	1.517207E-03	1.536589E-03	1.528137E-03			
846.8	1.357150E-03	1.357669E-03	1.362798E-03	1.367162E-03	1.366693E-03	1.371203E-03	1.357150E-03	1.357669E-03	1.362798E-03	1.367162E-03	1.366693E-03	1.371203E-03	1.357150E-03	1.357669E-03	1.362798E-03	1.367162E-03	1.366693E-03	1.371203E-03	1.357150E-03	1.357669E-03	1.362798E-03	1.367162E-03	1.366693E-03			
873.2	1.323299E-03	1.326695E-03	1.326695E-03	1.331669E-03	1.313175E-03	1.331917E-03	1.323299E-03	1.326695E-03	1.326695E-03	1.331669E-03	1.313175E-03	1.331917E-03	1.323299E-03	1.326695E-03	1.326695E-03	1.331669E-03	1.313175E-03	1.331917E-03	1.323299E-03	1.326695E-03	1.326695E-03	1.331669E-03	1.313175E-03			
996.3	1.205604E-03	1.201808E-03	1.201808E-03	1.203123E-03	1.205034E-03	1.214877E-03	1.205604E-03	1.201808E-03	1.201808E-03	1.203123E-03	1.205034E-03	1.214877E-03	1.205604E-03	1.201808E-03	1.201808E-03	1.203123E-03	1.205034E-03	1.214877E-03	1.205604E-03	1.201808E-03	1.201808E-03	1.203123E-03	1.205034E-03			
1004.7	1.193191E-03	1.199024E-03	1.199024E-03	1.188140E-03	1.193882E-03	1.195898E-03	1.193191E-03	1.199024E-03	1.199024E-03	1.188140E-03	1.193882E-03	1.195898E-03	1.193191E-03	1.199024E-03	1.199024E-03	1.188140E-03	1.193882E-03	1.195898E-03	1.193191E-03	1.199024E-03	1.199024E-03	1.188140E-03	1.193882E-03			
1037.8	1.182573E-03	1.163961E-03	1.163961E-03	1.176064E-03	1.186575E-03	1.202357E-03	1.182573E-03	1.163961E-03	1.163961E-03	1.176064E-03	1.186575E-03	1.202357E-03	1.182573E-03	1.163961E-03	1.163961E-03	1.176064E-03	1.186575E-03	1.202357E-03	1.182573E-03	1.163961E-03	1.163961E-03	1.176064E-03	1.186575E-03			
1238.3	1.024560E-03	1.021684E-03	1.021684E-03	1.013378E-03	1.016046E-03	1.024045E-03	1.024560E-03	1.021684E-03	1.021684E-03	1.013378E-03	1.016046E-03	1.024045E-03	1.024560E-03	1.021684E-03	1.021684E-03	1.013378E-03	1.016046E-03	1.024045E-03	1.024560E-03	1.021684E-03	1.021684E-03	1.013378E-03	1.016046E-03			
1274.5	9.974498E-04	9.962560E-04	9.962560E-04	9.986380E-04	9.958709E-04	9.970873E-04	9.974498E-04	9.962560E-04	9.962560E-04	9.986380E-04	9.958709E-04	9.970873E-04	9.974498E-04	9.962560E-04	9.962560E-04	9.986380E-04	9.958709E-04	9.970873E-04	9.974498E-04	9.962560E-04	9.962560E-04	9.986380E-04	9.958709E-04			
1771.3	7.472999E-04	7.618984E-04	7.618984E-04	7.639388E-04	7.561557E-04	7.790060E-04	7.472999E-04	7.618984E-04	7.618984E-04	7.639388E-04	7.561557E-04	7.790060E-04	7.472999E-04	7.618984E-04	7.618984E-04	7.639388E-04	7.561557E-04	7.790060E-04	7.472999E-04	7.618984E-04	7.618984E-04	7.639388E-04	7.561557E-04			
2598.5	5.519496E-04	5.520315E-04	5.520315E-04	5.509227E-04	5.452829E-04	5.521516E-04	5.519496E-04	5.520315E-04	5.520315E-04	5.509227E-04	5.452829E-04	5.521516E-04	5.519496E-04	5.520315E-04	5.520315E-04	5.509227E-04	5.452829E-04	5.521516E-04	5.519496E-04	5.520315E-04	5.520315E-04	5.509227E-04	5.452829E-04			

UNCERTAINTIES (95% CL) FROM INDIVIDUAL EFFICIENCY CALCULATIONS																										
GAMMA ENERGY	SPECTRUM NO. 1 (7-14-93)	2 (8-3-93)					3 (8-5-93)					4 (8-13-93)					5 (8-21-93)					6 (8-31-93)				
247.7	2.16%	2.03%	2.03%	2.09%	2.03%	1.92%	2.16%	2.03%	2.03%	2.09%	2.03%	1.92%	2.16%	2.03%	2.03%	2.09%	2.03%	1.92%	2.16%	2.03%	2.03%	2.09%	1.91%			
427.9	2.79%	2.65%	2.65%	2.72%	2.65%	2.53%	2.79%	2.65%	2.65%	2.72%	2.65%	2.53%	2.79%	2.65%	2.65%	2.72%	2.65%	2.53%	2.79%	2.65%	2.65%	2.72%	2.53%			
463.4	3.14%	2.91%	2.91%	3.01%	2.90%	2.70%	3.14%	2.91%	2.91%	3.01%	2.90%	2.70%	3.14%	2.91%	2.91%	3.01%	2.90%	2.70%	3.14%	2.91%	2.91%	3.01%	2.69%			
591.8	2.63%	2.42%	2.42%	2.52%	2.41%	2.24%	2.63%	2.42%	2.42%	2.52%	2.41%	2.24%	2.63%	2.42%	2.42%	2.52%	2.41%	2.24%	2.63%	2.42%	2.42%	2.52%	2.21%			
600.6	2.96%	2.76%	2.76%	2.86%	2.76%	2.58%	2.96%	2.76%	2.76%	2.86%	2.76%	2.58%	2.96%	2.76%	2.76%	2.86%	2.76%	2.58%	2.96%	2.76%	2.76%	2.86%	2.56%			
635.9	3.08%	2.81%	2.81%	2.95%	2.81%	2.59%	3.08%	2.81%	2.81%	2.95%	2.81%	2.59%	3.08%	2.81%	2.81%	2.95%	2.81%	2.59%	3.08%	2.81%	2.81%	2.95%	2.57%			
723.3	2.10%	1.98%	1.98%	2.04%	1.98%	1.87%	2.10%	1.98%	1.98%	2.04%	1.98%	1.87%	2.10%	1.98%	1.98%	2.04%	1.98%	1.87%	2.10%	1.98%	1.98%	2.04%	1.87%			
846.8	4.51%	4.74%	4.74%	4.76%	4.75%	4.93%	4.51%	4.74%	4.74%	4.76%	4.75%	4.93%	4.51%	4.74%	4.74%	4.76%	4.75%	4.93%	4.51%	4.74%	4.74%	4.76%	5.16%			
873.2	2.53%	2.37%	2.37%	2.45%	2.37%	2.22%	2.53%	2.37%	2.37%	2.45%	2.37%	2.22%	2.53%	2.37%	2.37%	2.45%	2.37%	2.22%	2.53%	2.37%	2.37%	2.45%	2.22%			
996.3	3.04%	2.86%	2.86%	2.94%	2.86%	2.68%	3.04%	2.86%	2.86%	2.94%	2.86%	2.68%	3.04%	2.86%	2.86%	2.94%	2.86%	2.68%	3.04%	2.86%	2.86%	2.94%	2.68%			
1004.7	5.82%	2.27%	2.27%	2.34%	2.28%	2.16%	5.82%	2.27%	2.27%	2.34%	2.28%	2.16%	5.82%	2.27%	2.27%	2.34%	2.28%	2.16%	5.82%	2.27%	2.27%	2.34%	2.15%			
1037.8	5.82%	6.00%	6.00%	5.99%	5.75%	6.45%	5.82%	6.00%	6.00%	5.99%	5.75%	6.45%	5.82%	6.00%	6.00%	5.99%	5.75%	6.45%	5.82%	6.00%	6.00%	5.99%	6.45%			
1238.3	5.50%	5.72%	5.72%	5.74%	5.68%	6.15%	5.50%	5.72%	5.72%	5.74%	5.68%	6.15%	5.50%	5.72%	5.72%	5.74%	5.68%	6.15%	5.50%	5.72%	5.72%	5.74%	6.15%			
1274.5	1.86%	1.76%	1.76%	1.81%	1.76%	1.66%	1.86%	1.76%	1.76%	1.81%	1.76%	1.66%	1.86%	1.76%	1.76%	1.81%	1.76%	1.66%	1.86%	1.76%	1.76%	1.81%	1.65%			
1771.3	6.21%	6.53%	6.53%	6.33%	6.02%	6.81%	6.21%	6.53%	6.53%	6.33%	6.02%	6.81%	6.21%	6.53%	6.53%	6.33%	6.02%	6.81%	6.21%	6.53%	6.53%	6.33%	6.81%			
2598.5	6.42%	6.55%	6.55%	6.54%	6.18%	7.05%	6.42%	6.55%	6.55%	6.54%	6.18%	7.05%	6.42%	6.55%	6.55%	6.54%	6.18%	7.05%	6.42%	6.55%	6.55%	6.54%	7.05%			

GAMMA ENERGY	AVERAGE EFFICIENCY	95% C.L. INTERVAL		% UNC OF AVG @ 95% C.L.	AVG % UNC FROM EFFS	95% C.L. INTERVAL	SUM OF % UNC (95% C.L.)
247.7	3.6731E-03	4.2368E-05	1.153%	2.026%	0.188%	3.367%	
427.9	2.3602E-03	2.9253E-05	1.239%	2.648%	0.196%	4.084%	
463.4	2.2269E-03	4.8933E-05	2.198%	2.892%	0.342%	5.432%	
591.8	1.7954E-03	3.9770E-05	2.215%	2.406%	0.314%	4.935%	
600.6	1.7876E-03	3.2057E-05	1.793%	2.746%	0.301%	4.840%	
635.9	1.7037E-03	2.9151E-05	1.711%	2.801%	0.389%	4.901%	
723.3	1.5318E-03	1.5446E-05	1.008%	1.975%	0.170%	3.154%	
846.8	1.3638E-03	1.0993E-05	0.806%	4.810%	0.426%	6.042%	
873.2	1.3241E-03	1.4532E-05	1.097%	2.363%	0.237%	3.698%	
996.3	1.2081E-03	1.3296E-05	1.101%	2.846%	0.268%	4.215%	
1004.7	1.1930E-03	8.5168E-06	0.714%	2.269%	0.204%	3.187%	
1037.8	1.1804E-03	2.6385E-05	2.235%	6.008%	0.480%	8.723%	
1238.3	1.0195E-03	9.0431E-06	0.887%	5.778%	0.432%	7.096%	
1274.5	9.9718E-04	1.9860E-06	0.199%	1.750%	0.159%	2.108%	
1771.3	7.6102E-04	2.0650E-05	2.714%	6.345%	0.511%	9.569%	
2598.5	5.4987E-04	5.9014E-06	1.073%	6.552%	0.558%	8.184%	

Efficiency Curves for Protons-R-US HPGe Detector

Notes on Appendix A-6.

This spreadsheet is an example of the template used to calculate the cross section measured for a single-product, proton-induced reaction in one of the target foils. The data needed to perform the calculation of the cross section (see Section III, equation 3) are entered in sections. A single format was chosen so that sections could be easily copied between the spreadsheets for a given bombardment, target, radionuclide, or spectrum. The sections include data from the bombardment, target weighing, and collection of the gamma ray spectrum, with decay-correction of the measured activity back to the end of the bombardment. Uncertainties for all reference and measured values are included (95% CL) where significant. These uncertainties are squared and summed and the square root of the sum taken to give the overall uncertainty associated with the measured cross section.

Appendix A-6. Example of Spreadsheet for Calculation of Radionuclide Production Cross Section.

INTERACTION CROSS-SECTION CALCULATION PER SCHNEIDER, SISTERTSON, ET AL.

CALCULATION OF CROSS-SECTION FOR $\text{Al-27(p,3pX3n)Na-22}$

COUNTS TAKEN AT SJSU
SPECTRUM COLLECTED ON 17-Jul-93

PROTON BOMBARDMENT DATA:

RUN NUMBER 1
RUN DATE= 19-Feb-93
PROTON BEAM ENERGY= 64.09 MeV
CURRENT COLLECTED AT FARADAY CUP= 70 uC $\pm$ 1.00%
NUMBER OF PROTONS= 4.3691E+14 protons
BEAM-ON TIME= 19:12:00
BEAM-OFF TIME= 19:38:00
IRRADIATION TIME= 00:26:00
IRRADIATION TIME (s)=t(0)= 1560 seconds
PROTON CURRENT=I(p)= 2.8007E+11 protons/second

TARGET DATA:

TARGET NUMBER AL-2
DIAMETER= 15.00 mm $\pm$ 0.467% @ 95% C.L.
THICKNESS= 0.055 mm
MASS= 0.022000 g $\pm$ 1.818%
MOL WEIGHT= 26.981538 g/mol
NO. ATOMS= 4.9103E+20
TARGET AREA= 1.76715 cm²
ATOMS/cm²= 2.7786E+20
*ADJUST FOR
FOR CAHN WEIGHTS*

HPGe GAMMA-RAY SPECTRUM DATA:

DISTANCE FROM DETECTOR 15.00 cm
PRODUCT PEAK ENERGY= 1274.5 keV
ABUNDANCE OF GAMMA= 0.9994 0.039%
DETECTOR EFFICIENCY @ PEAK 0.00099718
EFFICIENCY UNCERTAINTY (AT 95% C.L.)= $\pm$ 2.108%
COUNT START TIME= 23:08:08
COUNT DATE= 17-Jul-93
LIVE TIME= 11:08:08 +24:00:00
REAL TIME= 11:09:05 +24:00:00
LENGTH OF COUNT= 126545 seconds
PEAK AREA= 3083 counts (ADJUSTED FOR BACKGROUND)
1-s AREA UNC. FR. MCA= 4.549 %
UNCERTAINTY OF PEAK AREA AT 95% C.L.= $\pm$ 8.916%

TIME ELAPSED FROM END OF BOMBARDMENT TO COUNT:

DAYS FROM IRRADIATION TO COUNT= 147 days
TIME WAITED END BEAM TO COUNT= 1.145925926 decimal days
E.T. FROM ACTIVATION TO START COUNT= 1.2800E+07 seconds

NCRP 58 (2 ed.) HALF-LIFE Na-22 2.602 years $\pm$ 0.001
Na-22 LAMBDA= 0.2664 1/years
LAMBDA= 8.4416E-09 1/seconds
MEAN LIFE=T= 1.1846E+08 seconds
UNCERTAINTY AT 95% C.L. OF t(1/2)= $\pm$ 0.075%

CALCULATE CROSS SECTION:

g[t(0)]= 7.5937E+04
g[t(2)]= 9.3662E+02
f[t(1),t(2)]= 1.0435E+03

INTERACTION CROSS-SECTION= 2.6591E-26 cm²
2.6591E-02 barns
26.59 millibarns $\pm$ 9.4% @ 95% C.L.

Notes on Appendix A-7.

This spreadsheet was used to calculate the loss of proton beam energy in the target stacks. The modified Bethe-Bloch formula for stopping powers was used to obtain the change of energy that occurred within each target foil. This value was multiplied by the experimentally-determined density and the thickness of our target foils to give the proton energy at the downbeam surface of the individual targets. This exit energy was then used as the entrance energy for the next foil in the stack.

Appendix A-7.

Example of Spreadsheet for Calculation of Proton Beam Energy Losses in Target Stacks.

**CALCULATE ENERGY LOSS OF PROTONS IN MATERIALS
FOR STACKS CONTAINING MAGNESIUM**

FROM ATTIX P168

$$(dT/pdx) = 0.3071 \cdot (Z/A) \cdot (z^2/B^2) \cdot (13.8373 + \ln(B^2/(1-B^2))) - B^2 - \ln I$$

(MeV*cm²/g)

FROM ATTIX P169

$$\beta = \text{SQRT}(1 - (T/Moc^2 + 1)^{-2})$$

FOR PROTONS; Moc²= 938.28 MeV
z=1

RUN NO.	8 PROTON ENERGY=					67.5 MeV	RUN DATE	26-Mar-93	
TARGET	p=	DEPTH=	Z/A=	$\beta(i)=$	I=	dT/pdx=	dT=	E(EXIT)=	
Al-B	2.283	0.0055	0.4818	0.360167	166	9.14882	0.114877158	67.39	
Mg-1	1.787	0.0125	0.4937	0.359891	156	9.460739	0.211329258	67.17	
Mg-2	1.787	0.0125	0.4937	0.359382	156	9.485382	0.211879718	66.96	
Mg-3	1.787	0.0125	0.4937	0.358871	156	9.51024	0.212434985	66.75	
Al-14	2.283	0.0055	0.4818	0.358357	166	9.233894	0.115945389	66.63	

RUN NO.	11 PROTON ENERGY=					50 MeV		RUN DATE	02-Apr-93	
TARGET	p=	DEPTH=	Z/A=	$\beta(i)=$	I=	dT/pdx=	dT=	E(EXIT)=		
Al-R	2.283	0.0055	0.4818	0.314048	166	11.76984	0.147787994	49.85		
Mg-8	1.787	0.0125	0.4937	0.313619	156	12.18672	0.272220931	49.58		
Mg-9	1.787	0.0125	0.4937	0.312825	156	12.24367	0.273493006	49.31		
Mg-10	1.787	0.0125	0.4937	0.312025	156	12.3015	0.274784671	49.03		
Al-S	2.283	0.0055	0.4818	0.311219	166	11.96738	0.150268412	48.88		

RUN NO.	13 PROTON ENERGY=					42.5 MeV	RUN DATE	05-May-93	
TARGET	p=	DEPTH=	Z/A=	$\beta(i)=$	I=	dT/pdx=	dT=	E(EXIT)=	
Al-AC	2.283	0.0055	0.4818	0.291184	166	13.52582	0.169836911	42.33	
Mg-AA	1.787	0.0125	0.4937	0.290639	156	14.01926	0.313155188	42.02	
Mg-AB	1.787	0.0125	0.4937	0.289631	156	14.10924	0.315165132	41.70	
SiO2-8	2.320	0.0500	0.4995	0.288611	139.2	14.57778	1.691022919	40.01	
Al-AD	2.283	0.0055	0.4818	0.283063	166	14.24837	0.178909627	39.83	

RUN NO.	14 PROTON ENERGY=					60 MeV	RUN DATE	20-May-93	
TARGET	p=	DEPTH=	Z/A=	$\beta(i)=$	I=	dT/pdx=	dT=	E(EXIT)=	
Al-H	2.283	0.0055	0.4818	0.341459	166	10.09116	0.126709655	59.87	
Mg-7	1.787	0.0125	0.4937	0.341131	156	10.43967	0.233196149	59.64	
Mg-4	1.787	0.0125	0.4937	0.340525	156	10.47387	0.23396006	59.41	
Mg-5	1.787	0.0125	0.4937	0.339915	156	10.50844	0.234732296	59.17	
Si-A	2.320	0.0500	0.4985	0.339915	173	10.47356	1.214933051	58.19	
Al-I	2.283	0.0055	0.4818	0.336726	166	10.35348	0.130003469	58.06	

RUN NO.	17 PROTON ENERGY=					30 MeV	RUN DATE	21-Jun-93	
TARGET	p=	DEPTH=	Z/A=	$\beta(i)=$	I=	dT/pdx=	dT=	E(EXIT)=	
Al-AG	2.283	0.0055	0.4818	0.246993	166	18.31051	0.229915863	29.77	
Mg-AC	1.787	0.0125	0.4937	0.246088	156	19.04544	0.425427512	29.34	
SiO2-15	2.320	0.0500	0.4995	0.244404	139.2	19.80709	2.297622142	27.05	
Al-AH	2.283	0.0055	0.4818	0.235057	166	20.05791	0.251857099	26.80	