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Production of ^{7}Be, ^{22}Na, and ^{28}Mg from Mg, Al, and SiO$_2$ by protons between 82 and 800 MeV*

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Cross sections for the production of ^{7}Be, ^{22}Na, and ^{28}Mg from Mg, Al, and SiO$_2$ by protons in the 80 to 800 MeV energy range have been determined by direct foil γ-ray spectrometry. These nuclides are of interest in several fields of astrophysics, cosmochemistry, and nuclear science. The values obtained are compared with other experimental values and with values predicted using empirical formulas and Monte Carlo methods. A mathematical form for the Al$(p, X)^{22}$Na excitation function above 100 MeV is proposed.

[NUCLEAR REACTIONS Natural Mg, Al, SiO$_2(p,X)^{7}$Be, ^{22}Na, ^{28}Mg, E =82–800 MeV; measured $\sigma(E)$.]

INTRODUCTION

The interest in the spallation of light elements by protons has grown considerably in recent years. Accurate knowledge of excitation functions for such nuclear reactions is important for applications in several fields: (1) in astrophysics, for interpretation of data on the composition of cosmic rays (cf. Raisbeck and Yiou[1]); (2) in planetary science, for the analysis of radioactivities induced by cosmic rays and solar protons (cf. Reedy and Arnold[2]); (3) in the design of shielding for particle accelerators, to estimate the production of radioactive isotopes in the surroundings due to energetic particle leakage (cf. Gilbert, Shaw, and Fortune[3]); (4) in proton beam monitoring and as activation detectors (cf. Tobailem *et al.*[4]).

Although several excitation functions for nuclear reactions have been sufficiently well studied to permit use as proton beam monitors (e.g., ^{11}C from ^{12}C, ^{24}Na from ^{27}Al, cf. Cumming[5]), the half-lives of these products are too short for monitoring the long irradiations required to produce in convenient quantities certain other nuclides of interest (e.g., 1.7×10^{6} yr ^{10}Be, 7.4×10^{5} yr ^{26}Al). Among the longer-lived radioactive species, 53.0 day ^{7}Be and 2.60 yr ^{22}Na are attractive as beam monitors. The production of the latter nuclide from Al has been studied quite extensively (cf. Cumming[5]), however, the published data on the excitation function in the 50–500 MeV range are marked by some discordant values. Production of ^{7}Be and of ^{22}Na from other targets has been less extensively studied and the excitation functions are also somewhat unclear over this energy range. Therefore, it seemed worthwhile to investigate these reactions using high-specificity γ-ray measurement techniques. This work reports several cross section measurements for the production of ^{7}Be, ^{22}Na, and ^{28}Mg from Mg, Al, and SiO$_2$ by protons in the 82 to 800 MeV energy range. A mathematical form for the Al$(p,X)^{22}$Na excitation function above 100 MeV is proposed.

Rather recent studies of some of the nuclear reactions of interest here have been carried out at lower[6] and at higher[7] proton energies. Thus, it seems appropriate to present our own values in the full context of the previous work, and as complete a collection of published cross section values for each reaction as available to us is provided in each of the figures.

The present experimental results are also compared with cross sections predicted via empirical formulas and via Monte Carlo simulation of intranuclear processes.

EXPERIMENTAL

Most of the data reported in the present work were obtained from targets irradiated with the internal proton beam of The University of Chicago synchrocyclotron. These bombardments were made in two series separated in time by about five years. In addition, the following irradiations were performed at the Los Alamos Meson Physics Facility: two at 800 MeV in the Nuclear Chemistry Target Area (line B) and one at 400 MeV in line A. The individual targets utilized were: 19.9–22.5 mg cm^{-2} Mg [$>$99.8% pure; (Na) $<$50 ppm; (Al) $<$30 ppm; (Si) $<$50 ppm]; 5.29–7.27 mg cm^{-2} Al [$>$99.9% pure; (Na+Mg) $<$500 ppm; (Si) $<$500 ppm]; 209–237 mg cm^{-2} SiO_2 [$>$99.9999% pure; (B) $<$0.01 ppm; (Na) $<$0.1 ppm; (Mg) $<$0.1 ppm; (Al) $<$0.1 ppm]. The Mg and SiO_2 targets were irradiated individually; the Al targets were nearly all run as portions of target stacks involving from 45 to 1000 mg cm^{-2} of other (much higher Z) materials. In general, only one target was run at a given energy except for Al, for which there was some replication for intercalibration purposes. Irradiation durations ranged from five minutes to one hour, with typical integrated proton intensities of the order of 10^{16}. Beam intensities were derived by measurement of the production of the internal monitor nuclide ^{24}Na in each of the targets. The monitor cross section values employed are given in Table I. The proton energies for the synchrocyclotron runs were determined by the radial position of the target, with small corrections for radial oscillations[8]; these oscillations also lead to the indicated spread in the incident energy.

All radioactivity measurements were made by "direct foil counting." Some early radioactivity measurements (all on Al targets) were made with a 7.6 cm × 7.6 cm NaI(Tl) multichannel analyzer system. The rest of the measurements (including about one-third of the Al runs) were made with two different 42 cm^3 Ge(Li) multichannel analyzer systems. All systems were calibrated with NBS-standard samples (e.g., ^{22}Na). Directly comparable replicate ^{22}Na production cross section results obtained with the three detection systems agree to

TABLE I. Production cross sections for ^{7}Be, ^{22}Na, and ^{28}Mg from Mg, Al, and SiO_2 targets.

Target	Proton energy (MeV)	Assumed monitor value (mb) ^{24}Na[b]	Observed cross sections[a] (mb)		
			^{22}Na[c]	^{28}Mg[d]	^{7}Be[c]
$_{12}$Mg	119± 10	5.1	46	···	1.8
	219± 14	4.3	32	···	2.3
	290± 17	4.8	32	···	2.9
	435± 24	5.2	31	···	4.0
$_{13}$Al	82± 8	10.0	18.3	···	···
	111± 10	10.1	17.4 (3)	···	···
	118± 10	10.1	17.4	≤0.0002	0.8
	187± 13	9.3	14.7 (2)	···	···
	218± 14	9.5	13.5	≤0.0003	1.3
	283± 17	10.0	14.8	···	···
	384± 21	10.4	13.5	≤0.0003	2.2
	400± 5	10.5	12.2	···	2.0
	416± 21	10.5	14.1 (2)	···	···
	434± 24	10.6	14.1 (2)	≤0.0004	2.5
	800± 5	10.5	15.0 (2)	≤0.02	6.4 (2)
SiO_2	121± 10	3.0	17.4	0.81	16[e]
	221± 14	3.4	16.2	0.92	18[e]
	295± 17	3.6	16.6	1.29	17[e]
	435± 24	4.2	18.4	1.58	23[e]

[a] Standard deviations are estimated to be ± 10% for ^{22}Na and ^{7}Be and ± 15% for ^{28}Mg from all targets, including monitor cross section precision.

[b] σ_{24} values for Al are from Cumming (Ref. 5); other σ_{24} are from Korteling and Caretto (Refs. 46 and 67) except for Si at 295 MeV, which is based on smooth interpolation between their 200 and 400 MeV values, ignoring their 300 MeV value. σ_{24} from Mg at 400 MeV is from Korteling and Caretto (Ref. 45).

[c] Number of replicates is given in parentheses if other than one.

[d] For Al targets, the upper limits for ^{28}Mg are based on observed net + 3σ. For the SiO_2 targets, the cross sections are for the production from ^{30}Si.

[e] ^{7}Be is produced both from O and Si in an SiO_2 target. The cross section listed is based on 3 atoms/mol.

TABLE II. Decay properties of products.

			Nuclide				
	^{7}Be	^{22}Na	^{24}Na	^{28}Mg + ^{28}Al			
γ energies (MeV)	0.478	1.275	1.369	0.40	0.98	1.35	1.780
Branching ratio (%)	10.3	NBS Std.	100	31	29	70	100
Half-life (days)	53.0	949	0.625		0.888 and 0.001 60		

within an average of ± 5%. The γ rays sought and branching ratios employed are presented in Table II. Sample decay was generally followed for about one year to observe the 53 day and 2.60 year half-lives of ^{7}Be and of ^{22}Na, respectively.

RESULTS AND DISCUSSION

The cross sections obtained in this work are presented in Table I. These observed cross section values may reflect several processes in addition to the nuclear reaction of interest. Such processes include: (a) formation of the product of interest by secondary particles (i.e., those emitted in reactions induced by the primary projectiles); (b) formation of the product of interest from impurities of the target material; (c) loss of product nuclei formed with sufficient kinetic energy to escape from the target (recoil losses).

Production by secondaries is clearly related to target thickness, primary projectile energy and reaction type. Among those important in this work, the reaction most sensitive to secondaries is ^{27}Al$(n, \alpha)^{24}$Na, which has a maximum cross section value of about 0.1 b near 14 MeV. Previous workers[9-12] have reported contributions to ^{24}Na production in targets of comparable thickness irradiated with protons of comparable energy, well within the uncertainties quoted for our results [a maximum effect of about 10% reported for a few GeV protons on very thick (several g/cm^2) targets[12]]. Therefore, we have not applied corrections to our results for such effects.

The nominal abundances of various contaminants in our targets are listed above and the production of any of the nuclides of interest from such contaminants is estimated to be less than 1% in all cases. [The undetected presence of an oxide layer of normal thickness on the metal foils irradiated would have perturbed the ^{7}Be results negligibly since the cross section for production of this nuclide from O is within an order of magnitude of those from the metals of interest over the proton energy range explored in this work (Figs. 1–4).]

Of the product nuclides studied in this work, recoil losses would be expected to effect ^{7}Be to the largest extent due to its longer range for a given kinetic energy. Comparison of the ^{7}Be cross section from Al at 400 MeV, where a stack of Al foils was irradiated, with results at 384 and 434 MeV, where mixed element targets were irradiated, in-

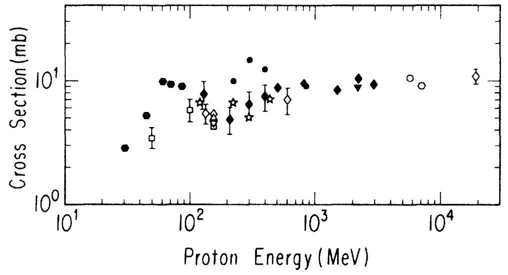

FIG. 1. Production of ^{7}Be from O by protons. ☆, this work. ◆, Ref. 13. △, Ref. 14. ○, Ref. 15. ▼, Ref. 16. ◇, Refs. 17 and 18. ∇, Ref. 19. □, Ref. 20. •, Ref. 21. O, Ref. 22. ●, Ref. 23.

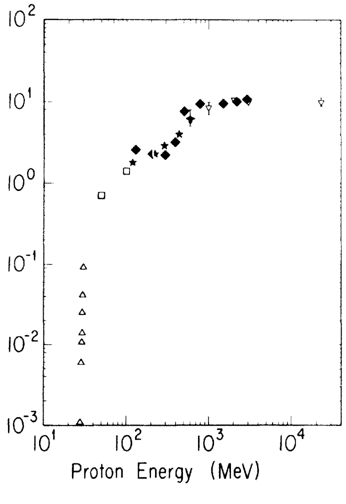

FIG. 2. Production of ^{7}Be from Mg by protons. ★, this work. □, Ref. 20. ◆, Ref. 13. △, Ref. 24. ▼, Ref. 25. ◆, Ref. 1. ∇, Ref. 7.

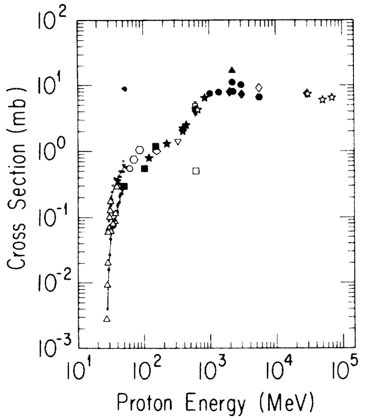

FIG. 3. Production of ^{7}Be from Al by protons. ★, this work. ■, Ref. 20 at 50, 100, and 150 MeV; Ref. 1 at 600 MeV. ●-●-●, Ref. 26. ○, Ref. 27. ∇, Ref. 28. □, Ref. 29. ☆, Ref. 30 at 30, 50, and 70 GeV; Ref. 31 at 630 MeV. ⬢, Ref. 22. ♦, Ref. 32. ◇, Ref. 33. ▲, Ref. 34. ●, Ref. 35. ○, Ref. 21. ◇, Ref. 36. ▼, Ref. 25. △, Refs. 37 and 24. ♦, Ref. 7. -o-o-o- Ref. 38.

dicates that the net recoil loss of ^{7}Be was negligible within the precision of the experiments.

COMPARISON WITH OTHER EXPERIMENTAL CROSS SECTIONS

Our production cross sections are presented in Figs. 1–8 along with values from the literature.[1,7,12–54] Where possible, literature values have been corrected to conform to Cumming's[5] standard monitor cross section values. In general, values from the literature which are either based on or corrected to Cumming or are based on current measuring devices have been indicated with closed symbols. Other values from the literature have been indicated with open symbols.

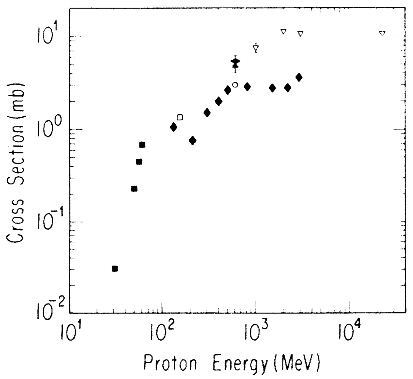

FIG. 4. Production of ^{7}Be from Si by protons. □, Ref. 20. ♦, Ref. 13. ▲, Ref. 25. ■, Ref. 11. ♦, Refs. 1 and 39. ○, Ref. 40. ∇, Ref. 7.

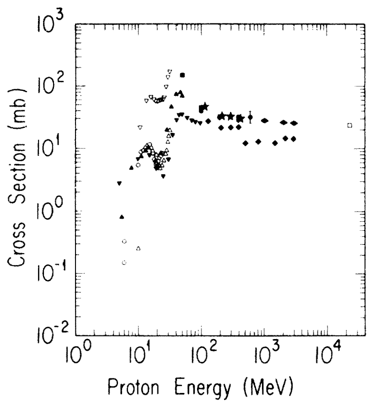

FIG. 5. Production of ^{22}Na from Mg by protons. ★, this work. ∇, Ref. 41. △, Ref. 42. ■, Ref. 20 at 50 and 100 MeV; Ref. 1 at 600 MeV. ○, Ref. 43. ▲, Ref. 44. ●, Refs. 45 and 46. ♦, Ref. 13. ▼, Ref. 47. ⬢, Refs. 25 and 1. ♦, Ref. 7. □, Ref. 7.

Agreement of our values with the pattern of other results is generally good, although there is a great deal of scatter to the data for most of the reactions of interest. For both Mg and Al targets the production of ^{7}Be more than doubles as the projectile energy is increased over the range studied, while for all three target elements the production of ^{22}Na is reasonably constant. Both of these observations are quite consistent with expectations.

The usefulness of Al$(p,X)^{22}$Na as a beam monitor is clearly subject to proper interpretation of the data shown in Fig. 6. At energies below about 600

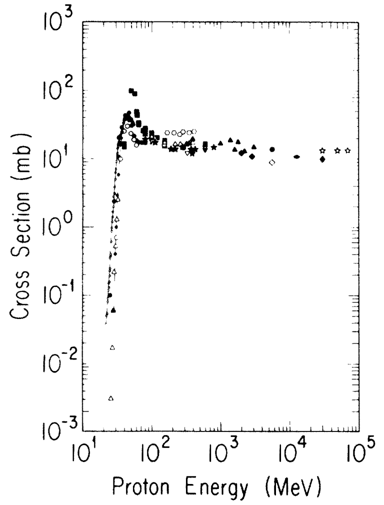

FIG. 6. Production of ^{22}Na from Al by protons. ★, this work. △, Ref. 42. ●-●-●, Ref. 26. ■, Ref. 48. ●, Ref. 49. ○, Ref. 27. ▲, Ref. 50. ▼, Ref. 51 at 150 MeV; Ref. 25 at 600 MeV. ∇, Ref. 28. □, Ref. 29. ☆, Ref. 30. ⬢, Ref. 22. ♦, Refs. 32 and 52. ◇, Ref. 33. ♦, Ref. 12. ○, Ref. 53. o-o-o, Ref. 38.

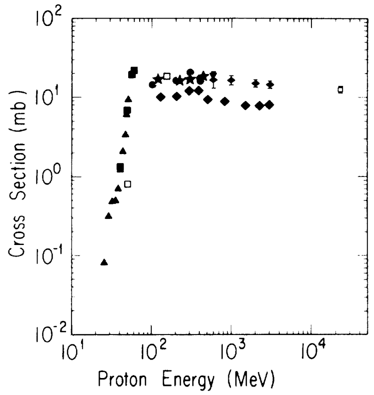

FIG. 7. Production of ^{22}Na from Si by protons. ★, this work. □, Ref. 20 at 50 and 153 MeV; Ref. 7 at 23 000 MeV. ▲, Ref. 44. ●, Refs. 45 and 46. ◆, Ref. 13; ■, Ref. 11. ▼, Ref. 25. ◆, Refs. 1 and 7 at 600, 1000, 2000, and 3000 MeV; Ref. 39 at 600 MeV only.

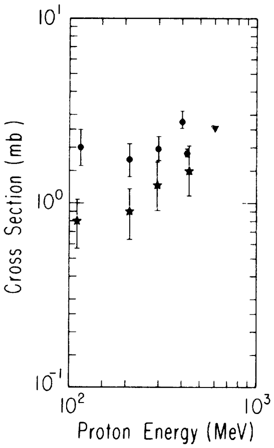

FIG. 8. Production of ^{28}Mg from ^{30}Si by protons. ★, this work. ●, Ref. 54. ▼, Ref. 25.

MeV there is a very large uncertainty as to the level and shape of the excitation function; such difficulties have been noted by Cumming,[5] who did not attempt to deduce a standard curve for this reaction, and by Tobailem *et al.*[4] who did present such a curve, based on selected values. We have chosen to fit all of the data previously published in refereed literature (and corrected to Cumming[5] where necessary, as mentioned above) for proton energies above 200 MeV (a total of 22 values) along with our own data (combined to give single values at 0.197, 0.283, 0.404, and 0.800 GeV) to a function of the form $\sigma(\text{mb}) = b + (m/T_p^{0.5})$, where T_p is in GeV. Values of $m = (1.74 \pm 0.75)$ mb GeV$^{0.5}$ and $b = (12.5 \pm 1.8)$ mb were obtained, where the uncertainties are the usual 1σ values. Such a function fits all of our ^{22}Na from Al data reported in this work with a root-mean-square deviation of less than 10% despite the fact that our own data constituted less than 20% of the input data. This function, therefore, appears to provide a useful representation of the Al$(p,X)^{22}$Na excitation function between 0.1 and 10 GeV. Beyond 10 GeV the scatter of the limited data indicates cautious application.

While such an approach for the production of ^{22}Na from Mg and Si would be equally useful in estimating those excitation functions, the quantity and quality of data presently available do not seem to warrant such an undertaking.

A similar argument appears valid for ^{7}Be production from Mg and Si. However, Tobailem *et al.*[4] have provided a ^{7}Be standard excitation function for Al as a target, and that curve is in good agreement with our experimental values between about 100 and 800 MeV (rms deviation less than 10%).

While SiO$_2$ is a target of substantial geochemical interest, the production of ^{7}Be from the individual elements is of more interest in the study of cosmic rays themselves. The cross section for production of ^{7}Be from Si is expected to be sufficiently small, between 100 and 400 MeV, that we may use essentially any reasonable estimate thereof to deduce a cross section for the production of ^{7}Be from oxygen. Using cross sections for ^{7}Be production from Si (column 3, Table III) obtained by smooth interpolation (using the shapes of the excitation functions for ^{7}Be production from Mg and Al as guides) between the lower energy data of Sheffey *et al.*[11] and the recent data of Raisbeck and Yiou,[1,7] Weigel *et al.*,[39] and Dropesky and O'Brien,[25] we have obtained the values for ^{7}Be production from oxygen shown in column 4 of Table III and in Fig. 1. Standard deviations for these calculated cross sections for production of ^{7}Be from oxygen are estimated to be ±20%. Although the scatter amongst values from the literature is large, our values appear (except for that at 295 MeV) to lie close to the best fit through the full array.

The case of ^{28}Mg production from ^{30}Si is of in-

TABLE III. Calculated cross sections for production of ^{7}Be from oxygen.

Proton energy (MeV)	Observed cross section[a] SiO$_2$→^{7}Be (mb)	Assumed cross section[b] Si→^{7}Be (mb)	Estimated cross section[c] O→^{7}Be (mb)
121	16	1.6	6.5
221	18	2.6	6.5
295	17	3.3	5.0
435	23	4.5	7.0

[a] Taken from Table I, column 6.

[b] Values obtained by interpolation (see text).

[c] The standard deviations for these values are estimated to be ± 20%.

terest in that only one other study had been previously reported for this reaction and energy range. While relative uncertainties are rather large in both studies; the cross sections reported by Morrison and Caretto[54] are considerably higher and tend to be roughly independent of proton energy while our data suggest increasing cross section with energy. Reactions of this type (p,xp) generally have been found to exhibit an increase of cross section with increased energy over this energy range as was found in this work. This increase is reflected in both experimental (Morrison and Caretto[54] for a variety of targets; Dostrovsky, Gauvin, and Lefort[55] for light element targets) and calculated results (Harp[56] for Mg, Al, and Si targets). The value of Dropesky *et al.*[25] at 600

TABLE IV. Comparison of calculated and experimental cross section values.

				Ratio $\sigma_{\mathrm{exp}}/\sigma_{\mathrm{calc}}$ [a]						
Target[b]	Product	Proton energy (MeV)	Experimental cross section[c] (mb)	Rudstam[d]	Chackett and Chackett	Audouze *et al.*	Silberberg and Tsao[e]	Bertini[f]	VEGAS-DFF[f]	Other work
Mg	^{7}Be	150	2.0	85	57	0.46	0.99	···	≥100[g]	2[h]
		300	3.0	21	14	···	1.2	···	···	···
		400	3.7	13	8.6	···	1.2	···	≥185[g]	···
Al	^{7}Be	150	1.0	125	96	0.17	0.79	≥5[g]	≥200[g]	10[h]
		300	1.8	23	17	···	1.0	≥9[g]	≥360[g]	···
		400	2.2	13	10	···	1.0	10	≥110[g]	···
		800	6.4	12	8.9	···	1.5	···	≥320[g]	···
Mg	^{22}Na	150	38	0.72	0.39	2.2	1.1	···	0.77	···
		300	32	1.4	0.73	···	1.1	···	···	···
		400	31	1.5	0.79	···	1.3	···	0.79	···
Al	^{22}Na	80	18.3	1.4	0.94	···	1.1	0.63	0.64	···
		150	15.6	0.90	0.59	1.2	0.91	0.67	0.63	···
		300	13.9	1.1	0.71	···	0.85	0.54	0.64	···
		400	13.8	1.0	0.68	···	0.87	0.69	···	0.27[i]
		800	15.0	1.2	0.78	···	1.1	1.0	0.81	···
Si	^{22}Na	150	17	1.5	0.77	1.6	0.96	···	0.70	···
		300	17	1.7	0.87	···	0.89	···	···	···
		400	18	1.7	0.85	···	1.06	···	0.86	0.59[i]
Mg	^{24}Na	150	4.8	0.033	0.072	0.27	0.97	···	0.81	···
		300	4.9	0.11	0.22	···	1.0	···	···	···
		400	5.3	0.14	0.29	···	1.1	···	0.87	···
Al	^{24}Na	80	10.0	0.17	0.28	···	0.86	1.2	0.64	···
		150	9.4	0.20	0.32	2.5	0.80	2.5	0.82	···
		300	10.0	0.40	0.66	···	0.91	2.2	0.93	···
		400	10.5	0.45	0.73	···	1.0	2.2	···	≡1.0[i]
		800	10.6	0.56	0.92	···	1.1	2.5	0.83	···
Si	^{24}Na	150	3.2	0.10	0.24	2.9	0.58	···	0.55	···
		300	3.8	0.20	0.46	···	0.61	···	···	···
		400	4.2	0.22	0.51	···	0.71	···	0.71	1.2[i]
^{30}Si	^{28}Mg	150	0.88	0.26	0.38	···	0.45	···	···	···
		300	1.21	0.81	1.2	···	0.44	···	···	···
		400	1.51	1.1	1.7	···	0.49	···	···	···

[a] Calculated values include precursors (see text).

[b] Natural isotopic composition.

[c] Interpolated values based on this work except for ^{24}Na values which are referenced in Table I.

[d] Production of ^{7}Be from Mg and Al is not within the limits of applicability of this method (Rudstam, Ref. 57).

[e] This method is limited to projectile energies of 100 MeV or greater [Silberberg and Tsao (Ref. 60)].

[f] Evaporation of particles heavier than ^{4}He not considered in these methods.

[g] No nuclei of this product reported at this energy; therefore 1σ upper limits were used.

[h] Reference 55.

[i] Reference 45.

TABLE V. Summary comparison of observed vs calculated cross sections.

		Mean value for $\log_{10}(\sigma_{obs}/\sigma_{calc}) \pm S$ [a]					
Products	Targets	Rudstam	Chackett and Chackett	Audouze *et al.*	Silberberg and Tsao	Bertini	VEGAS-DFF
$^{22}Na + ^{24}Na$	Mg+Al+Si	−0.34 ± 0.10	−0.30 ± 0.06	0.15 ± 0.16	−0.030 ± 0.019	b	−0.129 ± 0.016
$^{22}Na + ^{24}Na$	Al	−0.22 ± 0.10	−0.21 ± 0.06	0.24 ± 0.16	−0.025 ± 0.017	0.076 ± 0.086	−0.134 ± 0.024
^{7}Be	Mg+Al	1.44 ± 0.16 [c]	1.29 ± 0.16	−0.55 ± 0.22	0.032 ± 0.033	0.87 ± 0.10 [d]	2.26 ± 0.08 [d]

[a] $S \equiv \{[\sum_{i=1}^{n} (\log_{10} Q_i - \overline{\log_{10} Q_i})]/[(n)(n-1)]\}^{1/2}$.

[b] Only Al targets among those of interest here were considered in this study.

[c] This method is not applicable to ^{7}Be production.

[d] Except for Bertini's value at 400 MeV on Al, no ^{7}Be nuclei were observed (see footnote g of Table IV).

MeV would represent a reasonable extrapolation for either set of lower energy results. It should be noted that Morrison and Caretto[54] made radioactivity measurements with Geiger-Müller and β-γ coincidence systems which necessitated certain scattering and absorption corrections in addition to uncertainties common to both studies.

COMPARISON WITH CALCULATED CROSS SECTIONS

It is also of interest to consider the agreement of our experimental values with cross section values calculated via various methods reported in the literature. The two general approaches which have been taken are (1) empirical fitting of observed cross sections to formulas using various functions of projectile energy and of target and product A and Z with four or more fitting parameters and (2) detailed consideration of intranuclear collision and deexcitation processes via Monte Carlo methods.

The empirical methods have varied in their emphases while following the pattern established by Rudstam. Calculations via four such methods (Rudstam;[57] Chackett and Chackett;[58] Audouze, Epherre, and Reeves;[59] Silberberg and Tsao[60]) have been performed for the reactions of interest. Cross sections for all reactions of interest here could not be calculated via the Audouze *et al.*[59] method because the relevant constants are not available for some of the reactions and energies of interest. In Table IV are presented values for the ratio of the experimental cross section (σ_{exp}) to the calculated cross section (σ_{calc}) for each reaction of interest at 150, 300, 400, and 800 MeV. All calculated values include contributions from all precursors consistent with a measurement one day after irradiation, conditions similar to those under which our experimental values were obtained. The pattern of results for production of ^{22}Na and of ^{24}Na from Mg, Al, and Si suggests that the increased attention to N/Z provided by Chackett and Chackett vs Rudstam does provide better agreement for cases in which this ratio varies considerably between product and target, but at the expense of worse agreement in cases where there is no great variation in this ratio. Thus, there is no significant overall difference between results via the two methods for the cases studied here. The method of Rudstam is, strictly speaking, not applicable to either large ΔA or very simple (e.g., *p, pn*) reactions; therefore the results for production of ^{7}Be from all targets would not be expected to provide good agreement. Similar limitations apparently apply to the treatment of Chackett and Chackett. This poor agreement is presumably due to the failure of these "spallation" calculations to include the enhancement in yields of light products via formation directly by evaporation or knockout. The considerably more elaborate method of Silberberg and Tsao (employing about a dozen fitting parameters for targets below $Z = 30$) does provide the best agreement for all cases except ^{28}Mg from ^{30}Si, where their constants were based on the experimental work of Morrison and Caretto[54] discussed above.

The following results of Monte Carlo calculations were available to us: (1) published results of Bertini[61]; (2) unpublished results of Friedlander and co-workers (discussed in Barashenkov *et al.*[62]) for Al at 150 and 300 MeV; (3) special calculations by Harp,[56] using the VEGAS[63]-DFF[64] programs for all other combinations under the heading VEGAS-DFF. A number of isolated values of interest were also available in the literature.[45,55] In columns 8, 9, and 10 of Table IV, the ratio $\sigma_{exp}/\sigma_{calc}$ is presented for the cases of interest for which σ_{calc} was available via Monte Carlo methods.

The two principal Monte Carlo calculations provide poor agreement between calculated and observed values for the production of ^{7}Be from Al due to failure to include evaporation of particles beyond ^{4}He. When evaporation of ^{7}Be is included, as in Dostrovsky *et al.*[55] and Lafleur, Porile, and

Yaffe,[21] somewhat better agreement is obtained.

Although the two Monte Carlo methods are about equally good at fitting the experimental data for production of ^{22}Na from Al, the results of Bertini for production of ^{24}Na from Al are about a factor of 2 lower than the experimental values. Such a deficiency in the calculated ^{24}Na production has also recently been reported for 0.5–3.0 GeV protons on Al by Bertini.[65]

A summary of the comparison of our experimental values with the calculated values is presented in Table V. The method of Rudstam tends to give cross section estimates higher, on average, than the experimental values for ^{24}Na and lower for ^{22}Na. The latter tendency was true of the generally neutron deficient products of proton irradiations of Cu over this same energy range previously reported by Heydegger, Garrett, and Van-Ginneken.[66] The tendency in VEGAS - DFF to overestimate, on average, the cross sections for products lying near stability was also noted for copper targets irradiated by protons from 82–416 MeV.[66] Nevertheless, for the production of ^{22}Na and ^{24}Na from the limited range of target-projectile energies considered in this work, VEGAS-DFF does provide good agreement with our experimental values. However, the best overall agreement is clearly provided by the method of Silberberg and Tsao when all target-product-projectile energy combinations are considered.

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