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Nuclear reactions of silver with 300-GeV protons*

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The interaction of silver with 300-GeV protons was studied and compared with that of 11.5-GeV protons. Cross section ratios, $\sigma_{300}/\sigma_{11.5}$, were determined for 74 nuclides ranging from ^{7}Be to $^{106}Ag^{m}$. The weighted average value of $\sigma_{300}/\sigma_{11.5}$ is 1.01 ± 0.10. A detailed examination of the dependence of the ratios on product A and N/Z reveals that the only difference occurs in the $A \sim 20-30$ mass region, where a $17 \pm 5\%$ increase in cross sections is observed at 300 GeV.

[NUCLEAR REACTIONS Ag + 300-GeV protons; measured σ for formation of 74 nuclides ranging from ^{7}Be to $^{106}Ag^{m}$; compared with corresponding σ at 11.5 GeV.]

I. INTRODUCTION

The recent availability of 300-GeV proton beams at the National Accelerator Laboratory (NAL) makes it of interest to extend the study of the interaction of high-energy protons with complex nuclei into this new energy range. The results of various studies of the interaction of 300-Gev protons with vanadium and cobalt[1] as well as uranium[2,3] have been published to date. We report here the results of a study of the nuclear reactions of silver with 300-GeV protons. In order to determine whether there are any significant changes with bombarding energy we have performed a comparative study at 11.5 GeV. The results of this work are presented in an accompanying report,[4] hereafter referred to as I. Both studies were performed by use of the same techniques and instrumentation so that an accurate comparison is possible. A preliminary report of some of the present results has been published.[5]

II. EXPERIMENTAL

Targets were irradiated in external proton beams at either the neutrino or meson halls at NAL. Seven irradiations ranging in duration from 7 min to 10 h were performed. The target stack consisted of three aluminum and three silver foils as described in further detail in I. In the first two irradiations (in the neutrino hall) additional target stacks were located just outside the beam line in order to check for scattered protons or secondary particles originating upstream from the target. No significant activity was found in these stacks. In the remaining irradiations, performed at the meson hall, a small piece of the target foil, located at least 1 cm away from the $2 \times 0.1\text{-cm}^2$ beam spot was assayed. Once again no significant activity was found indicating that the proton beam had not undergone any significant scattering upstream from the target position.

Following irradiation the target foil was directly assayed with a calibrated Ge(Li) γ-ray spectrometer. Measurements on short-lived nuclides were performed at NAL and commenced approximately 15 min after end of bombardment. The NAL system consisted of a detector with an efficiency of 10% (relative to NaI) and a resolution of 1.9 keV (at 1332.5 keV). The detector was connected to a 4096-channel analyzer equipped with magnetic tape readout. Measurements on products having half-lives longer than 4 h were performed at Purdue. Assay commenced from 3 to 12 h after bombardment, depending on the half-lives of interest, and continued for as long as 1 yr. The Purdue detection system is fully described in I. The various samples were positioned from 2.5 to 10 cm away from the face of these detectors. It was established that under these conditions corrections due to summing effects could be neglected. The aluminum monitor foils were also assayed with these same Ge(Li) detectors in order to determine the disintegration rate of ^{24}Na.

The γ-ray spectra were analyzed with the BRUTAL-FRANTIC[6,7] and CLSQ[8] codes in order to obtain formation cross sections. The details of this procedure, including various checks on the accuracy of the method, are described in I. The relevant data on half-lives, γ-ray energies, and abundances, as well as various other pertinent details are summarized in Table I of I. In addition to the nuclides listed in that table results were also obtained for ^{83}Sr and ^{88}Nb. The 381.5-keV and the 1053- and 1083-keV γ rays emitted, respectively, in the decay of these nuclides were

TABLE I. Product cross sections from bombardment of silver with 300-GeV protons and $\sigma_{300}/\sigma_{11.5}$ ratios.

Nuclide	Type of yield	σ_{300} (mb)	No. of det.	$\sigma_{300}/\sigma_{11.5}$	Nuclide	Type of yield	σ_{300} (mb)	No. of det.	$\sigma_{300}/\sigma_{11.5}$
^{7}Be	C	13.55 ± 0.03	2	0.95 ± 0.07	^{84}Rb	I	1.28 ± 0.03	2	0.98 ± 0.03
^{22}Na	C	1.9 ± 0.1	2	1.19 ± 0.05	^{84}Rb^{m}	I	1.03 ± 0.03	2	1.16 ± 0.04
^{24}Na	C	4.7 ± 0.1	4	1.20 ± 0.12	^{82}Sr	C	7.2 ± 0.8	2	1.01 ± 0.13
^{28}Mg	C	0.64 ± 0.05	5	1.07 ± 0.09	^{83}Sr	C	···	2	0.97 ± 0.32
^{38}Cl	I	1.2 ± 0.1	2	1.03 ± 0.04	^{84}Y	I	5.1 ± 0.3	2	1.13 ± 0.07
^{41}Ar	C	0.64 ± 0.03	2	0.98 ± 0.06	^{86}Y^{m}	I	6.9 ± 0.2	2	1.19 ± 0.05
^{44}Sc	I	1.4 ± 0.1	3	0.99 ± 0.09	^{87}Y	C	15.4 ± 1.4	4	0.88 ± 0.05
^{44}Sc^{m}	I	2.4 ± 0.3	2	1.25 ± 0.09	^{87}Y^{m}	C	15.0 ± 0.5	4	1.00 ± 0.09
^{46}Sc	I	2.9 ± 0.3	2	0.97 ± 0.08	^{88}Y	I	3.0 ± 0.7	2	0.78 ± 0.18
^{47}Sc	I	1.9 ± 0.2	5	0.92 ± 0.08	^{86}Zr	C	4.5 ± 0.1	5	0.91 ± 0.05
^{48}Sc	I	0.49 ± 0.09	3	0.94 ± 0.13	^{88}Zr	C	13.4 ± 0.5	3	0.91 ± 0.08
^{48}V	C	2.6 ± 0.2	4	1.01 ± 0.07	^{89}Zr	C	14.9 ± 0.6	5	0.95 ± 0.07
^{52}Mn	I	1.7 ± 0.1	3	1.01 ± 0.05	^{88}Nb	C	···	2	1.09 ± 0.06
^{52}Mn^{m}	I	0.40 ± 0.02	2	1.03 ± 0.14	^{89}Nb	C	1.4 ± 0.4	2	0.86 ± 0.24
^{54}Mn	I	4.7 ± 0.2	2	0.99 ± 0.05	^{90}Nb	C	14.1 ± 0.7	5	0.89 ± 0.06
^{59}Fe	C	0.52 ± 0.03	2	0.89 ± 0.05	^{92}Nb^{m}	I	0.57 ± 0.06	2	0.89 ± 0.12
^{56}Co	C	1.4 ± 0.08	2	0.94 ± 0.09	^{95}Nb	I	0.53 ± 0.10	2	1.23 ± 0.26
^{57}Co	C	3.9 ± 0.5	2	0.88 ± 0.19	^{90}Mo	C	2.7 ± 0.4	5	0.83 ± 0.19
^{58}Co	I	6.0 ± 0.7	4	1.04 ± 0.17	^{93}Mo^{m}	I	3.6 ± 0.6	4	0.93 ± 0.15
^{60}Co	I	1.9 ± 0.1	2	1.10 ± 0.06	^{94}Tc	C	6.5 ± 0.3	2	0.90 ± 0.09
^{60}Cu	C	0.62 ± 0.02	2	0.89 ± 0.05	^{95}Tc	C	14.7 ± 0.4	5	0.93 ± 0.08
^{65}Zn	C	8.6 ± 0.2	2	0.98 ± 0.04	^{95}Tc^{m}	I	0.74 ± 0.08	2	0.99 ± 0.09
^{66}Ga	C	4.5 ± 0.1	2	1.05 ± 0.05	^{96}Tc	I	7.0 ± 0.5	4	0.99 ± 0.07
^{67}Ga	C	8.7 ± 0.6	3	0.98 ± 0.19	^{95}Ru	C	4.8 ± 0.4	2	0.84 ± 0.08
^{71}As	C	7.3 ± 0.5	4	1.04 ± 0.07	^{97}Ru	C	14.4 ± 1.6	4	1.03 ± 0.05
^{72}As	I	6.1 ± 0.5	5	1.03 ± 0.10	^{103}Ru	C	1.29 ± 0.05	2	1.02 ± 0.04
^{74}As	I	1.9 ± 0.1	4	0.92 ± 0.13	^{100}Rh	I	9.9 ± 0.8	2	0.90 ± 0.05
		2.17 ± 0.02	2		^{101}Rh	I	4.4 ± 0.1	2	1.17 ± 0.04
^{72}Se	C	1.8 ± 0.2	5	0.84 ± 0.09	^{101}Rh^{m}	C	21.2 ± 1.0	5	1.14 ± 0.10
^{73}Se	C	4.3 ± 0.6	6	1.15 ± 0.18	^{102}Rh	I	1.2 ± 0.1	2	1.02 ± 0.25
^{75}Se	C	9.4 ± 0.4	2	0.95 ± 0.06	^{102}Rh^{m}	I	5.6 ± 0.1	2	1.23 ± 0.08
^{76}Br	I	6.8 ± 0.9	4	0.85 ± 0.18	^{99}Pd	C	1.5 ± 0.1	2	0.92 ± 0.04
^{77}Br	C	8.1 ± 0.9	4	0.91 ± 0.12	^{100}Pd	C	5.1 ± 0.4	2	1.10 ± 0.12
^{79}Rb	C	2.5 ± 0.1	2	1.27 ± 0.11	^{103}Ag	C	13.1 ± 0.1	2	1.06 ± 0.03
^{81}Rb	C	14.5 ± 2.1	6	0.91 ± 0.13	^{104}Ag	I	11.7 ± 1.6	2	1.36 ± 0.24
^{82}Rb^{m}	I	3.8 ± 0.7	5	0.79 ± 0.14	^{104}Ag^{m}	C	4.7 ± 0.3	2	0.93 ± 0.13
^{83}Rb	C	11.2 ± 0.4	2	0.91 ± 0.04	^{105}Ag	C	24.3 ± 2.1	2	0.97 ± 0.06
					^{106}Ag^{m}	I	9.7 ± 0.6	3	1.05 ± 0.05

observed. Although absolute cross sections could not be obtained because the γ-ray abundances are unknown it was possible to obtain the ratio of cross sections at 300 and 11.5 GeV.

III. RESULTS AND DISCUSSION

The results are tabulated in Table I which lists the observed nuclides, the type of yield, cumulative (C) or independent (I), the cross sections at 300 GeV, the number of replicate determinations, and the ratios of cross sections at 300 and 11.5 GeV, $\sigma_{300}/\sigma_{11.5}$. The cross sections are based on a value of 8.6 mb for the cross section of the ^{27}Al-(p, 3pn) monitor reaction.[9,10] In those cases where more than one γ ray was observed for a given nuclide the listed cross sections represent a weighted average provided the criteria described in I were met. As discussed in I, corrections due to secondary effects should be <2% and the listed cross sections were not corrected for this effect. The quoted uncertainties in the cross sections are based on the agreement between duplicate measurements. Additional sources of uncertainty in the cross sections are due to detector efficiency (±5%), γ-ray abundance (± 0–15%), and the cross section of the monitor reaction, ~25% at 300 GeV.[10] Table II of I contains a tabulation of the 11.5-GeV cross sections, including specific details about some of the yields. In the case of nuclides for which more than one γ ray was observed the values of $\sigma_{300}/\sigma_{11.5}$ are a weighted average of the ratios of cross sections based on individual γ rays. This procedure yields the greatest accuracy in

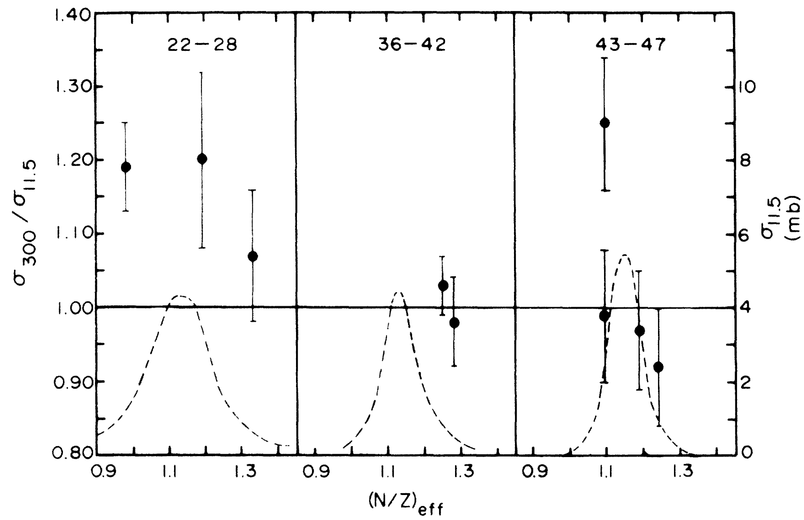

FIG. 1. Dependence of $\sigma_{300}/\sigma_{11.5}$ on effective product N/Z within the indicated mass intervals. The dashed lines are the 11.5-GeV charge dispersions (from I) for these mass intervals and the cross section scale is on the right side.

the ratios. The cross-section ratios are free of any systematic errors except for those in the monitor reaction cross section at the two energies. This uncertainty affects all the ratios in a uniform way.

The values of $\sigma_{300}/\sigma_{11.5}$ fluctuate about unity. The weighted average value of the 74 measured ratios is 1.01 ± 0.10. The results are sufficiently complete to permit a close inspection for possible trends with mass number or composition. This may be conveniently done by plotting the ratios as a function of effective N/Z for each of the mass regions for which a charge dispersion was determined at 11.5 GeV in I. The effective N/Z value of a cumulatively formed nuclide was obtained as the average of the N/Z of its progenitors, weighted by their production cross sections as given by the 11.5-GeV charge dispersions. The results are shown in Figs. 1–3. The charge dispersion curves from I are superimposed for easy reference. The only mass region for which the cross-section ratios differ significantly from unity is $A = 22–28$, for which the weighted average value is 1.17 ± 0.05. In all the other mass regions the weighted average ratios are consistent with unity. In addition, there appears to be no discernible trend with product N/Z in any of the mass regions. In a study of the reactions of silver with 3- and 29-GeV protons

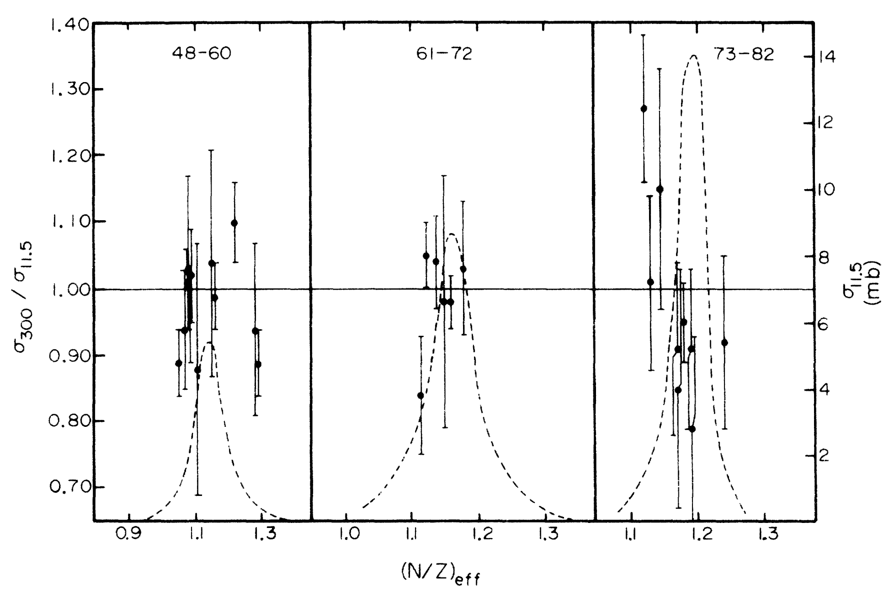

FIG. 2. Dependence of $\sigma_{300}/\sigma_{11.5}$ on product $(N/Z)_{eff}$ within the indicated mass intervals.

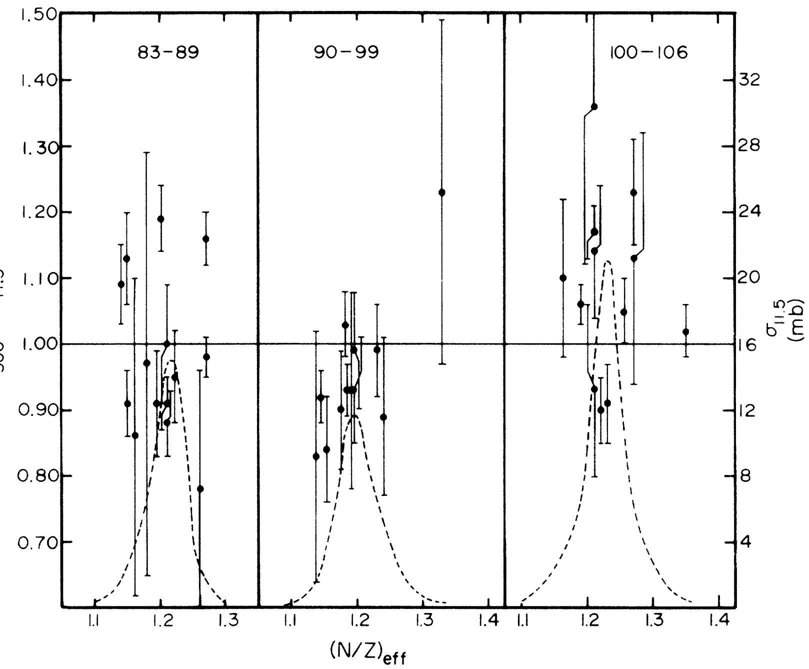

FIG. 3. Dependence $\sigma_{300}/\sigma_{11.5}$ on product $(N/Z)_{eff}$ within the indicated mass intervals.

Katcoff, Fickel, and Wyttenbach[11] found that the values of σ_{29}/σ_3 were about 2 at $A \sim 20$, decreased to a minimum value of approximately 0.8 at $A \sim 70-90$, and finally increased towards unity for products close to the target. A comparison of the 29-GeV data with the 11.5-GeV results presented in I showed little, if any, difference within the limits of error. In particular, the average value of $\sigma_{29}/\sigma_{11.5}$ for products in the $A = 22-28$ mass region was found to be 1.17 ± 0.21. In view of the uncertainty in this value we can not determine whether the increase between 11.5 and 300 GeV merely reflects a change between 11.5 and 29 GeV or whether there is an additional small increase in the yields of light nuclides at higher energies.

The present results are consistent with the other reported 300-GeV data[1-3] in indicating that there is very little difference between formation cross sections measured at 300 GeV and at lower energies. Katcoff *et al.*[1] thus report that the mean ratio $\langle\sigma_{300}/\sigma_{29}\rangle$ for V is 0.96 ± 0.04, while $\langle\sigma_{300}/\sigma_{11.5}\rangle$ for Co is 1.02 ± 0.09. The situation is less clear for uranium, for which only rather incomplete results are presently available. Chang and Sugarman[2] report $\langle\sigma_{300}/\sigma_{11.5}\rangle$ of about 0.9 based on values for 30 nuclides ranging from ^{45}Ca to ^{177}Ta. In a more detailed study of the formation of products in the $A \sim 130$ mass region from uranium, Yu and Porile[3] find that $\langle\sigma_{300}/\sigma_{11.5}\rangle$ is essentially unity for products with $A \geq 130$. On the other hand, the values of $\sigma_{300}/\sigma_{11.5}$ for neutron deficient iodine nuclides decrease with decreasing A becoming as low as 0.64 ± 0.05 for ^{123}I.

The constancy of the cross-section ratios indicates that the spectrum of excitation energies deposited in the struck nucleus must be essentially invariant above 10–30 GeV. It is known, however, that the production of charged secondaries (mostly pions) in p-p collisions increases by about a factor of 3 between 10 and 300 GeV.[12] These facts suggest that these additional pions escape from the nucleus, possibly as components of isobars, with virtually no energy loss. Alternatively, the constancy of the excitation energy spectrum, and hence of the mass-yield curve, may be the result of the depletion of target nucleons in the course of the intranuclear cascade. This effect has been incorporated in recent[13,14] Monte Carlo cascade calculations and appears to correctly predict that the mean excitation energy levels off above ~5 GeV.

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