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Interaction of 300-GeV protons with uranium*

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The cross sections and thick-target recoil properties of 30 nuclides produced in the interaction of 300-GeV protons with a ^{238}U target have been measured. The cross sections were determined relative to the monitor reaction ^{27}Al(p, $3pn$)^{24}Na, whose cross section was assumed to be constant above 10 GeV. The average cross section of all products is found to be ~10% lower at 300 GeV than at 11.5 GeV. The recoil ranges of observed nuclides are ~8% shorter than at lower proton energy and F/B values are closer to unity. A preliminary study of the effect of secondary particles is presented.

[NUCLEAR REACTIONS ^{238}U(p, f, and spallation), E = 300 GeV; measured σ and thick-target recoil properties of 30 product nuclides.]

I. INTRODUCTION

The interaction of 300-GeV protons with complex nuclei is currently being studied. Spallation cross sections for V,[1] Co,[1] and Ag[2] targets have recently been reported. These represent targets of low to medium mass. On the assumption that the cross section of the monitor reaction ^{27}Al(p, $3pn$)^{24}Na remains unchanged above 10 GeV, the spallation yields from these targets were found to be essentially independent of the incident proton energy. In this report we present the cross sections and recoil properties of various product nuclides with mass number between 45 and 177 from U irradiated with 300-GeV protons. The results are compared with those obtained at lower proton energies.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Four irradiations were performed in the external 300-GeV proton beam at the neutrino area of the National Accelerator Laboratory. The target assemblies are shown in Fig. 1. In two irradiations the target consisted of a ~50-mg/cm^2 U foil sandwiched between two ~7-mg/cm^2 Al foils and wrapped by another Al foil [Fig. 1(a)]. In order to study the effect of secondary particles three U foils, each surrounded by Al foils, were used in two other experiments [Fig. 1(b)]. The length of irradiations varied from 10 to 24 h. After the irradiation, a circular area of 2.4 cm^2 was punched out. The Al monitor foils were counted on β proportional counters for the ^{24}Na activities. The target and catcher foils were dissolved in the presence of carriers. Standard chemical procedures[3] were followed for separation and yield determination. Activity measurements on the chemically separated samples were made with proportional counters for β emitters, a 2-mm NaI crystal for x rays, a Ge(Li) x-ray detector, and Ge(Li) γ-ray detectors. The efficiencies of the detectors were calibrated with sources of known energy and disintegration rate. They decay properties and the measured radiations of the observed nuclides are listed in Table I. The decay curves were analyzed by the Cumming CLSQ[4] computer code. The radioactivity of the target was corrected for counter efficiency, branching ratio, chemical yield, and recoil loss. The cross sections are determined relative to that of the ^{27}Al(p, $3pn$)^{24}Na reaction whose value is assumed to be 8.6 mb at 300 GeV.[1,2] The variation of incident beam intensity during the irradiation was taken into account in the calculation of saturation factors.

The results of the cross-section measurements at 300 GeV are listed in column 6 of Table II, with the number of determinations in parentheses. The values given are those obtained with a ~50-mg/cm^2 U target foil assembly [Fig. 1(a)] *uncorrected* for secondary particle effects in the Al monitor or the U target. The precision of the measurements, as determined from separate experiments or from counting statistics when only one experiment was performed, is the order of 5%. The over-all uncertainty in the measured cross sections, including the estimated systematic and random errors and errors in detector efficiency, chemical yield determination, and branching ratio, is estimated to be about 15%. The (I) or (C) adjacent to the nuclides of column 1 refers to independent or cumulative production, respectively. The previously reported cross sections at lower energies (3–28 GeV) are also given in Table II. In order to minimize the uncertainty in the decay scheme and detector efficiency calibration in the comparison of cross-section results at 300 GeV with those at lower energy, cross sections of several nuclides were also studied at 11.5 GeV.[5] These irradiations were performed at the zero gradient synchroton of the Argonne National Laboratory. The same chemical procedures and counting equipment were used and the data were analyzed in the same way as in the 300-GeV experiments.

The thick-target recoil properties measured at 300 GeV are given in Table III along with previously reported results at lower proton energies. F and B are the fractions of the total activity of the specific nuclide in the forward and backward catcher foils, respectively. W is the surface density of the uranium target in mg/cm^2 of U. The $2W(F+B)$ values have been corrected for edge and scattering effects.[6]

III. DISCUSSION

From Table II it can be seen that the cross sections for all product nuclides from U measured at 300 GeV are generally somewhat smaller than those observed at 11.5 GeV. The mean cross-section ratio $\sigma_{300}/\sigma_{11.5}$ for all measured products is 0.89 ± 0.18 compared with 0.96 ± 0.04 for V,[1] 1.02 ± 0.09 for Co,[1] and 0.91 ± 0.07 for Ag.[2] Thus, even for U the proton interaction with the nucleus leads to excited nuclei whose average deposition energy does not change significantly between 11.5 and 300 GeV.

A more detailed examination of the $\sigma_{300}/\sigma_{11.5}$ ratio indicates a difference between products in the $A < 70$ mass region and those for $70 < A < 140$. The average cross-section ratio for products of $A < 70$ is 1.03 ± 0.14, whereas that for products of $70 < A < 140$ is 0.81 ± 0.14. It would appear that the cross

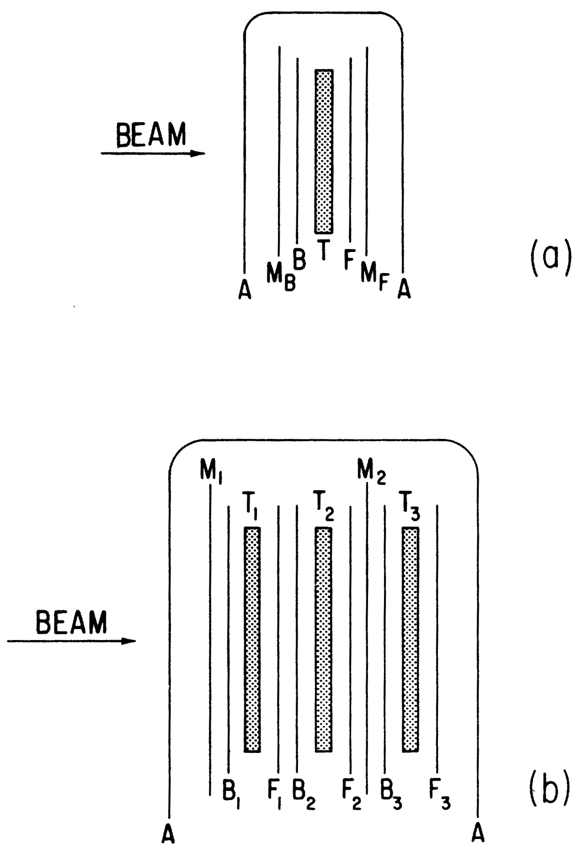

FIG. 1. Target assemblies for cross-section and recoil measurements. (a) Single U target, ~50 mg/cm^2. (b) Multiple uranium target. A, Al wrapper foil; M, Al monitor; F and B, forward and backward catcher foils, respectively; T, U target foil.

TABLE I. Decay properties of the observed radionuclides. Data taken from *Table of Isotopes* [C. M. Lederer, J. M. Hollander, and I. Perlman (Wiley, New York, 1967), 6th ed.], current *Nuclear Data Sheets* [edited by Nuclear Data Group (Academic, New York)], and recent literature.

Nuclide	Mode of decay	$t_{1/2}$	Radiation measured	Branching ratio
^{45}Ca	β^-	165 day	β^-	1.00
^{47}Ca	β^-	4.5 day	1.308-MeV γ	0.74
^{59}Fe	β^-	45.6 day	1.095-MeV γ	0.56
^{56}Co	EC, β^+	77.3 day	0.847-MeV γ	1.00
^{57}Co	EC	270 day	0.122-MeV γ	0.87
^{58}Co	EC, β^+	71.3 day	0.810-MeV γ	0.99
^{60}Co	β^-	5.26 yr	1.173-MeV γ	1.00
^{64}Cu	β^-, β^+, EC	12.8 h	0.511-MeV γ	0.38
^{67}Cu	β^-	61.7 h	0.185-MeV γ	0.41
^{82}Sr	EC	25 day	0.511-MeV γ [a]	1.92
^{83}Sr	EC, β^+	33 h	0.511-MeV γ	0.32
^{85}Sr	EC	64 day	0.514-MeV γ	1.00
^{89}Sr	β^-	52.7 day	β^-	1.00
^{91}Sr	β^-	9.7 h	0.651-MeV γ	0.12
^{93}Mo^m	IT	6.9 h	0.685-MeV γ	1.00
^{99}Mo	β^-	66.7 h	β^-	1.00
^{100}Pd	EC	3.7 day	0.084-MeV γ	0.49
^{103}Pd	EC	17 day	x ray	0.81
^{109}Pd	β^-	13.5 h	0.088-MeV γ [a]	0.042
^{111}Pd^m	β^-, IT	5.5 h	0.175-MeV γ	0.31
^{112}Pd	β^-	21 h	0.617-MeV γ [a]	0.41
^{105}Ag	EC	40 day	0.280-MeV γ	0.32
^{106}Ag^m	EC	8.4 day	0.512-MeV γ	0.86
^{110}Ag^m	β^-, IT	253 day	0.658-MeV γ	0.96
^{111}Ag	β^-	7.5 day	β^-	1.00
^{128}Ba	EC	2.4 day	0.511-MeV γ [a]	1.10
^{131}Ba	EC	12.0 day	0.122-MeV γ	0.28
^{133}Ba^m	IT	39 h	0.276-MeV γ	0.17
^{135}Ba^m	IT	28.7 h	0.268-MeV γ	0.16
^{140}Ba	β^-	12.8 day	0.537-MeV γ	0.20
^{177}Ta	EC	56.6 h	x ray	0.94

[a] Daughter activity.

sections for nuclides in the binary-fission mass region[7] at 300 GeV decreases by about 19% from those at 11.5 GeV, while the cross sections for the products in the lighter-mass region does not change. Further studies on products of the $A < 40$ mass region should be most informative.

The recoil properties $2W(F+B)$ and F/B of the measured product nuclides (Table III) are also changed somewhat from those at 11.5 GeV. The $2W(F+B)$ values are smaller at 300 GeV than at 11.5 GeV, the mean ratio $2W(F+B)_{300}/2W(F+B)_{11.5}$ being 0.93 ± 0.05, indicating a slightly lower mass for the average excited nucleus at the higher energy. The F/B values are also smaller at 300 GeV, implying that the incident proton imparts less forward momentum to the excited nucleus. Beg and Porile[8] studied the recoil properties of Sr and Ba nuclides as a function of incident proton energy. They found that the F/B values of the neutron-rich nuclides stay constant with increasing proton energy, whereas those of neutron-deficient nuclides go through a maximum at ~3 GeV and then decrease

TABLE II. Formation cross sections of products from multi-GeV proton bombardment of uranium (in mb).

Nuclide	3 GeV	6 GeV	11.5 GeV [a]	28 GeV	300 GeV [b]	$\sigma_{300}/\sigma_{11.5}$
^{45}Ca (C)	3.7 [c]				3.3(2)	0.89 [d]
^{47}Ca (C)	1.2 [c]				1.59(2)	1.33 [d]
^{59}Fe (C)			5.0 [e]		4.8(3)	0.96
^{56}Co (C)			0.31 [e]		0.32(2)	1.03
^{57}Co (I)			1.45 [e]		1.54(3)	1.06
^{58}Co (I)			3.8 [e]		4.0(2)	1.05
^{60}Co (I)			5.0 [e]		5.4(3)	1.08
^{64}Cu (C)			2.9 [e]		2.5(2)	0.86
^{67}Cu (C)	4.7 [f]	3.7 [g]	2.9 [e]		2.8(3)	0.97
^{83}Sr (C)	4.1 [h]	7.1 [h]	5.8 [h]	3.32 [i]	3.2(1)	0.54
^{85}Sr (C)					6.3(1)	
^{89}Sr (C)					24.3(1)	
^{91}Sr (C)	14.2 [h]	14.7 [h]	14.3 [h]	17.1 [i]	13.6(1)	0.95
^{93}Mo^m (C)		2.2 [g]	2.3 [e]		2.20(2)	0.97
^{99}Mo (C)		25 [g]	23.5 [e]		23.4(4)	1.00
^{100}Pd (C)	0.88 [k]		0.90 [l]	1.31 [i]	0.85(3)	0.94
^{103}Pd (C)	3.6 [k]		5.1 [l]	4.1 [k]	3.1(2)	0.61 [j]
^{109}Pd (C)	21.4 [k]	19.1 [m]	18.3 [e]	18 [i]	17.2(3)	0.94
^{111}Pd^m (I)	5.5 [k]	2.2 [m]	4.0 [e]	3.9 [k]	3.2(1)	0.79
^{112}Pd (C)	16.9 [k]		15.0 [e]	14.3 [k]	14.3(1)	0.95
^{105}Ag (C)			2.01 [e]		1.78(3)	0.89
^{106}Ag^m (I)			1.80 [e]		1.52(3)	0.84
^{110}Ag^m (I)			3.3 [e]		2.5(3)	0.76
^{111}Ag (C)		21.5 [g]	24.3 [l]		17.6(4)	0.72
^{128}Ba (C)	5.1 [h]	6.6 [h]	6.5 [h]	6.0 [i]	4.9(1)	0.59 [j]
^{131}Ba (C)	8.2 [h]	9.4 [h]	8.8 [h]		6.2(1)	0.70
^{133}Ba^m (I)					8.1(1)	
^{135}Ba^m (I)					1.23(1)	
^{140}Ba (C)	7.4 [h]	7.6 [h]	7.8 [h]	10.0 [i]	7.4(1)	0.76 [j]
^{177}Ta (C)			2.85 [e]		3.0(2)	1.05

[a] Average precision ~4%.
[b] Average precision ~5%.
[c] G. Friedlander and L. Yaffe, Phys. Rev. 117, 578 (1960).
[d] σ_{300}/σ_3.
[e] Reference 5.
[f] S. Kaufman, Phys. Rev. 129, 1866 (1963).
[g] J. M. Alexander, C. Baltzinger, and M. F. Gazdik, Phys. Rev. 129, 1826 (1963).
[h] Reference 8.
[i] Reference 11. Results corrected for secondary effects.
[j] Ratio corrected for different branching ratios used at 11.5 and 300 GeV.
[k] N. T. Porile, Phys. Rev. 148, 1235 (1966).
[l] J. A. Panontin and N. T. Porile, J. Inorg. Nucl. Chem. 32, 1775 (1970).
[m] R. H. Shudde, University of California Laboratory Report No. UCRL-3419, 1956 (unpublished).

TABLE III. Thick-target recoil properties of product nuclides from multi-GeV proton bombardment of uranium.

Nuclide	3 GeV $2W(F+B)$, (mg/cm^2 U)	3 GeV F/B	6 GeV $2W(F+B)$, (mg/cm^2 U)	6 GeV F/B	11.5 GeV [a,b] $2W(F+B)$, (mg/cm^2 U)	11.5 GeV F/B	300 GeV [c,b] $2W(F+B)$, (mg/cm^2 U)	300 GeV F/B	$\frac{2W(F+B)_{300}}{2W(F+B)_{11.5}}$
^{45}Ca							9.51	1.02	
^{47}Ca							8.43	1.06	
^{64}Cu			8.0	1.25 [d]	8.05	1.08 [e]	7.05	1.01	0.88
^{67}Cu			9.9	1.13 [d]	9.76	1.11 [e]	8.90	1.08	0.91
^{83}Sr	8.04	1.32 [f]	6.35	1.18 [f]	6.12	1.18 [f]	5.27	1.09	0.86
^{85}Sr							4.89	1.08	
^{89}Sr							8.63	1.03	
^{91}Sr	10.22	1.03 [f]	10.23	1.08 [f]	10.09	1.09 [f]	9.53	1.05	0.94
^{93}Mo^m					5.83	1.12 [g]	5.84	1.07	1.00
^{99}Mo			9.3	1.15 [d]	9.51	1.06 [g]	9.24	1.05	0.97
^{100}Pd					4.68	1.11 [g]	4.00	1.03	0.85
^{103}Pd					5.48	1.13 [g]	4.68	1.08	0.85
^{109}Pd					8.83	1.09 [g]	8.62	1.06	0.98
^{111}Pd^m					9.39	1.10 [g]	8.70	1.11	0.93
^{112}Pd			8.1	1.17 [d]	9.47	1.08 [g]	8.68	1.11	0.92
^{105}Ag					4.66	1.24 [g]	4.06	1.15	0.87
^{106}Ag^m					5.70	1.21 [g]	5.46	1.09	0.96
^{110}Ag^m					7.98	1.12 [g]	7.66	1.11	0.96
^{111}Ag			8.1	1.17 [d]	8.72	1.12 [g]	7.98	1.11	0.92
^{128}Ba	4.15	1.80 [f]	3.34	1.50 [f]	2.99	1.25 [f]	2.89	1.21	0.97
^{131}Ba	4.46	1.66 [f]	3.92	1.41 [f]	3.58	1.27 [f]	3.38	1.25	0.94
^{133}Ba^m							4.75	1.36	
^{135}Ba^m							6.85	1.23	
^{140}Ba	7.27	1.08 [f]	8.06	1.07 [f]	7.95	1.04 [f]	7.49	1.05	0.94
^{177}Ta					0.96	2.11 [g]	0.91	1.85	0.95

[a] Average precision ~4%.
[b] Values corrected for edge and scattering effects (Ref. 6).
[c] Average precision ~6%.
[d] J. M. Alexander, C. Baltzinger, and M. F. Gazdik, Phys. Rev. 129, 1826 (1963).
[e] S. K. Chang and N. Sugarman, Phys. Rev. C 8, 775 (1973).
[f] Reference 8.
[g] Reference 5.

slowly with increasing energy. The values reported here for 300 GeV are a continuation of this trend.

A preliminary study of the effect of target thickness on the cross section and recoil properties measured for thick U target foils was made at 300 GeV. The purpose of this experiment was the comparison of the effect of secondary particles at 300 GeV with that at 11.5 and 28 GeV on the production of ^{24}Na in the Al monitor foils and the production and recoil properties of neutron-deficient (^{103}Pd, ^{105}Ag, ^{106}Ag^m) and neutron-excess (^{111}Ag) products from U in the target foil. The results from two target assemblies, a ~50-mg/cm^2 U target [single target, Fig. 1(a)] and a 230-mg/cm^2 U target [multiple-target assembly, Fig. 1(b)], are given in Table IV. The first row of Table IV gives the results for the ~50-mg/cm^2 U target; the second row, the

TABLE IV. Effect of target thickness on the cross section and recoil properties at 300 GeV.

Target thickness (mg/cm^2 U)	^{103}Pd σ (mb)	^{103}Pd $2W(F+B)$ (mg/cm^2 U)	^{103}Pd F/B	^{105}Ag σ (mb)	^{105}Ag $2W(F+B)$ (mg/cm^2 U)	^{105}Ag F/B	^{106}Ag^m σ (mb)	^{106}Ag^m $2W(F+B)$ (mg/cm^2 U)	^{106}Ag^m F/B	^{111}Ag σ (mb)	^{111}Ag $2W(F+B)$ (mg/cm^2 U)	^{111}Ag F/B
~50	3.21	4.68	1.08	1.78	4.06	1.15	1.52	5.46	1.09	17.6	7.98	1.11
230	3.28			1.79	3.93	1.13	1.43			19.5	7.93	1.34
0–48.5	3.38	4.59	1.07	1.82	3.89	1.12	1.50	5.33	1.08	18.3	7.83	1.17
48.5–177.5	3.26	4.77	1.08	1.78			1.40			19.6		
177.5–230	3.26			1.81	3.89	1.14	1.46			20.3	8.06	1.17

results for the combined thick U target, 230-mg/cm^2 U; the third, fourth, and fifth rows, the results for the individual U targets of the combined target.

A comparison of the results of the ~50-mg/cm^2 U target with those of the 230-mg/cm^2 U target shows that the results for neutron-deficient products are not affected by target thickness, whereas those for ^{111}Ag are to about the same extent observed at 11.5 GeV[9,10] and 28 GeV.[11] The "upstream" buildup of secondary production of ^{111}Ag is evident from the increase in the cross section along the path of the combined target. That there is also an effect of target thickness on the production of ^{24}Na from Al is evident from the ratio M_F/M_B [Fig. 1(a)] of 1.02 for the ~50-mg/cm^2 U target and the ratio M_2/M_1 [Fig. 1(b)] of 1.15 for the combined target. It is estimated from these results that the secondary production of ^{24}Na in the Al monitor foil and of the neutron-excess products in U is ~11% for a 100-mg/cm^2 U target, essentially the same as that reported at lower energies.[10,11]

IV. CONCLUSION

The cross sections and thick-target recoil properties of 30 nuclides produced in the interaction of 300-GeV protons with uranium have been measured. The recoil range values [$2W(F+B)$] of all products are slightly lower than those observed at lower energy and the F/B ratios are closer to unity. The cross sections of product nuclides in the mass region $40<A<70$ are about the same as at 11.5 GeV, while those in the mass region $70<A<140$ are ~20% lower. Although pion production in proton-proton interaction is known to increase with proton energy,[12] the evidence from these experiments and others[1,2] points to a relatively constant deposition energy spectrum, implying noninteraction of the extra pions with the nucleus. The production of nuclides by secondary particles is about the same as observed at lower energy.[10,11] Radiochemical studies in the mass regions $A<40$ and $140<A<238$, along with charge-dispersion measurements, are necessary for a more complete comparison of the interaction of 300-GeV protons with U compared to that at lower energy.

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