Interaction of ^{238}U with 300- and 11.5-GeV protons: Cross sections and recoil properties in the $A \sim 130$ mass region*

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Formation cross sections and thick-target recoil properties of 13 products in the $A \sim 130$ mass region from the interaction of ^{238}U with 300- and 11.5-GeV protons have been determined. The values of $\sigma_{300}/\sigma_{11.5}$ are consistent with unity for $A > 130$ and decrease with decreasing A below this mass number, a trend that is most notably exhibited by neutron deficient iodine nuclides. The recoil ranges and F/B values are essentially the same at both energies.

[NUCLEAR REACTIONS Measured σ, $2W(F+B)$, F/B of 13 I, Cs, and Ba nuclides from 300- and 11.5-GeV proton bombardment of ^{238}U.]

I. INTRODUCTION

The recent availability of 300-GeV protons at the National Accelerator Laboratory has made it possible to study their interaction with complex nuclei. Preliminary results have been reported for vanadium,[1] cobalt,[1] silver,[2] and uranium[3] targets. We present here the results of a detailed comparison of cross sections and recoil properties of products in the $A \sim 130$ mass region from the interaction of ^{238}U with 300- and 11.5-GeV protons. The charge dispersion and recoil ranges have been thoroughly studied in this mass region up to 30 GeV.[4-10] It is known as a result of these studies that at least two mechanisms are of importance at multi-GeV energies: spallation accompanied by fragment emission and fission. The purpose of the present study is to determine whether the characteristics and relative importance of these two processes change between 11.5 and 300 GeV.

II. EXPERIMENTAL AND RESULTS

The irradiations with 300-GeV protons were performed in external beams at the neutrino or meson halls at the National Accelerator Laboratory for times ranging from 18 to 34 h. The 11.5-GeV bombardments were performed in the internal circulating beam of the ZGS at Argonne National Laboratory and had a duration of 20 min.

The target stacks consisted of 20 μm depleted uranium foil surrounded by three layers of 20 μm high-purity (99.999%) aluminum. The innermost foils served as recoil catchers, the middle foils as beam monitors, and the outer ones as guard foils. In the case of the 300-GeV bombardments, the target stacks were sealed in evacuated plastic bags in order to prevent the air layer between target and catcher foils from perturbing the recoil range determinations. Prior to irradiations the oxide layer was removed from the uranium foil with dilute HNO_3.

After irradiation the most intensely activated portions of the target stack were cut for subsequent radiochemical analysis. Iodine, cesium, and barium were separated from the target and catcher foils by previously[9] described procedures. The various samples were assayed with a calibrated 70 cm^3 Ge(Li) detector or with a calibrated thin Ge(Li) x-ray detector. Both detectors were operated in conjunction with 1024 or 4096 channel analyzers. The disintegration rate of ^{24}Na from the $^{27}Al(p, 3pn)$ monitor reaction was also determined by γ-ray spectrometry. Table I summarizes the decay properties of the observed nuclides.

The measured cross sections are summarized in Table II. The results are based on a value of 8.6 mb for the cross section of the $^{27}Al(p, 3pn)$ monitor reaction[11] at both energies. The listed values have been corrected for secondary effects on both the uranium and monitor reactions. The correction was made on the basis of previously[9] determined correction factors for $A = 131$ products at 11.5 GeV. In applying this correction to other products in this mass region it was assumed that the correction depended on the $(Z_A - Z_{eff})$ value of the product, whose determination is discussed below. The same correction factors were applied at 300 GeV as at 11.5 GeV on the basis of the secondary effect measurements by Chang and Sugarman[3] for 300-GeV proton bombardment of ^{238}U. The 300-GeV results also had to be corrected for discontinuities and changes in beam intensity during the rather long bombardment times.

Table II lists the mode of formation of the mea-

TABLE I. Decay properties of measured nuclides. Unless otherwise indicated all data are from C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967). 6th ed.

Nuclide	Half-life	γ ray (keV)	Abundance per 100 decays
^{123}I [a]	13.20 h	159	83
^{124}I [b]	4.18 day	603	61.4
^{126}I [c]	13.02 day	388.5	34
^{130}I	12.30 h	538	99
^{131}I [d]	8.05 day	364	82
^{133}I	20.30 h	530	90
^{129}Cs [e]	32.06 h	372	31.7
^{131}Cs	9.70 day	K x ray	76 [f]
^{132}Cs	6.59 day	668	99
^{136}Cs	13.70 day	340	53
^{128}Ba	2.42 day	443 (^{128}Cs)	27
^{131}Ba [g]	11.50 day	216	19
^{140}Ba [h]	12.80 day	537	20

[a] R. L. Auble, Nucl. Data B 7, 363 (1972).
[b] F. E. Bertrand, Nucl. Data B 10, 91 (1973).
[c] R. L. Auble, Nucl. Data B 9, 125 (1973).
[d] G. Graeffe and W. B. Walters, Phys. Rev. 153, 1321 (1967).
[e] D. J. Horen, Nucl. Data B 8, 123 (1972).
[f] Fluorescence yield and K capture branch. An incorrect abundance value was given in Ref. 9 for this nuclide. However, the correct value was used in the computation of the cross section.
[g] J. Fechner, A. Hammesfahr, A. Kuge, S. K. Sen, H. Toschinski, J. Voss, P. Weigt, and B. Martin, Nucl. Phys. 130, 545 (1969).
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sured nuclides, independent (I) or cumulative (C), the cross sections at the two energies, and their experimental standard deviations as based on the indicated number of replicate determinations, the ratio of cross sections, $\sigma_{300}/\sigma_{11.5}$, and the results of previous determinations above 10 GeV. The actual uncertainties in the cross sections include in addition to the listed standard deviations the errors in branching ratios, detector efficiencies, and cross sections of the monitor reaction. However, the cross section ratios are free of the first two of these uncertainties, while changes in the monitor reaction cross section can only affect all the ratios uniformly. The 11.5-GeV data for ^{131}I, ^{131}Cs, and ^{131}Ba have been reported previously.[9] The measured recoil properties, corrected for scattering at the target-catcher interface,[12] are tabulated in Table III. The quantities of interest are the experimental range in mg/cm^2 of uranium, denoted by $2W(F+B)$, and the forward-to-backward ratio, F/B, as well as their ratios at the energies of interest. The listed uncertainties are experimental standard deviations. Previous results above 10 GeV are also summarized.

The present cross sections are generally in satisfactory agreement with previous determinations when the latter were corrected for secondaries as indicated in Table II. The 18-GeV iodine cross sections reported by Rudstam and Sørensen[6] are mostly somewhat larger than the present values, the difference ranging from 1 to 24%. The cesium values agree, on the average, to within 10% with the 24-GeV results of Chaumont[7] and the barium values to within 8% with the 11.5-GeV data of Beg and Porile.[8] The 300-GeV Ba cross sections reported by Chang and Sugarman[3] are 6 to 33% lower than the present values. The recoil properties of iodine and barium products are in good agreement with the results of previous measurements at comparable energies.[3,6,8]

III. DISCUSSION

The isobaric variation of the cross sections and recoil properties is conveniently displayed in a plot versus $(Z_A - Z_{\rm eff})$. The most stable charge at mass number A, Z_A, was obtained[13] by a least-squares parabolic fit to the masses of isobaric nuclides. The effective charge of an observed product, $Z_{\rm eff}$, represents an average over all its isobaric precursors, weighted by their relative formation cross sections. The weighting factors were obtained on the basis of the charge dispersion previously[9] obtained at $A = 131$. The $Z_{\rm eff}$ of independently formed products obviously is just their actual Z.

Figure 1 summarizes the cross section data. The lower half shows a plot of the independent cross sections determined in the present work at 11.5 GeV as well as previously[9] reported results for $A = 131$ products. The solid curve is the published[9] two-Gaussian fit to the $A = 131$ independent and cumulative yields. The two peaks correspond, in a very approximate way, to spallation and fission although, as indicated below by the ranges, the contribution of fission extends into the neutron deficient hump. The present iodine and cesium independent yields are in fairly good agreement with the curve except for ^{126}I, whose yields appears to be anomalously high.

The upper half of Fig. 1 shows the values of $\sigma_{300}/\sigma_{11.5}$, including both independent and cumulative yields. The results display an interesting trend, approximated by the dashed lines, which is most clearly supported by the iodine data. It is seen that the values of $\sigma_{300}/\sigma_{11.5}$ for iodine decrease linearly with decreasing $(Z_A - Z_{\rm eff})$. The most neutron rich iodine product which has a sig-

TABLE II. Comparison of the formation cross sections of I, Cs, and Ba nuclides produced in 11.5- and 300-GeV proton interactions with ^{238}U.

		Present results			Previous results	
Product	Type of yield	$\sigma_{11.5}$ (mb)	σ_{300} (mb)	$\sigma_{300}/\sigma_{11.5}$	E_p (GeV)	σ (mb)
^{123}I	*C*	9.54 ± 0.30(4) [a]	6.10 ± 0.41(3) [a]	0.64 ± 0.05	18	8.6 ± 0.7 [b] (7.9) [c]
^{124}I	*I*	2.96 ± 0.12(4)	2.12 ± 0.21(3)	0.72 ± 0.09	18	3.0 ± 0.2 [b] (2.8)
^{126}I	*I*	3.28 ± 0.11(4)	2.62 ± 0.29(3)	0.80 ± 0.09	18	3.88 ± 0.31 [b] (3.56)
^{130}I	*I*	2.51 ± 0.07(4)	2.16 ± 0.24(3)	0.86 ± 0.10	18	3.10 ± 0.23 [b] (3.58)
^{131}I	*C*	9.09 ± 0.47(4)	8.46 ± 0.98(3)	0.93 ± 0.13	18	11.3 ± 1.3 [b] (13.1)
^{133}I	*C*	8.54 ± 0.32(4)	8.68 ± 0.36(3)	1.02 ± 0.05	18	9.0 ± 0.8 [b] (11.2)
^{129}Cs	*C*	9.48 ± 0.20(4)	7.88 ± 0.30(3)	0.83 ± 0.04		
^{131}Cs	*I*	2.32 ± 0.06(4)	2.16 ± 0.40(3)	0.93 ± 0.17	24.0	2.01 ± 0.05 [d]
^{132}Cs	*I*	1.99 ± 0.05(4)	2.00 ± 0.10(3)	1.01 ± 0.06	24.0	2.03 ± 0.08 [d]
					28.5	2.29 ± 0.12 [e] (2.10)
^{136}Cs	*I*	2.08 ± 0.07(4)	1.90 ± 0.20(3)	0.91 ± 0.09	24.0	2.53 ± 0.09 [d]
					28.5	2.28 ± 0.15 [e] (2.64)
^{128}Ba	*C*	6.01 ± 0.11(3)	5.39 ± 0.16(3)	0.90 ± 0.04	11.5	6.8 ± 0.6 [f] (6.5)
					28	6.04 ± 0.33 [g]
					300	5.1 [h] (4.9)
^{131}Ba	*C*	9.22 ± 0.14(5)	8.62 ± 0.91(3)	0.94 ± 0.11	11.5	9.2 ± 0.1 [f] (8.8)
					300	6.5 [h] (6.2)
^{140}Ba	*C*	8.27 ± 0.13(5)	8.50 ± 0.73(3)	1.03 ± 0.10	11.5	9.1 ± 0.36 [f] (7.8)
					28	10.01 ± 0.56 [g]
					300	6.9 [h] (7.4)

[a] Number of replicate determinations.
[b] Reference 6.
[c] The cross sections in parentheses are the reported values. The listed values were obtained by applying corrections for secondary reactions and for differences in assumed γ-ray abundances.
[d] Reference 7.
[e] E. M. Franz and G. Friedlander, Phys. Rev. C 4, 1671 (1971).
[f] Reference 8.
[g] Y. Y. Chu, E. M. Franz, and G. Friedlander, Nucl. Phys. B40, 428 (1972).
[h] Reference 3.

TABLE III. Comparison of recoil properties of products from 300- and 11.5-GeV proton bombardment of ^{238}U.

	11.5 GeV data		300 GeV data				Previous data		
Product	$2W(F+B)$ (mg/cm^2)	F/B	$2W(F+B)$ (mg/cm^2)	F/B	$\frac{[2W(F+B)]_{300}}{[2W(F+B)]_{11.5}}$	$\frac{(F/B)_{300}}{(F/B)_{11.5}}$	E_p (GeV)	$2W(F+B)$ (mg/cm^2)	F/B
^{123}I	4.38 ± 0.19(4) [a]	1.22 ± 0.05	4.13 ± 0.06(3) [a]	1.19 ± 0.09	0.94 ± 0.04	0.98 ± 0.08	18	4.0 ± 0.4	1.17 ± 0.12 [b]
^{124}I	6.59 ± 0.21(4)	1.15 ± 0.02	6.62 ± 0.08(3)	1.15 ± 0.02	1.00 ± 0.03	0.98 ± 0.04	18	6.9 ± 0.3	1.11 ± 0.07 [b]
^{126}I	7.42 ± 0.18(4)	1.11 ± 0.05	7.43 ± 0.08(3)	1.22 ± 0.05	1.00 ± 0.03	1.10 ± 0.07	18	7.7 ± 0.5	1.11 ± 0.09 [b]
^{130}I	8.16 ± 0.26(4)	1.10 ± 0.04	7.60 ± 0.04(3)	1.14 ± 0.07	0.93 ± 0.03	1.03 ± 0.08	18	7.5 ± 0.8	0.97 ± 0.10 [b]
^{131}I	8.25 ± 0.20(4)	1.06 ± 0.02	8.17 ± 0.11(3)	1.07 ± 0.02	0.99 ± 0.03	1.01 ± 0.03	18	7.9 ± 0.8	0.97 ± 0.17 [b]
^{133}I	8.77 ± 0.21(4)	1.06 ± 0.03	8.33 ± 0.16(3)	1.07 ± 0.04	0.95 ± 0.03	1.01 ± 0.04	18	7.9 ± 0.6	0.96 ± 0.06 [b]
^{129}Cs	4.23 ± 0.21(4)	1.23 ± 0.04	4.09 ± 0.08(3)	1.12 ± 0.07	0.97 ± 0.05	0.91 ± 0.06			
^{131}Cs	6.95 ± 0.31(4)	1.12 ± 0.09	6.53 ± 0.79(2)	0.89 ± 0.13	0.94 ± 0.13	0.79 ± 0.13			
^{132}Cs	7.59 ± 0.21(4)	1.14 ± 0.01	8.23 ± 0.69(2)	1.16 ± 0.23	1.09 ± 0.10	1.01 ± 0.20			
^{136}Cs	8.00 ± 0.36(4)	1.12 ± 0.0[illegible]	8.40 ± 0.11(2)	1.04 ± 0.02	1.05 ± 0.05	0.93 ± 0.03			
^{128}Ba	2.88 ± 0.06(3)	1.27 ± 0.01	2.49 ± 0.08(3)	1.18 ± 0.17	0.86 ± 0.03	0.93 ± 0.14	11.5	2.99 ± 0.15	1.25 ± 0.15 [c]
							300	2.89	1.21 [d]
^{131}Ba	3.47 ± 0.15(5)	1.30 ± 0.06	3.09 ± 0.11(3)	1.22 ± 0.07	0.89 ± 0.05	0.94 ± 0.07	11.5	3.58 ± 0.11	1.27 ± 0.02 [c]
							300	3.38	1.25 [d]
^{140}Ba	7.97 ± 0.26(5)	1.08 ± 0.01	8.07 ± 0.25(3)	1.06 ± 0.06	1.01 ± 0.05	0.98 ± 0.06	11.5	7.95 ± 0.26	1.04 ± 0.03 [c]
							300	7.49	1.05 [d]

[a] Number of replicate determinations.
[b] Reference 5.
[c] Reference 8.
[d] Reference 3.

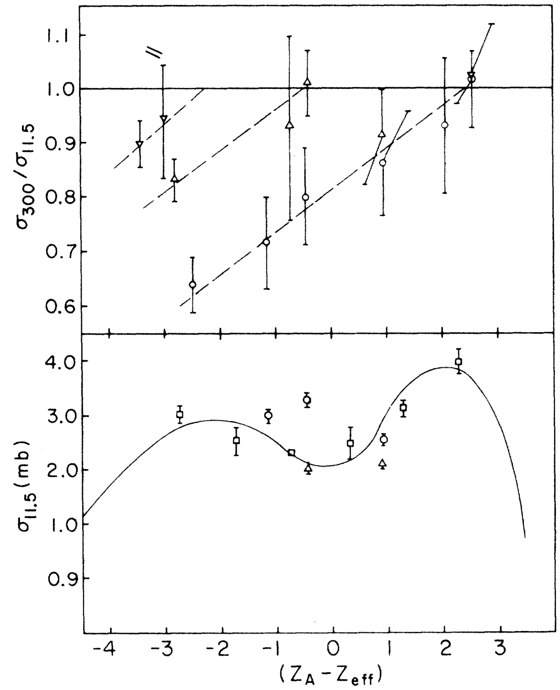

FIG. 1. Top: values of $\sigma_{300}/\sigma_{11.5}$ for iodine (○), cesium (△), and barium (▽) nuclides; the dashed lines show the trends of the data. Bottom: charge dispersion at $A = 131$ from 11.5-GeV proton bombardment of ^{238}U (curve, from Ref. 9); independent yields of I(○), Cs (△), Ba(▽), and products with $A = 131$(□) are shown.

nificantly lower cross section at 300 than at 11.5 GeV, ^{130}I, lies on the neutron deficient side of the fission peak but most of the decrease in cross section occurs over the spallation peak. The values of $\sigma_{300}/\sigma_{11.5}$ become as low as 0.64 ± 0.05 for ^{123}I. The cesium data display a similar but less striking trend than the iodine results while the trend is nearly, if not completely, absent from the barium data.

It is apparent that the observed decrease in cross sections cannot be attributed primarily to a change in the charge dispersion at 300 GeV because of the lack of correlation between the cross section ratios and $(Z_A - Z_{eff})$. A much better correlation is obtained when the ratios are plotted as a function of mass number, as shown in Fig. 2. It is seen that the ratios are essentially equal to unity for $A > 130$ but decrease rapidly below this mass number. In order to test the statistical significance of this trend χ^2 values were computed both for the dashed line fit to the data as well as for a constant value of 0.87, the average value of the experimental ratios exhibiting the indicated trend. χ^2 values of 4.5 and 41 were obtained, respectively. The two fits may be compared by

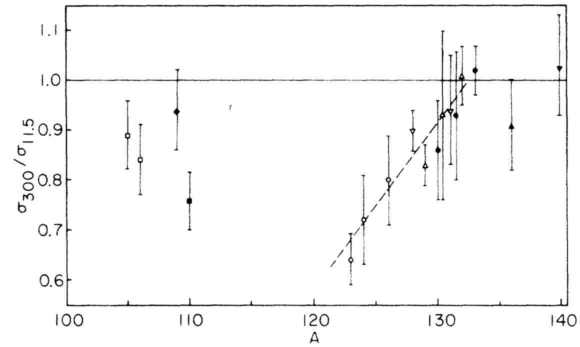

FIG. 2. Dependence of $\sigma_{300}/\sigma_{11.5}$ on A; ○, I nuclides; △, Cs; ▽, Ba; □, Ag (Ref. 3); ◇, Pd (Ref. 3). Open points represent neutron deficient products and closed points neutron excessive ones. The dashed line shows the trend of the data.

means of an F test which shows that, for the appropriate number of degrees of freedom, the dashed line trend is more valid than a constant value of $\sigma_{300}/\sigma_{11.5}$ at a 99% confidence level. Since no cross sections of any neutron excessive products having $A < 130$ were measured it is not known as yet whether the decrease in cross section occurs for both neutron excessive and neutron deficient products or only for the latter. Measure-

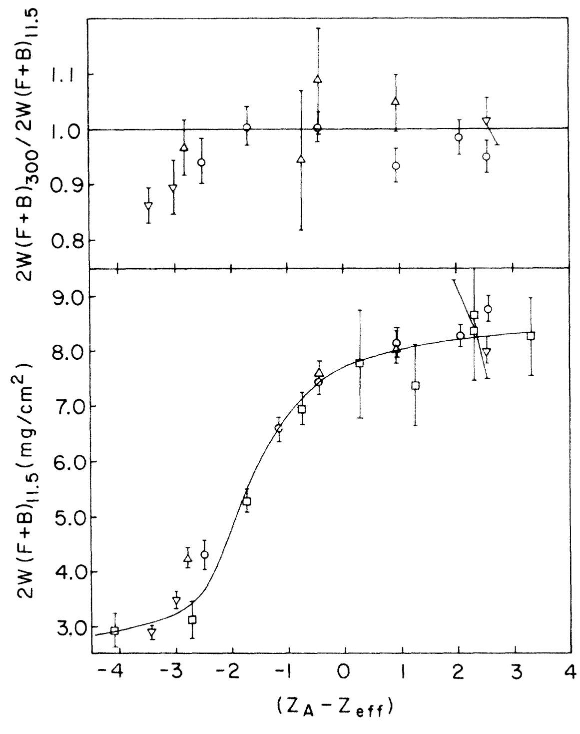

FIG. 3. Top: values of $2W(F+B)_{300}/2W(F+B)_{11.5}$ for products from ^{238}U. Bottom: values of $2W(F+B)$ at 11.5 GeV. The points and curve have the same meaning as in Fig. 1.

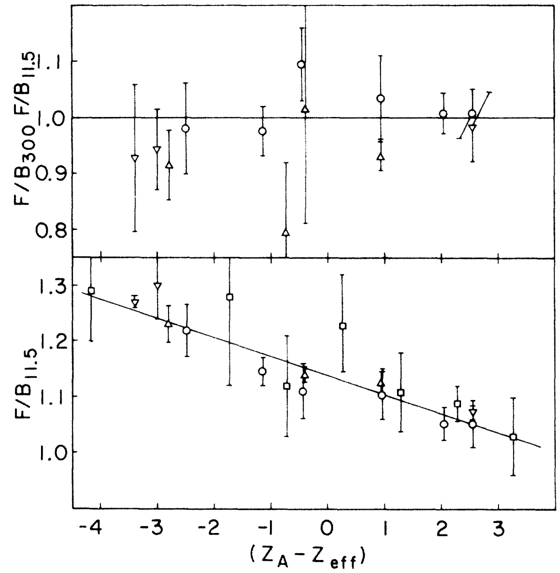

FIG. 4. Top: values of $(F/B)_{300}/(F/B)_{11.5}$ for products from ^{238}U. Bottom: values of F/B at 11.5 GeV. The points and curve have the same meaning as in Fig. 1.

ments on lower Z products, currently in progress, should provide the answer to this question. Figure 2 also includes some of the recent results obtained for somewhat lower A products by Chang and Sugarman.[3] It appears that the trend observed in the $A = 120-130$ mass region does not extrapolate into the $A = 100-110$ region.

The recoil ranges are plotted in Fig. 3 and the forward-to-backward ratios in Fig. 4. The bottom half of Fig. 3 shows the ranges determined in the present work at 11.5 GeV as well as those reported previously[9] for $A = 131$ products. The solid curve is taken from this earlier report. The striking decrease in the ranges of neutron deficient products is clearly apparent and the present results are in very good accord with the $A = 131$ data. The ratios of the ranges at 300 GeV to those at 11.5 GeV are plotted in the top half of Fig. 3. With the possible exception of the most neutron deficient Ba nuclides, the ranges appear to be independent of energy, the weighted average ratio being 0.96 $\pm$ 0.05.

The F/B values at 11.5 GeV decrease in linear fashion with increasing $(Z_A - Z_{eff})$. The values obtained at 300 GeV are, within the experimental uncertainties, equal to those at 11.5 GeV over the entire range of $(Z_A - Z_{eff})$ as witnessed by the weighted average value of $(F/B)_{300}/(F/B)_{11.5}$, 0.98 $\pm$ 0.05. The recoil data thus indicate that the energetics of fission and spallation are not particularly different at these two energies. Furthermore, the transition between fission and spallation appears to occur at essentially the same $(Z_A - Z_{eff})$ at both energies.

Our results may be compared with the previously reported 300 GeV data. The measurements on vanadium,[1] cobalt,[1] and silver[2] targets indicated that all the measured cross sections were nearly the same at 300 as at 10–30 GeV. The results for uranium[3] are similarly consistent with a cross section ratio of unity for products with $A < 70$ but $\sigma_{300}/\sigma_{11.5}$ decreases to about 0.8 for products in the $70 < A < 140$ mass region. The present data indicate that, at least in the $A \sim 130$ region, this decrease is confined to neutron deficient products having $A < 130$.

IV. CONCLUSIONS

Cross sections and recoil properties of 13 nuclides in the $A \sim 130$ mass region from the interaction of ^{238}U with 300- and 11.5-GeV protons have been determined. The values of $\sigma_{300}/\sigma_{11.5}$ of iodine products increase systematically with A and range from 0.64 ± 0.05 for ^{123}I to 1.02 ± 0.05 for ^{133}I. When the cross section ratios for all the measured nuclides are examined it is seen that they correlate well with A but poorly with the charge dispersion variable $(Z_A - Z_{eff})$. There appears to be a transition at $A \sim 130$ such that above this mass number the $\sigma_{300}/\sigma_{11.5}$ are unity while at lower A values the ratios decrease with decreasing A. The recoil ranges and F/B values of all products are essentially the same at 300 as at 11.5 GeV indicating that the energetics of fission and spallation as well as the transition point between these mechanisms remain unchanged.

The production of charged secondaries (mostly pions) in p-p collisions is known[14] to increase by about a factor of 3 between 10 and 300 GeV. The present as well as previous[1-3] comparisons of cross sections of complex nuclear reactions at these energies indicate that this increase in multiplicity has little effect on the deposition energy spectrum so that the additional pions produced at 300 GeV must escape from the struck nucleus with little or no energy loss. However, the trend described above gives the first indication that subtle differences may exist.

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