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# Nuclear reactions of $^{238}U$ with 300- and 11.5- GeV protons: Formation of nuclides in the A-110-140 mass region.*

Y. W. Yu, S. Biswas, and N. T. Porile
Department of Chemistry, Purdue University,
Lafayette, Indiana 47907.

Cross sections for the formation of a number of iodine, tellurium, and cadmium nuclides in the interaction of $^{238}U$ with 300- and 11.5- GeV protons have been determined. Including previously obtained results on cesium and barium nuclides we obtain a weighted average value of 0.92±0.14 for $\sigma_{300}/\sigma_{11.5}$ based on 34 values for nuclides in the A=110-140 region. The cross section ratios show little dependence on $Z_A$-Z.

NUCLEAR REACTIONS Measured σ of 28 Cd, Te, and I nuclides from 300- and 11.5- GeV proton bombardment of $^{238}U$.

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In a recent article[1] we reported the results of a comparative study of the cross sections and recoil properties of various iodine, cesium, and barium nuclides formed in the interaction of $^{238}U$ with 300 and 11.5 GeV protons. The most intriguing result of this work was the observed decrease of the cross section ratios, $\sigma_{300}/\sigma_{11.5}$, of the neutron deficient iodine isotopes to a value of 0.64±0.05 for $^{123}I$, the lightest nuclide detected in this study. These results were at variance with those obtained for the other nuclides measured in that work as well as with those obtained in previous[2-4] and more recent[5,6] comparative studies on other targets. All these other studies indicate that the differences in cross sections determined at 11.5 and 300 GeV are at most ∿ 10%.

In order to obtain more complete information on the energy dependence of the iodine production cross sections we have performed additional measurements designed to provide data on more neutron deficient iodine nuclides. In addition, we also determined values of $\sigma_{300}/\sigma_{11.5}$ for various cadmium and tellurium nuclides in order to examine in closer detail the A=110-130 mass region, where the previously observed decrease in cross sections appeared to be centered.

The 11.5 GeV irradiations were performed in the internal beam of the Zero Gradient Synchrotron at Argonne National Laboratory while the 300 GeV bombardments were done at the Meson Hall of the Fermi National Accelerator Laboratory. In both instances the target stacks consisted of 20 μm thick uranium foils surrounded by 20 μm aluminum catcher, monitor, and guard foils. Following the 10-30 minute irradiations the elements of interest were radiochemically separated and immediately assayed with Ge(Li) spectrometers.

Four irradiations were performed at 300 GeV and two at 11.5 GeV.

The results are summarized in Table I which lists the observed nuclides, the assayed γ-rays and their assumed abundances[7], the mode of formation, cumulative (C) or independent (I), the 11.5 GeV cross sections, and the cross section ratios, $\sigma_{300}/\sigma_{11.5}$. The results are based on a value of 8.6 mb for the cross section of the $^{27}Al(p,3pn)$ monitor reaction[8]. The cross sections have been corrected by up to 10% for secondary effects on both the uranium and monitor reactions on the basis of previously reported measurements in this mass region[9]. Some of the tabulated nuclides have progenitors whose half-lives are comparable to the irradiation and separation times. The experimentally determined cross sections of these nuclides represent partial cumulative yields and these were corrected on the basis of the 11.5 GeV charge dispersion curve for this mass region[9,10] to yield the tabulated cumulative cross sections. A similar correction had to be applied to the $\sigma_{300}/\sigma_{11.5}$ ratios although the effect is less important in this case because attempts were made to keep the bombardment and separation times at the two energies comparable. The corrections to the 300 GeV data were applied by an iterative procedure. The data were first corrected by use of the 11.5 GeV charge dispersion. The resulting $\sigma_{300}/\sigma_{11.5}$ values were used to obtain a corrected set of progenitor cross sections which were then used to obtain the tabulated values. Ratios requiring corrections greater than 10% due to this effect are identified in the table. The uncertainties in the tabulated data include an estimate of the effect of this correction as well as the random error obtained from the agreement between replicate determinations. The results listed for iodine nuclides with A=123-131 and A=133 include those determined in our previous study[1] as well as the present values.

The values of $\sigma_{300}/\sigma_{11.5}$ for the iodine nuclides are consistent with the previously reported trend[1], namely, a decrease from unity for the neutron-excessive isotopes to $\sim$ 0.6-0.7 for the most neutron deficient ones. The present results for the still more neutron deficient $^{121}I$, $^{120}I$, and $^{119}I$ indicate, however, that the above trend reverses itself so that the small values of $\sigma_{300}/\sigma_{11.5}$ are rather localized and only marginally different from those obtained for neighboring iodine nuclides.

In order to examine the measured ratios in the context of the charge dispersion curve applicable in this mass region it is convenient to plot the values of $\sigma_{300}/\sigma_{11.5}$ against $(Z_A-Z_{eff})$. The effective charge of a cumulative product, $Z_{eff}$, represents an average over all its isobaric precursors weighted by their relative formation cross sections while that of an independent product is given by its nuclear charge. The weighting factors were obtained by use of previously determined charge dispersions in this mass region[9,10]. The results are shown in Fig. 1. In addition to the present data we include the results for cesium and barium nuclides from our earlier work[1]. The top panel of Fig. 1 shows the charge dispersion curve obtained in this mass region at 11.5 GeV[9]. Recoil studies[9-12] have shown that deep spallation is the principal mechanism for $(Z_A-Z_{eff})<-2$ while fission predominates for $(Z_A-Z_{eff})\geq 0$. Both mechanisms presumably contribute to the formation of nuclides with intermediate $(Z_A-Z_{eff})$ values. Table II summarizes the weighted average values of $\sigma_{300}/\sigma_{11.5}$ for each of these regions.

It is apparent that the cross sections obtained at 300 GeV are, within the limits of error, equal to those obtained at 11.5 GeV for both the fission and the deep spallation regions. However, it appears that the 300 GeV cross sections are marginally smaller in the intermediate region. This may result from a

narrowing of the spallation and fission charge dispersions in the overlap region. The recoil ranges obtained for products in this region at 300 GeV are the same as those measured at 11.5 GeV indicating that the relative contribution of both mechanisms stays about the same[1].

The weighted average ratio of all 34 cross sections determined in the present and previous[1] studies is 0.92±0.14. This indicates that, at least in the A=110-140 mass interval, there is little overall difference in the cross sections for the formation of products from the interaction of $^{238}U$ with 300 and 11.5 GeV protons.

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Table I. Comparison of the formation cross sections of I, Te, and Cd nuclides produced in 11.5 and 300 GeV proton bombardment of $^{238}U$.

| Nuclide | γ-ray (keV) | Intensity per 100 decays | Mode of formation | $\sigma_{11.5}$ (mb) | $\sigma_{300}/\sigma_{11.5}$ |
|---|---|---|---|---|---|
| $^{119}I$ | 257 | 100 | C | 2.77±0.20 | 1.08±0.15 |
| $^{120}I$ | 560 | 100 | C | 2.65±0.15 | 0.86±0.10[a] |
| $^{121}I$ | 212 | 90 | C | 4.89±0.25 | 1.02±0.14[a] |
| $^{123}I$ | 159 | 83 | C | 9.54±0.30 | 0.70±0.10 |
| $^{124}I$ | 605 | 61 | I | 2.96±0.12 | 0.71±0.09 |
| $^{126}I$ | 388 | 34 | I | 3.28±0.11 | 0.71±0.08 |
| $^{130}I$ | 538 | 99 | I | 2.51±0.07 | 0.90±0.09 |
| | 740 | 87 | | | |
| $^{131}I$ | 364 | 82 | C | 9.09±0.47 | 0.96±0.11 |
| $^{132}I$ | 772 | 75 | I | 2.52±0.14 | 1.09±0.15 |
| $^{133}I$ | 530 | 90 | C | 8.54±0.32 | 1.02±0.05[a] |
| $^{134}I$ | 845 | 96 | C | 5.18±0.31 | 1.28±0.14[a] |
| | 883 | 66 | | | |
| $^{135}I$ | 1260 | 35 | C | 5.52±0.05 | 1.04±0.06 |
| $^{116}Te$ | 1294 | 85 | C | 2.99±0.15 | 1.00±0.10 |
| $^{117}Te$ | 719 | 65 | C | 4.92±0.05 | 1.05±0.10 |
| $^{119}Te$ | 644 | 85 | C | 4.55±0.48 | 1.21±0.13[a] |
| $^{119}Te^{m}$ | 153 | 62 | C | 3.64±0.25 | 1.27±0.10[a] |
| $^{121}Te$ | 573 | 80 | C | 8.11±0.44 | 0.93±0.10 |
| $^{121}Te^{m}$ | 212 | 82 | I | 3.22±0.21 | 0.79±0.11 |
| $^{123}Te^{m}$ | 159 | 84 | I | 3.27±0.34 | 0.67±0.10 |
| $^{129}Te^{m}$ | 455 | 15 | I | 2.60±0.05 | 0.60±0.18 |

Table I - Continued

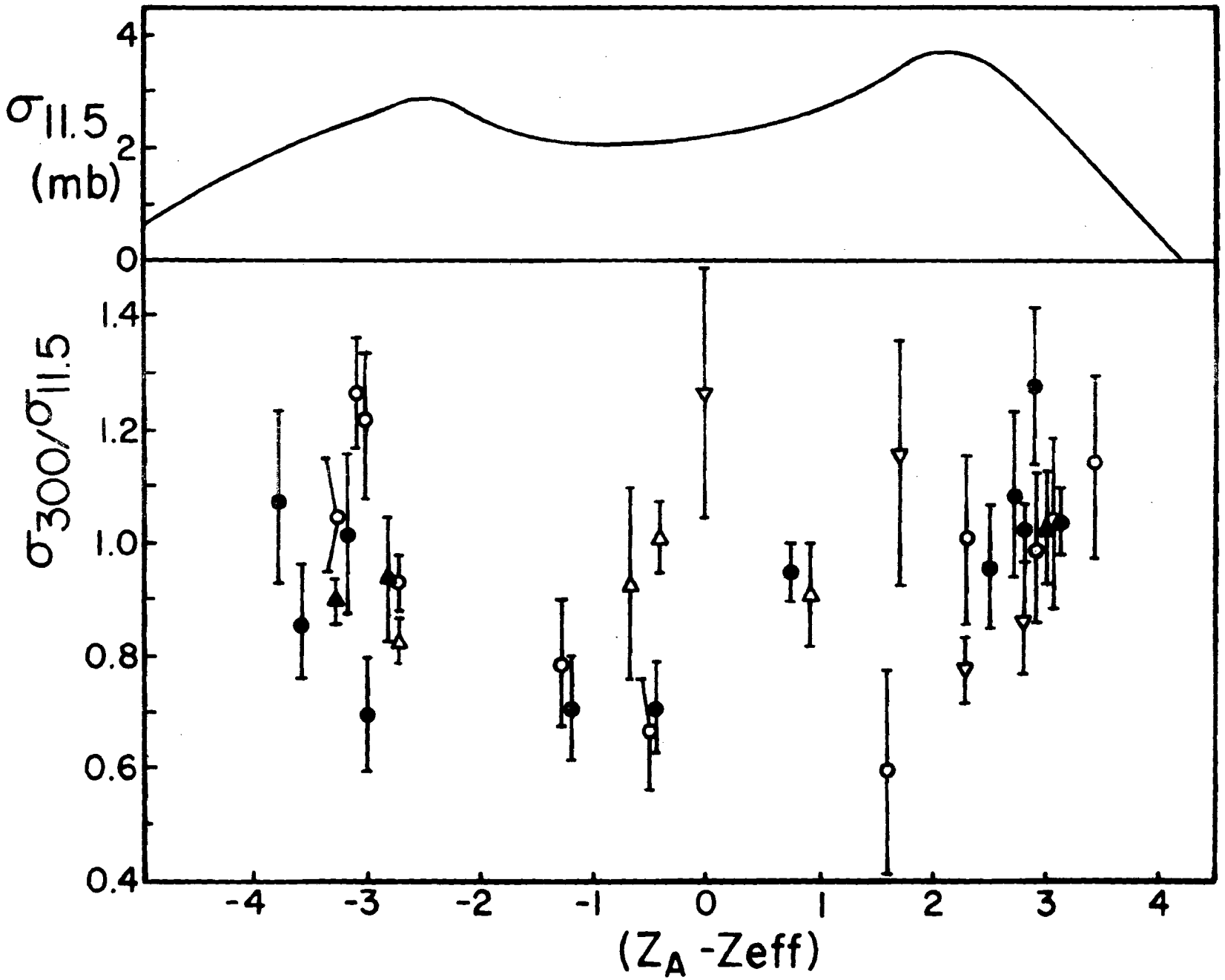
| Nuclide | γ-ray (keV) | Intensity per 100 decays | Mode of formation | $\sigma_{11.5}$ (mb) | $\sigma_{300}/\sigma_{11.5}$ |
|---|---|---|---|---|---|
| $^{131}Te^{m}$ | 850 | 31 | I | 2.39±0.35 | 1.01±0.15 |
| $^{132}Te$ | 230 | 90 | C | 6.68±0.74 | 0.99±0.14 |
| $^{133}Te^{m}$ | 754 | 85 | C | 2.87±0.49 | 1.04±0.15 |
| $^{134}Te$ | 181 | 22 | C | 3.13±0.31 | 1.14±0.16 |
| | 210 | 25 | | | |
| $^{111}Cd^{m}$ | 247 | 94 | I | 2.54±0.15 | 1.27±0.22 |
| $^{115}Cd$ | 530 | 28 | C | 13.8 ±0.8 | 0.78±0.08[a] |
| $^{117}Cd^{m}$ | 1247 | 11 | I | 1.94±0.09 | 1.15±0.22 |
| | 1337 | 8 | | | |
| $^{118}Cd$ | 1228 | 97 | C | 0.93±0.05 | 0.87±0.10 |

a. Correction for precursor decay prior to separation exceeds 10%

Table II. Weighted average cross-section ratios for products with A=110-140 lying in the indicated charge dispersion intervals.

| $(Z_A - Z_{eff})$ | $\langle\sigma_{300}/\sigma_{11.5}\rangle$ |
|---|---|
| < -2 | 0.92±0.12 |
| -2 to 0 | 0.83±0.14 |
| > 0 | 0.98±0.12 |
| -4 to 4 | 0.92±0.14 |

Figure 1 - Values of $\sigma_{300}/\sigma_{11.5}$ for products in the A=110-140 mass region formed in proton bombardment of $^{238}U$. ∇ - Cd isotopes, o - Te, ● - I, Δ - Cs (ref. 1), ▲ - Ba (ref. 1). The top panel shows the 11.5 GeV charge dispersion at A=131 (ref. 9).


$\sigma_{11.5}$ (mb)
4
2
0
$\sigma_{300}/\sigma_{11.5}$
1.4
1.2
1.0
0.8
0.6
0.4
-4
-3
-2
-1
0
1
2
3
4
$(Z_A - Zeff)$