# *THE FISSION OF URANIUM AND PROTACTINIUM AT HIGH EXCITATION ENERGIES*

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The fission of uranium and protactinium at initial excitation energies of up to 100 Mev is considered. The analysis is based on comparison of the yields of the uranium isotopes $U^{236} - U^{232}$ and protactinium isotopes $Pa^{231} - Pa^{227}$ (equal values of the parameter $Z^2/A$) produced in the disintegration of uranium $U^{238}$ by 340 Mev protons. The results of the analysis point to the emission nature of uranium and protactinium fission in the indicated range of initial excitation energy.

## INTRODUCTION

A series of studies carried out in our laboratory[1-4] have investigated the mechanism of the fission of heavy nuclei at high initial energies of excitation. The subjects of these investigations have been three fissionable heavy nuclei of distinctly different compostion ($_{92}U$, $_{83}Bi$, $_{74}W$).

Analysis of the fission events in tungsten[1] showed that the cross-sections for pure emission fission for nuclei with charge $Z \leq 71 - 72$ become sufficiently small that fission from a level somewhat higher than the level of emission fission begins to compete successfully. In the work studying the fission of Bi (Ref. 2) with 660-Mev protons an evaluation was carried out of the threshhold for emission fission for a series of elements (from Z = 72 to Z = 82). The values obtained for the threshholds for emission fission agree well with the corresponding values calculated by Gol'danskii.[5] Finally, an analysis of fission events in uranium ($E_p$ = 660 Mev) showed that the fission process at high initial energies of excitation can be divided into two stages. In the first stage the very highly excited uranium nucleus cools off by the evaporation of many particles (primarily neutrons). Fission occurs as the final act of the cooling process and takes place after the original nucleus has lost practically all of its initial excitation.

Thus heavy nuclei (U, Bi, W), having high excitation energies $U_0$, emit nucleons in the first stage of cooling down. Because of the Coulomb barrier, the most probable process is the evaporation of neutrons. Owing to the evaporation of neutrons, the critical value of the barrier for fission $U_f$ gradually decreases while the binding energy $\epsilon_n$ of a neutron in the residual nucleus increases. As a result of this process there comes a time when the critical value for fission becomes equal to the binding energy of a neutron in the residual nucleus ($U_f = \epsilon_n$).

According to the estimates made by Gol'danskii,[5] in order to get a condition $U_f = \epsilon_n$, tungsten must emit 16 neutrons, bismuth must emit 6, while for uranium, in general, no preliminary evaporation of neutrons is necessary. The initial energies of excitation necessary for the evaporation of the required number of neutrons with subsequent fission of the elements in question are as follows:

$$U_0(\mathrm{W}) = 210\ \mathrm{Mev};\ U_0(\mathrm{Bi}) = 61\ \mathrm{Mev};\ U_0(\mathrm{U}) = 5.2\ \mathrm{Mev}.$$

Since a cross-section for emissive fission can be regarded as the cross-section for the emission before fission of the required number of neutrons ($N \geq N_{fis} = A_0 - A_{fis}$), the number of which is determined by the relation $U_f \leq \epsilon_n$, and the relative probability for the emission of neutron to that for the emission of a proton decreases rapidly both with the increase in initial energy excitation and with decreasing charge of the fissioning nucleus, it is obvious that the cross-section for emissive fission should decrease strongly with decreasing charge of the fissioning nucleus. Nuclei lighter than tungsten must lose more than 16 neutrons to achieve the conditions for emissive fission (in the case that a charged particle is not emitted), and such a process is extremely unlikely at an initial energy of excitation $U_0 > 210$ Mev. Because of these reasons the cross-section for emissive fission becomes so small that fission from a level somewhat higher than the level for emissive fission begins to compete.[1] For nuclei in the region of bismuth the conditions for emissive fission $U_f \leq \epsilon_n$ are reached very easily, since at an initial excitation energy

$U_0 \sim 60$ Mev the most probable process is the emission of neutrons only. Thus the overwhelming majority of fissions are emissive.[2]

The most interesting situation in our opinion lies in the fission of highly excited nuclei ($U_0 \gg U_f$) with charge $Z > 88$. For this group of heavy nuclei, in agreement with the considerations of Gol'danskii, it is not necessary to emit neutrons in order to reach the condition $U_f = \epsilon_n$. For this reason the usual picture of emissive fission for these nuclei loses its meaning.

At an initial energy of excitation $U_0 \gg U_f$ there are possible three different variations of fission: (A) fission from the top level of excitation $E(E = U_0)$, (B) fission from an intermediate stay of excitation ($U_f < E < U_0$), (C) fission from a low state of excitation ($U_f < E \approx \epsilon_n$).

Fission from the low state of excitation will be designated "deep" emissive fission to emphasize that fission is the final act of cooling and occurs after the initial nucleus has gotten rid of almost all the initial energy of excitation by the preliminary evaporation of particles. Analysis of the results of the above mentioned work[5] led us to the conclusion that the fission of uranium, when it is initially very highly excited, proceeds according to this "deep" emissive fission mechanism. Additional confirmation of our conclusions about this "deep" emissive fission can be obtained, it seems to us, by analysis of the experimental data of Lindner and Osborne.[6] We now proceed to examine this work.

## ANALYSIS OF THE RESULTS OF LINDNER AND OSBORNE ON THE YIELDS OF SPALLATION PRODUCTS IN THE 340 MEV PROTON BOMBARDMENT OF URANIUM

The authors of this work,[6] studying the spallation products from the bombardment of uranium with 340 Mev protons, were able to determine the yields (among others) of isotopes of uranium and protactinium to mass A = 237. The cross-sections for the formation of the different isotopes of uranium and protactinium are given in Table I.

Since the masses of the lightest isotopes ($U^{228}$, $Pa^{227}$) differ from the original nucleus $U^{238}$ only by 10 mass numbers it is reasonable to assume that the original energy of excitation $U_0$ for those nuclei which, as a result of the cascade-evaporation process, lead to the formation of the given isotopes, does not exceed 80 — 100 Mev. The evaporation of a proton at such initial energies of excitation can be neglected. It follows, therefore, that those cases in which isotopes of protactinium are formed as a result of subsequent evaporation involve a first-stage cascade process in which two protons are ejected; in nuclei which gave rise to isotopes of uranium, the cascade process caused one proton to be knocked out.

An additional argument in favor of this picture is obtained from a comparison of the yields of two isobars (uranium and protactinium). Since the yields of the protactinium isobars ($A < 236$) are greater than the yields of the corresponding uranium isobars (Table I) it is very unlikely that one of the two protons arose from an evaporation process (at an initial excitation energy $U_0 \approx 80 - 100$ Mev the evaporation of only neutrons is a more probable process than the evaporation of one proton and the rest neutrons). Thus, if the original fast proton collides with a neutron and then (after several collisions) both leave the nucleus, the result is an excited $U^{237}$ nucleus, which, by subsequent cooling, gives some isotope of uranium (depending on the original energy of excitation). If, however, the original proton collides with a proton and both (likewise after several collisions) leave the nucleus, then the result is an excited $Pa^{237}$ nucleus which, by subsequent evaporation, gives various isotopes of protactinium. The relative probability of these two processes can be determined from the following equation:

TABLE I

| A | Cross-Section for the Formation of Uranium Isotopes, millibarns | Cross-Section for the Formation of Protractinium Isotopes, millibarns | $\sigma(Pa)/\sigma(U)$ |
|---|---|---|---|
| 237 | 50 | 35 | 0.7 |
| 236 | 30 | 25 | 0.84 |
| 235 | 20 | 21±2 | 1.05 |
| 234 | 10 | 14 | 1.4 |
| 233 | 6 | 12 | 2 |
| 232 | 3 | 8.7±1 | 2.9 |
| 231 | 1.1 | 7 | 6.4 |
| 230 | 0.35 ±0.12 | 5.1±0.5 | 14.5 |
| 229 | 0.06 ±0.005 | 2.5 | 42 |
| 228 | 0.038±0.002 | 1.7±0.2 | 45 |
| 227 | | 0.71±0.06 | |
| | $\Sigma\sigma$=121 mbn. | $\Sigma\sigma$=132 mbn. | |

$$\frac{N(U_{92}^{237})}{N(Pa_{91}^{237})} \approx \frac{A-Z}{Z}\left(\frac{\sigma_{pn}}{\sigma_{pp}}\right)_{\text{ins.nucl.}} \quad (1)$$

In order to evaluate the ratio $(\sigma_{pn}/\sigma_{pp})_{\text{ins.nucl.}}$ we start from the known relation of Goldberger,[7] according to whose calculations the correction to the cross-section for isotropic scattering is given by the relation

$$\sigma_{\text{ins.nucl.}} = \sigma_{\text{free}}\left(1 - \frac{7}{5}\frac{P_F^2}{P_i^2}\right) = \sigma_{\text{free}}\left(1 - \frac{7}{5}\frac{E_F}{E_i}\right). \quad (2)$$

Here $E_F$ is the nucleon energy corresponding of the Fermi momentum, $E_i$ is the energy of the incoming nucleus inside the nucleus ($E_i = E_0 + v$), where v is the depth of the potential hole. The values of the Fermi energies $E_F$ for a neutron and proton Fermi gas in a uranium nucleus are equal to $E_F = 27$ Mev (neutron gas) and $E_F = 21$ Mev (proton gas).

The change in the cross-section $\sigma_{pp}$ on going from free to bound particles can be determined directly from Eq. (2). Since the cross-section $\sigma_{pp} = \sigma_{nn}$ we used for the calculations the cross-section $\sigma_{nn}$ for neutrons having an average effective energy $\bar{E}_{n_0} = 380$ Mev,[8]

$$\sigma_{nn} = (20 \pm 1.4) \cdot 10^{-27} \text{ cm}^2; \quad (\sigma_{pp})_{\text{ins. nucl.}} = (\sigma_{nn})_{\text{free}}\left(1 - \frac{7}{5}\frac{E_F}{E_i}\right) = (18.4 \pm 0.7) \cdot 10^{-27} \text{ cm}^2. \quad (3)$$

To evaluate the cross-section $(\sigma_{pn})_{\text{ins. nucl.}}$ we proceed from the following consideration: (A) the differential n-p scattering cross-section at $\bar{E}_{n_0} = 380$ Mev is practically independent of the angle[9] over over a large angular interval (50 — 130°); (B) there is a significant increase in the differential n-p scattering cross-section in the angular regions 0 — 50° and 130 — 180°, i.e., in the region where the imparted momentum is small and the Pauli exclusion principle is most important; (C) we can separate out from the total n-p scattering cross-section the isotropic part for which the Goldberger relation is valid

$$(\sigma_{np})_{\text{isotr.}} = \sigma_{np}(\Phi = 90°) \cdot 4\pi = 29 \cdot 10^{-27} \text{ cm}^2. \quad (4)$$

Thus the lower limit for the n-p scattering cross-section inside the uranium nucleus can be obtained from the relation

$$(\sigma_{np})_{\text{ins. nucl.}} \geqslant (\sigma_{np})_{\text{isotr.}}\left(1 - \frac{7}{5}\frac{E_F}{E_i}\right) = 26 \cdot 10^{-27} \text{ cm}^2. \quad (5)$$

An upper limit to this scattering cross-section inside the uranium nucleus can be obtained from the assumption that the total n-p scattering cross-section for free particles is isotropic

$$(\sigma_{np})_{\text{ins. nucl.}} < (\sigma_{np})_{\text{free}}\left(1 - \frac{7}{5}\frac{E_F}{E_i}\right) = 36 \cdot 10^{-27} \text{ cm}^2. \quad (6)$$

The cross-section for n-p scattering by free particles at an effective neutron energy $\bar{E}_{n_0} = 380$ Mev (Ref. 9) is $\sigma_{np} = (40 \pm 4) \times 10^{-27}$ cm$^2$. The actual value of $\sigma_{np}$ inside the nucleus must lie within the indicated limits.[4,6]

$$36 \cdot 10^{-27} \text{ cm}^2 > (\sigma_{np})_{\text{ins. nucl.}} \geqslant 26 \cdot 10^{-27} \text{ cm}^2. \quad (7)$$

Using Eqs. (3) and (7) we can determine the numerical value of the relation (1)

$$\frac{N(U^{237})}{N(Pa^{237})} \approx \frac{146}{92}\frac{(31 \pm 5) \cdot 10^{-27}}{(18.4 \pm 0.7) \cdot 10^{-27}} = 2.7 \pm 0.5.$$

Thus the total number of excited uranium nuclei (which during subsequent cooling either undergo fission or emit neutrons giving the observed isotopes of $U^{237} - U^{238}$) should be about 2.7 times as great as the total number of excited protactinium nuclei (which also either undergo fission or else split to give isotopes of protactinium $Pa^{237} - Pa^{227}$). Since the integrated yield of the uranium isotopes $\sum_{A=228}^{237} \sigma(U_{92}^A)$ is approximately equal to the integrated yield of protactinium isotopes $\sum_{A=227}^{237} \sigma(Pa_{91}^A)$, it follows that the integrated probability of spallation of the protactinium nuclei is 2.7 times greater than the integrated spallation probability of uranium. In the process of cooling of both uranium and protactinium there is primarily a competition between two processes: emission of neutrons and fission. Thus it is clear that the smaller integral probability of spallation of $U^{237}$ indicates a large integral probability of fission of $U^{237}$ nuclei in comparison with $Pa^{237}$ nuclei.

However, the mere fact of the higher integrated probability of fission of $U^{237}$ nuclei in comparison with $Pa^{237}$ nuclei does not allow one to establish by which of the possible schemes the fission of these nuclei occurs, since both in a case of over the barrier fission [(A) and (B), page 269] and in the case of

"deep" emission fission the probability of $U^{237}$ fission should be greater than the probability of $Pa^{237}$ fission. In order to establish by which of the possible paths the fission procedes it is necessary, in our opinion, to introduce into the discussion the fission parameter $Z^2/A$. Table II presents the values of $Z^2/A$ for isobars of uranium and protactinium.

The values of the parameter $Z^2/A$ for corresponding isobars of uranium and protactinium differ by about 2%. However, if the isotopes of uranium are compared with isotopes of protactinium of 5 mass numbers lower (following the arrows in Table II), it is seen that the values of the $Z^2/A$ parameter for such pairs are the same.

TABLE II

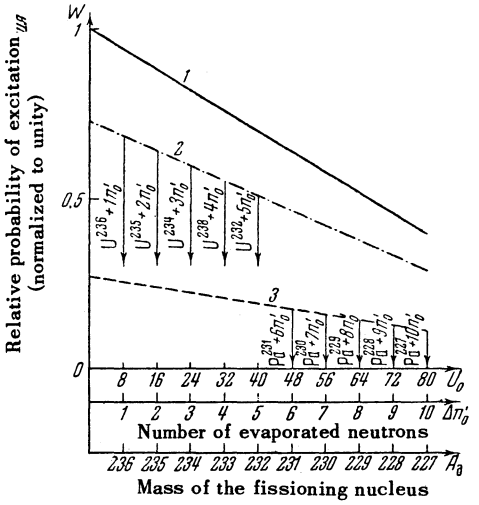
| A | $Z^2/A\ (U^A_{92})$ | $Z^2/A(Pa^A_{91})$ |
|---|---|---|
| 237 | 35.7 ← | 34.9 |
| 236 | 35.86 | 35.06 |
| 235 | 36.02 | 35.22 |
| 234 | 36.18 | 35.38 |
| 233 | 36.34 | 35.54 |
| 232 | 36.5 ← | → 35.7 |
| 231 | 36.66 | 35.86 |
| 230 | 36.82 | 36.02 |
| 229 | 36.98 | 36.18 |
| 228 | 37.14 | 36.34 |
| 227 | 37.3 | → 36.5 |

Using the numbers presented in Table I we can determine the relative yields from spallation for these indicated pairs. Table III shows that these ratios are practically constant for all the indicated pairs.

Further analysis of the data[6] must take into account the fact that, as a result of the cascade, there results a whole spectrum of excitation energies. It is known that the yield of excited nuclei decreases as the initial energy of excitation increases. According to indication given by the authors of the work being examined,[6] the spectrum of initial energies of excitation in the region 0 — 80 Mev changes in such a way that the yield of nuclei excited to energies $U_0 \sim 80$ Mev falls by a factor of 2 — 3.

The figure shows a possible spectrum of initial energy of excitation on the assumption that the yield of excited nuclei in the given interval of energy varies linearly. The solid line gives the total yield of uranium and protactinium nuclei, the dot-dash line gives the yield of uranium nuclei and the dashed line gives the yield of protactinium nuclei. The relative yield of excited uranium and protactinium nuclei is determined from relation (1).

Since we assume that as a result of the cascade process there is formed either a $U^{237}$ or $Pa^{237}$ nucleus, and that the final nuclei after spallation (for equal values $Z^2/A$) are shifted by 5 mass units, it follows that $Pa^{237}$ nuclei which give as a result of neutron evaporation an isotope of protactinium (for one of our comparable pairs) have initial energies of excitation 40 Mev higher than the initial energy of excitation of $U^{237}$ nuclei which give the corresponding isotope of uranium (it is assumed that each neutron emitted carries off an energy $\Delta U_0 = \epsilon_n + 2\bar{T} \approx 8$ Mev.




Distribution of uranium nuclei, $U^{237}$, and protactinium nuclei, $Pa^{237}$, as a function of initial excitation energy $U_0$. $\Delta n_0$ is determined from the relation $\Delta n_0 = U_0/(\epsilon_n + 2\bar{T}) \approx U_0/8$; $A_b = 237 - (U_0/8)$. 1 — $N(U^{237} + Pa^{237})$; 2 — $N(U^{237})$; 3 — $N(Pa^{237})$.

Analysis of the numbers presented in the diagram shows that the number of $U^{237}$ nuclei having initial energies of excitation in the interval 8 — 40 Mev and giving as a result of neutron evaporation the isotopes of $U^{236} - U^{232}$ is 4.2 times more abundant than $Pa^{237}$ nuclei having initial energies of excitation in the interval 48 — 80 Mev which lead as a result of neutron evaporation (6 — 10) to the protactinium isotopes $Pa^{231} - Pa^{227}$.

If the fission of $U^{237}$ and $Pa^{237}$ occurs according to the process of "deep" emission fission, i.e., if fission occurs when the relation $U_f < E \approx \epsilon_n$ is satisfied, then the probability for fission should be determined by the final value of the parameter $Z^2/A$. Thus, in the case of "deep" emission fission, the following relations should be satisfied for our pairs of nuclei with equal $Z^2/A$ (aside from the pair $U^{237} - Pa^{232}$, in which the nucleus $U^{237}$ is formed directly in the cascade process and has, by the assumption made above, zero excitation energy):

$$\frac{W(U^{237})_{U_0}}{W(Pa^{237})_{U_0+40}} \approx 1; \quad \frac{|N(Pa^{237})|_{U_0+40}}{|N(U^{237})|_{U_0}} \quad \frac{\sigma_{spall}(U^A_{92})}{\sigma_{spall}(Pa^{A-5}_{91})} \approx 1; \qquad (8)$$

In this equation W is the probability for spallation, $N(Pa^{237})_{U_0+40}$ is the number of $Pa^{237}$ nuclei having initial excitation energy $U_0 + 40$ Mev, $N(U^{237})_{U_0}$ is the number of $U^{237}$ nuclei having initial excitation energy $U_0$, $\sigma_{spall}(U^A_{92})$ is the cross-section for the formation of uranium spallation products with the given value of A, $\sigma_{spall}(Pa^{A-5}_{91})$ is the cross-section for the formation of protactinium spallation products having mass numbers 5 lower than the corresponding

uranium spallation products. The results of the test of the relation (8) are presented in Table IV.

TABLE III

| Yield of Isotopes of U, millibarns | | Yield of Isotopes of Pa, millibarns | | Relative Yields |
|---|---|---|---|---|
| $A$ | $\sigma$ | $A$ | $\sigma$ | $\sigma(U^A)/\sigma(Pa^A)$ |
| 237 | 50 | 232 | 8±1 | 5.7 |
| 236 | 30 | 231 | 7 | 4.3 |
| 235 | 20 | 230 | 5.1±0.5 | 3.94 |
| 234 | 10 | 229 | 2.5 | 4 |
| 233 | 6 | 228 | 1.7±0.2 | 3.54 |
| 232 | 3 | 227 | 0.71±0.06 | 4.2 |

The fourth column of the table gives the ratio of the number of excited $Pa^{237}$ nuclei giving isotopes of protactinium (for the pairs being considered) to the number of excited $U^{237}$ nuclei giving the corresponding isotopes of uranium (the numbers are taken from the curves in the figure). The fifth column gives the ratio of the yields of spallation products for the pairs being considered (the values are taken from Table III.).

We shall now try to analyze relation (8) from the point of view of "over the barrier fission," i.e., assuming that fission competes with neutron emission during the whole process of cooling. This cooling process can be broken up into steps of size $\Delta U_0 = \epsilon_n + 2\bar{T} = 8$ Mev. At each of these steps the nucleus can either undergo fission or emit a neutron. The relationship (8) for the first of our pairs ($U^{236} - Pa^{231}$) gives a value of unity (Table IV). From the point of view of "over the barrier fission" this means that the relative probability of emitting a neutron from an excited uranium nucleus is considerably smaller than the relative probability of emitting a neutron from an excited protaction nucleus. We shall elaborate on this in more detail.

TABLE IV

| Investigated Pairs | $U_0(U^{237})$ | $U_0(Pa^{237})$ | $\frac{N(Pa^{237})_{U_0+40}}{N(U^{237})_{U_0}}$ | $\frac{\sigma_{spall}(U_{92}^A)}{\sigma_{spall}(Pa_{91}^{A-5})}$ | $\frac{N(Pa)_{U_0+40}\,\sigma(U_{92}^A)}{N(U)_{U_0}\,\sigma(Pa_{91}^{A-5})}$ |
|---|---|---|---|---|---|
| $U^{236}$—$Pa^{231}$ | 8 | 48 | 0.257 | 4.3 | 1.08 |
| $U^{235}$—$Pa^{230}$ | 16 | 56 | 0.253 | 3.94 | 0.98 |
| $U^{234}$—$Pa^{229}$ | 24 | 64 | 0.234 | 4 | 0.94 |
| $U^{233}$—$Pa^{228}$ | 32 | 72 | 0.236 | 3.54 | 0.85 |
| $U^{232}$—$Pa^{227}$ | 40 | 80 | 0.216 | 4.2 | 0.9 |

The number of $U^{236}$ nuclei which have formed as a result of the emission of one neutron from $U^{237}$ nucleus excited originally by an amount $U_0 = 8$ Mev is equal to

$$N(U_{92}^{236}) \approx \omega N(U_{92}^{237})_{U_0=8\ \text{MeV}}, \tag{9}$$

where $\omega$ is the relative probability of emission of a neutron from a uranium nucleus. The cooling process of $Pa_{91}^{237}$ having an initial exciting energy $U_0 = 47$ Mev proceeds in 6 steps ($n_{step} = U_0/(\epsilon_n + 2\bar{T}) \approx 6$), in each of these steps there being the probability of an emission of a neutron. The number of $Pa_{91}^{231}$ nuclei is determined by the relation

TABLE V

| Investigated Pairs | Actual Value of the Left Side of (11′) | Value of the Left Side of Eq. (11′) on the Assumption of "Over the Barrier Fission" |
|---|---|---|
| $U^{236}$—$Pa^{231}$ | 1.08 | 1 |
| $U^{235}$—$Pa^{230}$ | 0.98 | 0.445 |
| $U^{234}$—$Pa^{229}$ | 0.94 | 0.197 |
| $U^{233}$—$Pa^{228}$ | 0.85 | 0.087 |
| $U^{232}$—$Pa^{227}$ | 0.9 | 0.039 |

$$N(Pa_{91}^{231}) \approx \omega_1^6 N(Pa_{91}^{237})_{U_0=48}. \tag{10}$$

The relative yields of $Pa^{231}$ and $U^{236}$ are determined by the relations

$$\frac{W(Pa_{91}^{231})}{W(U_{92}^{236})} = \frac{\omega_1^6 N(Pa_{91}^{237})_{U_0=48}}{\omega N(U_{92}^{237})_{U_0=8}} = \frac{\sigma_{spall}(Pa_{91}^{231})}{\sigma_{spall}(U_{92}^{236})}, \tag{11}$$

$$\frac{\sigma_{spall}(U_{92}^{236}) \cdot N(Pa_{91}^{237})_{U_0=48}}{\sigma_{spall}(Pa_{91}^{231})\, N(U_{92}^{237})_{U_0=8}} = \frac{\omega}{\omega_1^6}. \tag{11′}$$

The left side of (11′) is nothing more than Eq. (8) written for the first of our pairs ($U_{92}^{236} - Pa_{91}^{231}$) and is equal to unity as is seen from Table IV. It thus follows that for "over the barrier fission" $\omega/\omega_1^6 = 1$. We can get numerical values for $\omega$ and $\omega_1$ in the following way. We have

$$\frac{\sigma_{spall}(U_{92}^{236})}{\sigma_{spall}(Pa_{91}^{236})} = \frac{N_{spall}(U_{92}^{236})}{N_{spall}(Pa_{91}^{236})} = \frac{\omega N(U_{92}^{237})_{U_0=8}}{\omega_1 N(Pa_{91}^{237})_{U_0=8}}. \tag{12}$$

From relation (1) we have $N(U_{92}^{237})_{U_0=8}/N(Pa_{91}^{237})_{U_0=8} \approx 2.7$, and from Table I $\frac{\sigma_{spall}(U_{92}^{236})}{\sigma_{spall}(Pu_{91}^{236})} \approx 1.2$ and thus $\omega/\omega_1 = 1.2/2.7 = 0.445$. Thus $\omega = 0.38$ and $\omega_1 = 0.85$. Knowing the values of $\omega$ and $\omega_1$ we can calculate the left part of (11′) for all 5 pairs that interest us on the assumption of "over the barrier fission;"

$$\frac{|N(\mathrm{Pa}^{237})|_{U_0+40}}{|N(\mathrm{U}^{237})|_{U_0}} \cdot \frac{\sigma_{\text{spall}}(\mathrm{U}_{92}^{A})}{\sigma_{\text{spall}}(\mathrm{Pa}_{91}^{A-5})} = \frac{\omega^{\alpha}}{\omega_1^{\beta}}; \tag{13}$$

$$\alpha = U_0/(\varepsilon_n + 2\bar{T}) \approx U_0/8; \quad \beta = (U_0 + 40)/(\varepsilon_n + 2\bar{T}) \approx (U_0 + 40)/8. \tag{14}$$

The results of these calculations are presented in Table V.

The data of Table V show that the assumption of "over the barrier fission" gives results (column 3) which, in our opinion, cannot be reconciled with the experimental data (column 2). On the other hand, the results of the analysis presented in Table IV, show that relation (8) is satisfied sufficiently well and therefore this can be taken as an additional argument for "deep" emission fission of uranium and protactinium nuclei in the initial energy of excitation range under consideration.

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# *ON THE CROSS SECTION FOR PRODUCTION OF MULTIPLY CHARGED PARTICLES IN THE INTERACTION BETWEEN PROTONS AND NUCLEI*

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Nuclear emulsions were used to study the bombarding proton energy and atomic weight dependence of the cross section for production of multiply charged ($Z \geq 4$) particles in nuclear disintegrations due to fast protons. The cross section for production of particles possessing an energy greater than 1 — 2 Mev per nucleon varies from 3 to $12 \times 10^{-27}$ cm$^2$ for incident particle energies lying between 300 — 660 Mev if heavy nuclei (Ag, Br) are disintegrated and remains equal to $2 \times 10^{-27}$ cm$^2$ if light nuclei (C, N, O) are disintegrated. For a given energy of the incident particles the cross section of the reaction increases with increase of the mass number of the target nuclei.

## I. INTRODUCTION

IT is presently well known that the cross section for the reaction leading to the production of multiply