UCRL-17588 Rev.

cy. 2

University of California

Ernest O. Lawrence Radiation Laboratory

EVAPORATION OF 3 TO 8 NEUTRONS IN REACTIONS BETWEEN ^{12}C AND VARIOUS URANIUM NUCLIDES

Torbjorn Sikkeland, Jaromir Maly, and Donald F. Lebeck

November 1967

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

UCRL-17588 Rev. cy. 2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Submitted to Physical Review

UCRL-17588 Rev.
Preprint

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

EVAPORATION OF 3 TO 8 NEUTRONS IN REACTIONS BETWEEN ^{12}C AND VARIOUS URANIUM NUCLIDES

Torbjorn Sikkeland, Jaromir Maly, and Donald F. Lebeck

November 1967

EVAPORATION OF 3 TO 8 NEUTRONS IN REACTIONS BETWEEN ^{12}C AND VARIOUS URANIUM NUCLIDES.*

Torbjorn Sikkeland, Jaromir Maly,† and Donald F. Lebeck

Lawrence Radiation Laboratory
University of California
Berkeley, California

May 1967

ABSTRACT

Cross sections for the production of ^{242}Cf, ^{243}Cf, ^{244}Cf, ^{245}Cf, and ^{246}Cf in reactions between ^{12}C and ^{233}U, ^{234}U, ^{235}U, ^{236}U, and ^{238}U have been measured in the energy range of 60 to 110 MeV for ^{12}C.

A good fit is obtained to the peaks of the cross section curves. The fit involved 1.) calculation of the compound nucleus cross section by the use of the parabolic approximation to the real part of the optical model, 2.) modification of Jackson's formula for P_x to include fission and angular momentum effects, 3.) use of the Γ_n/Γ_f formula by Fujimoto and Yamaguchi.

The analysis suggests that the value of $\overline{\Gamma_n/\Gamma_f}$ is independent of the energy of ^{12}C. The formula by Fujimoto and Yamaguchi reproduces the experimental $\overline{\Gamma_n/\Gamma_f}$ values with a standard deviation of 16%.

I. INTRODUCTION

Heavy ion reactions, that are characterized by the formation of a compound nucleus followed by neutron emission, constitute a powerful method for producing and identifying neutron deficient nuclides. The excitation functions exhibit sharp peaks and their positions depend upon the number, x, of neutrons emitted and can therefore be used for mass assignments.

In a region where fission and charged particle emission can be ignored the cross section, σ_x, as a function of energy fits well the formula:[1]

$$\sigma_x = \sigma_{CN} P_x \qquad (1)$$

where σ_{CN} is the cross section for the formation of the compound nucleus, and P_x is the probability for the emission of exactly x neutrons and is calculated according to the Jackson formula[2] modified to include angular momentum effects.[1]

In the heavy element region the cross sections are strongly influenced by fission competition. Formula (1) must then be modified to include this effect. Fission may take place at each step in the cascade and the cross section can then be written as:[3,4]

$$\sigma_x = \sigma_{CN} P_x \prod_{i=1}^{x} \left[\Gamma_n / (\Gamma_n + \Gamma_f) \right]_i \qquad (2)$$

where Γ_n and Γ_f are level widths for neutron emission and fission, respectively. Again other modes of decay have been ignored during the cascade. The last term in Eq. (2) represents the fraction of nuclei that survives fission through the cascade of x neutrons.

The present work was undertaken in order to investigate in some detail the validity of Eq. (2). Special emphasis shall be placed on the study of the ratio Γ_n/Γ_f and its variation with various nuclear quantities.

Similar studies have been undertaken in the heavy element region with

p, d, α,[4,5] and heavier ions [3,6,7,8] as projectiles. For most of these cases the Jackson formula has been successful in reproducing the experimental data and the ratio Γ_n/Γ_f has been found to be independent of the energy of the ion. In a recent work with ^{18}O, ^{19}F, and ^{22}Ne incident on ^{238}U, Donets et al. concluded that Γ_n/Γ_f increased with increasing ion energy.[7]

We chose ^{233}U, ^{234}U, ^{235}U, ^{236}U, and ^{238}U as target nuclei which were bombarded with ^{12}C of energy up to 110 MeV to produce known californium nuclides with mass number from 242 to 246. (The nuclides ^{242}Cf and ^{243}Cf were discovered during these investigations and their decay properties have been reported elsewhere.[9,10]) This gives us the possibility of studying reactions with a wide range in x (3 to 8), excitation energy, (30 to 80 MeV), and mass number of cascading nuclei (243 to 250).

The systems $^{238}U(^{12}C, 4n)$, $^{238}U(^{12}C, 5n)$, and $^{238}U(^{12}C, 6n)$ had previously been measured,[3,6] but were included in our experiments to minimize relative errors.

II. EXPERIMENTAL

The targets were made by molecular plating, from an isopropyl alcohol solution, uranyl nitrate onto 5-mg/cm^2 Be foils to a thickness of about 0.5 mg/cm^2. The amount of uranium on the target was determined by pulse height analysis.

Beams of 124-MeV ^{12}C from the Hilac were, after magnetic deflection through 30 deg, degraded to the desired energy by the use of weighed Be foils. The range-energy curve of ^{12}C in Be, as measured by Walton, was used to estimate the energy.[11] The degraded energy spectrum was also measured by the use of a diffuse-junction Si detector and was very nearly Gaussian in shape. The full width at half maximum increased almost linearly with decreasing energy from 0.7 at 110 MeV to about 2 MeV at 60 MeV. The most probable energy is believed to be accurate to within 2 MeV.

The collimator in front of the target had a diameter of 0.6 cm. The average beam current was about 1.5×10^{-6} A. At these intensities the degrader foils had to be in contact with a water cooled copper surface.

The yield of the various α emitting californium isotopes was determined by the use of an α grid chamber in conjunction with a 200-channel pulse-height analyzer. The decay of the various α groups was generally followed through several half-lives.

As energy calibration standards the 5.80 and 7.68 MeV α group[5] from ^{244}Cm and ^{214}Po, respectively, were used.

Two methods were used to measure the cross sections. In one the relative cross sections were determined as a function of ion energy by the use of the recoil technique as described in Ref. 9. The recoil atoms produced in the reaction were slowed down in helium at a pressure of about 700 torr contained inside a cylindrical chamber of diam. 2.5 cm and length 4.4 cm. A Faraday cup for beam intensity measurement was located at the end of that chamber. In the middle of the chamber wall and vertical to the beam axis was a 0.2-mm orifice through which the helium gas with the recoils flowed into a larger chamber that was kept at a pressure of about one torr. The recoils were collected on a platinum disk placed in front of the orifice at a distance of about 2 mm. After bombardment, the foil was flamed to remove β and α activities of volatile elements produced from the Be foils, and Pb and Bi impurities. The time between end of bombardment and start of analysis was about one min.

The overall yield of this recoil technique was determined by measuring the absolute cross section at the peak of the reaction $^{238}U(^{12}C,4n)^{246}Cf$. In this experiment the ^{238}U target was facing the beam such that the recoil products were caught in the target itself or in its backing. The actinides were separated from beryllium by the use of a NaOH precipitation with Fe^{3+}

as carrier and from uranium and iron by the use of an ion-exchange column, and were finally electroplated from a NH_4Cl solution onto a Pt disk and then α pulse-height analyzed. ^{244}Cm tracer was added in the dissolving step to check the overall chemical yield.

We found the cross section for this system to be 59 ± 6μb which is to be compared to the values 28μb [3] and 62μb [6] as determined by other experimenters. The yield of the recoil technique was 10% and was reproduced with a standard deviation of 25%.

The possibility that the yield of this method varied with bombarding energy was not checked directly. The geometry of the chamber and the pressure of He were such that all recoils should have been stopped in the gas and not on the walls. With ^{238}U as target we find the ratios σ_4/σ_6 and σ_4/σ_5 to have the values 4.1 and 0.60, respectively, which are, within errors, in agreement with the values 5.4[3] and 0.7[6] obtained in earlier experiments indicating no systematic change in yield.

In the analysis we assumed the following values for the α energy, half life, and α branching for californium isotopes: ^{242}Cf, 7.39 MeV, 3.4 min, 100%;[9] ^{243}Cf, 7.05 MeV, 10 min, 10%;[10] ^{244}Cf, 7.21 MeV, 20 min, 100%;[10] ^{245}Cf, 7.14 MeV, 45 min, 66%;[12] ^{246}Cf, 6.75 MeV, 36 hr, 100%.[12]

Since no chemical separation was performed we considered possible interference from other nuclides with similar decay properties. We found that the following two series [12] in some cases hampered the analysis:

$$^{228}U \xrightarrow[6.67\ \text{MeV}]{9.3\ \text{min}} {}^{224}Th \xrightarrow[7.13\ \text{MeV}]{1\ \text{sec}} {}^{220}Ra \xrightarrow[7.43\ \text{MeV}]{0.03\ \text{sec}} {}^{216}Rn \xrightarrow[8.01\ \text{MeV}]{10^{-4}\ \text{sec}} {}^{212}Po \xrightarrow[8.78\ \text{Me}]{3\times10^{-7}\ \text{se}}$$

$$^{224}Ra \xrightarrow[5.68\ \text{MeV}]{3.64\text{d}} {}^{220}Rn \xrightarrow[6.28\ \text{MeV}]{51.5\ \text{sec}} {}^{216}Po \xrightarrow[6.78\ \text{MeV}]{0.16\ \text{sec}}$$

With ^{228}U present, the α groups in this series could interfere with ^{242}Cf, ^{243}Cf, ^{244}Cf, and ^{245}Cf activities, and with ^{224}Ra present the 6.78 MeV α group could interfere with ^{246}Cf activity. The presence of ^{228}U was

spotted by the 8.01 and 8.78 MeV groups. The excitation functions for the production of ^{228}U were not determined. We observed this series with all targets used. The threshold for its production increases with increasing A of the target from about 70 MeV ^{12}C with ^{233}U to about 110 MeV with ^{238}U. The interference from the ^{228}U series was serious only at the tails of the functions for ^{242}Cf and to some extent for ^{243}Cf, ^{244}Cf, and ^{245}Cf. For the latter three a more difficult problem was the separation of their α groups at 7.05, 7.14, and 7.22 MeV in the cases when one of them was dominating. In such cases questionable data were eliminated.

The interference from the ^{224}Ra series in the analysis of ^{246}Cf was never serious over the main part of the peak. The possibility that at the highest energies, i.e., at the tail of the curve, we have a contribution from ^{216}Po is not ruled out.

III. EXPERIMENTAL RESULTS

The experimental cross sections are plotted versus the bombarding energy, E_i, in Figs. 1-4. Typical errors are indicated by error bars and include (1) statistical errors in the counting, (2) standard deviation of 25% in recoil collection efficienty, and (3) uncertainty in target thickness. The maximum cross sections for σ_x and the corresponding energies for E_i are given in Table I.

The effects of energy spread of the beam on the width of the excitation functions were not taken into account. Such a correction might make some of the peaks as much as 2 MeV narrower.

IV Discussion

We shall make the assumption that Γ_n/Γ_f is independent of the bombarding energy. According to Formula (2) this implies that the shape of the cross section curve is determined by the product $P_x\sigma_{CN}$ only. We shall therefore separate the analysis into two parts. In part A we shall attempt to fit the shapes of $\sigma_{CN}P_x$ to those of the experimental curves. In part B experimental values for Γ_n/Γ_f are derived from Formula (2) by the use of calculated $\sigma_{CN}P_x$ values and experimental σ_x values. Finally, calculated Γ_n/Γ_f values shall be fitted to the experimental values.

A. The Shape of the Excitation Function.

Attempts were made to fit the shapes of the experimental curves by the use of the original Jackson Formula that do not include angular momentum terms.[2]

It turned out that the main part of a particular function could be fairly well reproduced with a value for T that was independent of the ion energy. However, T had to be increased as we increased x. Similar effects have been observed by Tarantin.[13] Typically a temperature of about 1.2 MeV was required for a 4n reaction whereas a value of 1.5 MeV had to be used for a 6n reaction. The main part of the peak of the former is at a lower bombarding energy than that of the latter. We felt it was inconsistent not to use, at the same value of E^*, the same temperature for various xn reactions. Modified to include angular momentum effects[1] the expression for $\sigma_{CN}P_x$ is:

$$\sigma_{CN}P_x = \sum_{\ell=0}^{\ell CN} \sigma_\ell P_{x,\ell} \qquad (3)$$

A brief outline of the definitions and calculations of the terms in equation (3) follows in part a through c.

a. σ_ℓ is the cross section for the ℓ-th partial wave of the incident ion. Using the optical model of the nucleus this cross section is given by the formula:[14]

$$\sigma_\ell = \pi \lambda\!\!\!^{-2} (2\ell + 1) T_\ell \qquad (4)$$

where $\lambda\!\!\!^{-}$ is the de Broglie wavelength of the projectile, and T_ℓ is the transmission coefficient of the wave. In the estimation of T_ℓ we use a parabolic approximation[15] to the real part of the effective optical model potential with the following values for its parameters: $V_o = -70$ MeV, $r_o = 1.24$ fermis and $d = 0.48$ fermis.

These values for the optical model parameters were obtained in Ref. 16 by fitting the sum $\sum_{\ell=0}^{\infty} \sigma_\ell$, defined as the total interaction cross section, to the measured total fission cross sections for the system $^{238}U(^{12}C,f)$ from the barrier up to 124 MeV.

b. ℓ_{CN} is a cut-off value above which only surface reactions take place and is adjusted such that the value of the ratio $\sum_{\ell=0}^{\ell CN} / \sum_{\ell=0}^{\infty} \sigma_\ell$ is 0.8. This value is empirical and is based on results from fragment-fragment angular correlation measurements for the system ^{238}U + 124 MeV ^{12}C.[17] It is then assumed that the value is independent of ion energy.[18]

c. The last term in Eq (3) is the probability for boiling out exactly x neutrons from a compound nucleus of angular momentum ℓ and is given by[1]

$$P_{x,\ell} = I\,(\Delta_x \quad 2x - 3) - I(\Delta_{x+1}, 2x-1), \text{ where}$$

$I(Z,n)$ is the incomplete gamma function and

$$\Delta_x = (E^* - \sum_{i=1}^{x} B_i - E_R)/T$$

$$\Delta_{x+1} = (E^* - \sum_{i=1}^{x} B_i - E_f - E_R^f)/T$$

Here E^* is the excitation energy of the compound nucleus as estimated from the ion energy and masses involved; B_i is the binding energy of the i-th neutron in the cascade; E_f is the fission barrier of the product nucleus where $E_f < B_i$; E_R and E_R^f are some average values of the rotational energies of the cascading nuclei at the equilibrium and saddle configurations, respectively; T is the nuclear temperature and it is assumed that the temperature for fission is equal that for neutron evaporation.

The calculations of $\sigma_{CN}P_x$ were performed on a CDC 6600 computer. Values for the nuclear masses and B_i were taken from the Tables by Foreman and Seaborg.[19] Their values are in excellent agreement with the known decay data in this region. Values for the fission barrier shall be taken from Viola and Wilkins[20] who obtained their values from an analysis of spontaneous fission half-life.

The nuclear temperature was used as an adjustable parameter.

The values for the rotational energies depend on the angular momentum distributions and the moments of inertia of the nuclei in the neutron cascade.

The ℓ - distributions depend mainly on the variation of Γ_n/Γ_f with ℓ since the average angular momentum carried off by a neutron is negligible, and γ emission presumably does not compete favorably with neutron emission and fission when the excitation energy is larger than B_i and E_f.

We shall make the extreme assumption that Γ_n/Γ_f is independent of ℓ. At each step in the cascade the ℓ - distribution of the nuclei is then equal to that of the compound nucleus. In the framework of the simple model, Γ_n/Γ_f is predicted to be proportional to $\exp(E_R^f - E_R)/T$ [21] when $E_R^f = E_R$. The latter energy can be estimated from the expression $(\hbar^2/2\mathfrak{J})\,\ell(\ell+1)$, where $\mathfrak{J}$ is the effective moment of inertia.[21] We shall use $\mathfrak{J}^o/\mathfrak{J}$ as an adjustable parameter assumed to be independent of E^* and ℓ . Here $\mathfrak{J}^o$ is the rigid body moment of inertia of a spherical nucleus of constant density and is given by $\mathfrak{J}^o = (2/5)Mr^2 A^{2/3}$, where M and A are the nucleidic mass and mass

number, respectively, and r_o is the radius parameter for which we used the value 1.22×10^{-13} cm.

Best overall fit was obtained with T = 1.20 MeV and $\mathcal{J}^o/\mathcal{J}$ = 1.25 with an uncertainty of 0.05 MeV and 0.25, respectively.

The calculated curves for $\sigma_{CN} P_x$ are compared to the experimental σ_x values in Fig. 1-4. For each curve the peak value for $\sigma_{CN} P_x$ is normalized to that for σ_x. The energy scales of the calculated curves have been displaced a certain amount, ΔE, relative to those of the experimental ones. The values for ΔE are listed in Table I. They were never larger than two MeV which is within the experimental uncertainties.

As is seen from the Figures, when data are available, the experimental curves exhibit a tail that is not reproduced by the calculated ones. The effect is small; i.e., the cross section at the tail is of the order of one percent of that at the peak. However, the discrepancy is regarded as significant.

Similar tails were observed for the reactions $^{238}U(^{12}C, 4n)\ ^{246}Cf$ where the yield was determined after chemical separation.[2,6] It is believed that the tails can not fully be explained by the presence of low energy carbon ions in the beam. The discrepancy is due to a breakdown of either the Jackson formula or the assumption that Γ_n/Γ_f is independent of E_i.

B. Γ_n/Γ_f Systematics

1. Experimental Γ_n/Γ_f Values

We define a mean value of Γ_n/Γ_f as:[4]

$$\overline{\Gamma_n/\Gamma_f} = \bar{G}/(1-\bar{G}) \qquad (9)$$

Here $\bar{G}$ is a mean value of $\Gamma_n/(\Gamma_n+\Gamma_f)$ defined as:

$$\bar{G} = \left[\prod_{i=1}^{x} \Gamma_n/(\Gamma_n+\Gamma_f)_i \right]^{1/x} \tag{10}$$

that according to Eq (2) is given by:

$$\bar{G} = \left[\sigma_x/(\sigma_{CN} P_x) \right]^{1/x} \tag{11}$$

Values for $\overline{\Gamma_n/\Gamma_f}$, estimated at the peak of σ_x and $\sigma_{CN}P_x$, are listed in Table I together with the quantity A_{av} which represents the mass number of the intermediate fissioning nucleus halfway along the evaporation chain.

The errors for $\overline{\Gamma_n/\Gamma_f}$, given in Table I, include experimental errors in σ_x, uncertainties in σ_{CN} (arising from an error of 0.02 fermis in r_o and d), and in P_x (due to uncertainties of 0.05 MeV in T and 0.25 in $\mathfrak{S}^o/\mathfrak{S}$). It is apparent from the Table that $\overline{\Gamma_n/\Gamma_f}$ within errors is independent of E_i.

2. Semi Empirical Formula for Γ_n/Γ_f

In the estimation of $P_{x,\ell}$ we made the assumption that Γ_n/Γ_f is independent of ℓ. A sufficient condition for $\overline{\Gamma_n/\Gamma_f}$ to be independent of E_i will then be that Γ_n/Γ_f also is independent of the excitation energy. A formula that expresses such an independence of excitation energy and angular momentum is the following one, that was developed by Fujimoto and Yamaguchi,[22] and modified by Vandenbosch and Huizenga[5] to include odd even effects:

$$\Gamma_n/\Gamma_f = (2T/K_o)A^{2/3} \exp (E_f' - B_n')/T \tag{12}$$

Here T is the nuclear temperature,

$K_o \simeq 9.8$ MeV,

$$E_f' = E_f + \alpha\Delta_f; \alpha = \begin{cases} 2 \text{ for even-even fissioning nucleus} \\ 1 \text{ for even-odd } \quad " \quad " \end{cases}$$

$$B_n' = B_n + \alpha\Delta_n; \alpha = \begin{cases} 2 \text{ for even-even nucleus after emission of one neutron} \\ 1 \text{ for even-odd } \quad " \quad " \quad " \quad " \quad " \quad " \end{cases}$$

and Δ_f and Δ_n are the paring energies at saddle and equilibrium, respectively, and are assumed to be constants. It is then assumed that the exponential level density dependence on excitation energy is determined from the mass surface of the odd-odd nuclei, and that the temperature for fission is equal to that of neutron evaporation.[21]

In a cascade of x neutrons the geometric mean value for Γ_n/Γ_f can be written as:

$$\overline{\Gamma_n/\Gamma_f} = c\, A_{av}^{2/3} \left[\exp\left(\beta\, \Delta/x\right)\right] \exp(\Sigma\, E_f - \Sigma\, B_n)/(xT) \qquad (13)$$

where

$$c = (2T/K_o)\exp(1.5/T)(\Delta_f - \Delta_n) = \text{const.},$$

$$\beta = \begin{cases} 0, & n_{ee} = n_{eo} \\ 1, & n_{ee} > n_{eo} \\ -1, & n_{ee} > n_{eo} \end{cases}$$

(n_{ee} and n_{eo} are the numbers of even-even and even-odd nuclides in the cascade, respectively).

$$\Delta = (\Delta_f + \Delta_n)/2T = \text{const.}$$

Values for $\overline{\Gamma_n/\Gamma_f}$ calculated according to this formula were now fitted to experimental ones by adjusting the constants, c, Δ, and T. Taking values for B_n and E_f from Refs. 19 and 20, respectively, we obtained a best fit with c=0.33, Δ=1.5, and T=0.59 MeV with which experimental values were reproduced with a st. dev. of 16%. Calculated and experimental $\overline{\Gamma_n/\Gamma_f}$ values are compared in Table I.

We shall in the following make a few comments about the values of the parameters used in Eq (13).

c. It has been suggested from spontaneous fission systematics that Δ_f has the value 1.2 MeV[20] and Δ_n is about 0.7 MeV. Inserting these values and T = 0.59 and K_o = 9.8 MeV into the expression for c, we estimate its value to be 0.43 as compared to 0.33 found in the analysis. This good agreement is to be regarded as fortuitous. Considering the uncertainties in the values of the parameters in the expression for c its estimated value must have an error of at least 50%.

Δ. The first exponential term in Eq(13) represents the odd-even effect. The importance of this term is demonstrated by the fact that, for the cases where x is an odd number, the average deviations of calculated $\overline{\Gamma_n/\Gamma_f}$ values from experimental ones, with and without that term, were 16% and 32%, respectively,

From the values of 1.5 for Δ and 0.6 MeV for T we obtain the value 1.8 for the sum $(\Delta_f + \Delta_n)$ that is in agreement with the expected value of 1.9 MeV.

T. Our value for this parameter is in excellent agreement with the value of 0.6 MeV obtained by Vandenbosch and Huizenga[5] in a similar analysis, using experimental Γ_n/Γ_f values from p, d, and α induced reactions.

V. CONCLUSION

A good fit has been obtained to the peaks of measured cross section curves using formulas that are based on the assumptions that the temperature is independent of excitation energy, that the temperature for fission is equal to that for neutron evaporation and that Γ_n/Γ_f is independent of angular momentum. Angular momentum effects have to be introduced into Jacksons formula for P_x when used in the heavy element region as was the case in the rare earth region.[1]

We shall make a few remarks about some of the quantitive results of our analysis.

The value of the nuclear temperature as used in the formula for $P_{x,\ell}$ is 1.20±0.05 MeV, which is significantly higher than that of 0.59±0.05 MeV found to fit the $\overline{\Gamma_n/\Gamma_f}$ data. It is interesting to note that the former is the average temperature of the nuclides that survive fission through the cascade, whereas the latter is the corresponding one of all nuclides except the product nucleus. In the framework of the level density formula $\rho = \rho_0 \exp(aE/A)^{1/2}$ this difference in the temperatures suggests that Γ_n/Γ_f increases with increasing excitation energy.[23] The same level density formula does in fact predict such an energy dependence.[21]

The assumption that the angular momentum distribution is the same at each step of the cascade is not necessarily valid. In our analysis the adjustment of the value for $\mathcal{J}^o/\mathcal{J}$ can compensate for any breakdown of this assumption. However, the value of 4.5 keV obtained for the quantity $\hbar^2/2\mathcal{J}$ is not unreasonable. The value for the $\hbar^2/2\mathcal{J}^o$ is 3.6 keV for A = 250 . The deformed nuclei in this region of the periodic table, have $\hbar^2/2\mathcal{J}$ values, as deduced from the rotational energies near ground state, of about 7 keV. If, as is predicted,[21] E_R^f is smaller than E_R, and thus Γ_n/Γ_f decreases with increasing ℓ, the value for $\hbar^2/2\mathcal{J}$ will be less than 4.5 keV.

It is apparant from these results that one can not, on the basis of excitation functions, draw any detailed quantitative conclusions about the effect of angular momentum and excitation energy on the level widths for neutron emission and fission. However, the usefulness of the formulas for $P_{x,\ell}$ and Γ_n/Γ_f should be evident. They have few adjustable parameters, are relatively easy to use and can be used in mass assignments and in the prediction of cross sections in nucleo-synthesis.

As a final note we shall make a few remarks regarding the conclusion drawn by Donets et al that Γ_n/Γ_f increased with increasing excitation energy.[7] They used the unmodified Jackson Formula and values for σ_{CN} taken from those calculated by Thomas using the square well model.[24] These values are too high at the barrier.[13] This error decreases with increasing E_i. As shown in calculations[25] this will result in experimental $\overline{\Gamma_n/\Gamma_f}$ values that are too high for the lowest x, i. e., for the lowest excitation energies, and thus give the apparent effect that Γ_n/Γ_f increases with E^*. We believe that a variation of Γ_n/Γ_f with E^*, has not yet been experimentally demonstrated in reactions between heavy elements and heavy ions.

VI. ACKNOWLEDGMENT

We want to thank Dr. Albert Ghiorso for help in the experiments and the Hilac crew for furnishing excellent beams of ^{12}C ions. One of us (J. M.) expresses his gratitude to the International Atomic Energy, Vienna, Austria, for a research grant.

*This work was done under the auspices of the U. S. Atomic Energy Commission.

†On leave of absence from the Institute of Nuclear Research, Prague, Czechoslovakia.

1. T. Sikkeland, International Symposium on "Why and How Should we Investigate Nuclides far off the Stability Line?", Lysekil, Sweden, Aug. 1966.

2. J. D. Jackson, Can. J. Phys. 34, 767 (1956).

3. T. Sikkeland, S. G. Thompson, and A. Ghiorso, Phys. Rev. 112, 543 (1958).

4. R. Vandenbosch, T. D. Thomas, S. Vandenbosch, R. A. Glass, and G. T. Seaborg, Phys. Rev. 111, 1358 (1958).

5. For a review of these studies see R. Vandenbosch and J. R. Huizenga, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, 1958 (United Nations, New York, 1958) 15, P/688.

6. V. V. Volkov, L. I. Guseva, et al, J. Exptl. Theoret. Phys, (USSR) 36, 762 (1959).

7. E. D. Donets, V. A. Schegolev, and V. A. Ermakov, Soviet Journal of Nucl. Phys. 2, 1015 (1965).

8. V. L. Mihkeev, V. I. Ilyuschenko, and M. B. Miller, Preprint P-2694, Joint Institute for Nuclear Research, Dubna USSR (1966).

9. T. Sikkeland, and A. Ghiorso, Physics Letters 24B, 331 (1967).

10. T. Sikkeland, A. Ghiorso, J. Maly, and M. J. Nurmia, Physics Letters, 24B 333 (1967).

11. J. R. Walton, Lawrence Radiation Laboratory, University of California (1960), (unpublished results).

12. D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. 30, 585 (1958).

13. N. I. Tarantin, J. Exptl. Theoret. Phys. (USSR) 38, 250 (1960).

14. R. D. Woods and D. S. Saxon, Phys. Rev. 95, 577 (1954).

15. D. L. Hill and J.A. Wheeler, Phys. Rev. 89, 1102 (1953).

16. V. E. Viola, Jr., and T. Sikkeland, Phys, Rev. 128, 767 (1962).

17. T. Sikkeland, and V. E. Viola, Jr., In Proc. Third Conf. on Reactions between Complex Nuclei, Asilomar, April 14-18, 1963(University of California Press, Berkeley 1963).

18. T. Sikkeland, Phys. Rev. 135, B669 (1964).

19. B. M. Foreman, Jr, and G. T. Seaborg, J. Inorg. Nucl. Chem. 7, 305 (1958).

20. V. E. Viola, Jr., and B. D. Wilkins, Nuclear Phys. 82, 65 (1966).

21. J. R. Huizenga, and R. Vandenbosch, in Nuclear Reactions, ed. By P. M. Endt and P. B. Smith (North-Holland Publishing Company, Amsterdam, 1962).

22 Y. Fujimoto and Y. Yamguchi Prog. Theor. Phys. 5, 76 (1950).

23. J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley and Sons, Inc., New York, 1952).

24. T. D. Thomas, Phys. Rev. 116, 703 (1959).

25. T. Sikkeland, Lawrence Radiation Laboratory Report UCRL-16348, Aug. 1965 (unpublished).

Table I. Results of the analysis of experimental maximum cross sections obtained in $U(^{12}C, xn)Cf$ reactions. Symbols not defined in the text are, A_t = mass number of target nucleus, A_p = mass number of the product nucleus. The calculated values for $(\sigma_{CN}P_x)_{max}$ and $\overline{\Gamma_n/\Gamma_f}$ were obtained by the use of the formulas by Jackson (modified) and Fujimoto and Yamaguchi, respectively. The values for $E_{i,max}$ and $\sigma_{x,max}$ were taken from the curves in Figs. 1-4.

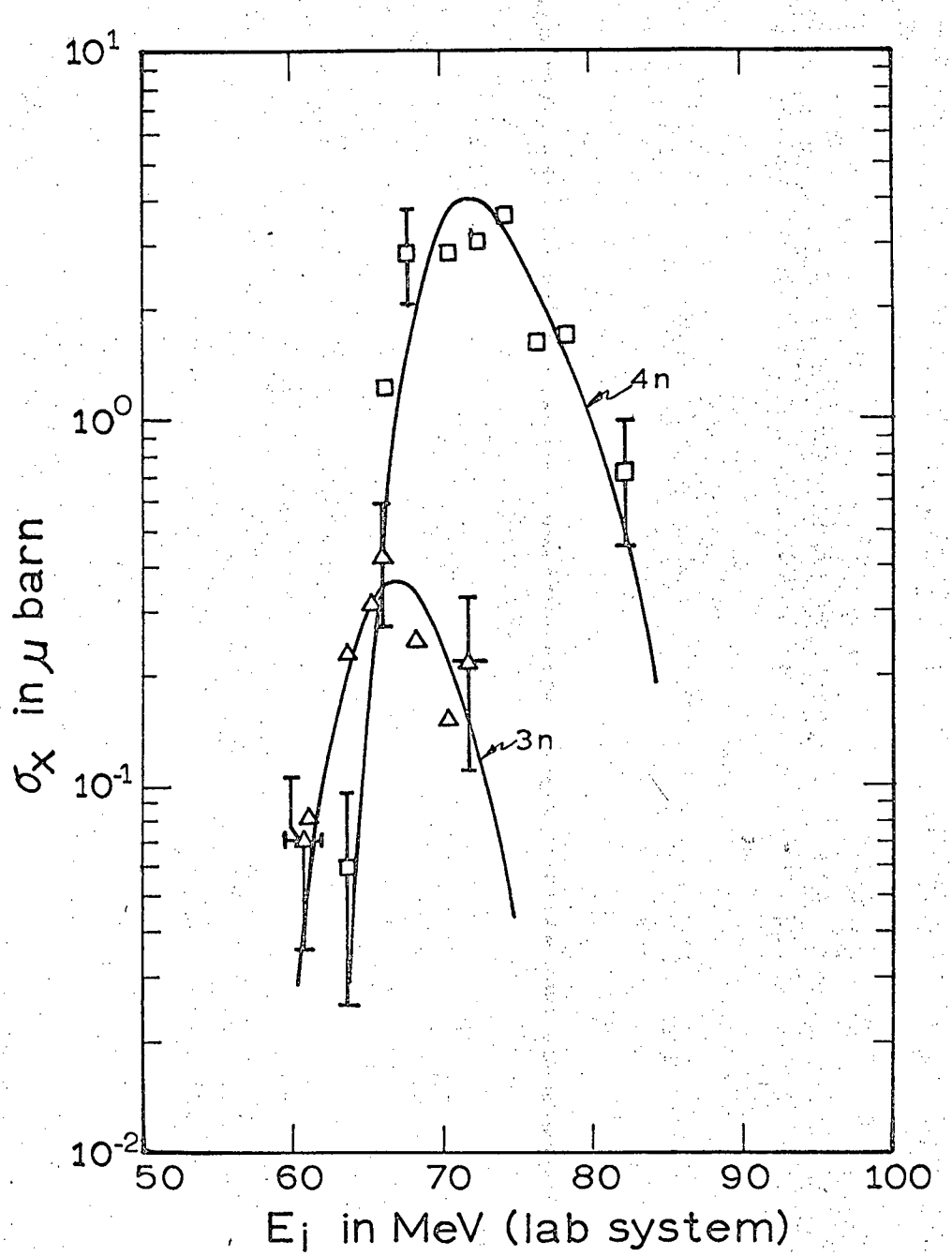
A_t	x	A_p	$E_{i,max}$ (MeV)	$\sigma_{x,max}$ (μb)	ΔE	$(\sigma_{CN}P_x)_{max}$ (mb)	A_{av}	$\overline{\Gamma_n/\Gamma_f}$ (exp)	$\overline{\Gamma_n/\Gamma_f}$ (calc)
238	4	246	67.5	62	2.0	26	248.5	0.28±0.03	0.30
238	5	245	73.5	100	1.5	260	248	0.26±0.01	0.25
238	6	244	83.5	15	0	400	247.5	0.22±0.01	0.23
238	7	243	~95	3.0	0.5	550	247	0.21±0.01	0.20
238	8	242	~115	0.29	1.0	520	246.5	0.20±0.01	0.17
236	3	245	67.5	2.5	0	1.5	247	0.13±0.03	0.19
236	4	244	70	22	0	48	246.5	0.17±0.02	0.17
236	5	243	77.5	9.8	0	300	246	0.15±0.01	0.14
236	6	242	88	2.1	~1.0	420	245.5	0.15±0.01	0.13
235	3	244	67.5	1.5	0	0.75	246	0.14±0.04	0.15
235	4	243	70.5	8.8	0	80	245.5	0.11±0.02	0.13
235	5	242	77.5	5.0	-0.5	270	245	0.13±0.01	0.12
234	4	242	72	4.0	1.0	90	244.5	0.089±0.009	0.098
233	3	242	67	0.37	-1.0	2.0	244	0.060±0.016	0.087

Fig. 1. Experimental cross sections, σ_x, plotted versus ^{12}C energy, E_i, for the systems $^{233}U(^{12}C, 3n)\ ^{242}Cf$ (△) and $^{234}U(^{12}C, 4n)\ ^{242}Cf$ (□). The curves represent the function $\sigma_{CN}P_x$ normalized at the peak to the experimental points. The energy scales for the curves are displaced ΔE MeV relative to that of the Figure. Values for ΔE are given in Table I.

Fig. 2. Experimental cross sections, σ_x, plotted versus ^{12}C energy, E_i, for the $^{235}U(^{12}C, xn)^{247-x}$ Cf reactions. The symbols and corresponding values of x for the experimental points are, △, 3n; □, 4n; O, 5. The curves represent the function $\sigma_{CN}P_x$ normalized at the peak to the experimental points. The energy scales for the curves are displaced ΔE MeV relative to that of the Figure. Values for ΔE are given in Table I.

Fig. 3. Experimental cross sections, σ_x, plotted versus ^{12}C energy, E_i, for $^{236}U(^{12}C, xn)^{247-x}$ Cf reactions. The symbols and corresponding values of x for the experimental points are, △, 3n; □, 4n; O, 5n; +, 6n. The curves represent the vunction $\sigma_{CN}P_x$ normalized at the peak to the experimental points. The energy scales for the curves are displaced ΔE MeV relative to that of the Figure. Values for ΔE are given in Table I.

Fig. 4. Experimental cross sections, σ_x, plotted versus ^{12}C energy, E_i, for $^{238}U(^{12}C, xn)^{250-x}$ Cf reactions. The symbols and corresponding values for x for the experimental points are, □, 4n; O, 5n; +, 6n; △, 7n; ●, 8n. The curves represent the function $\sigma_{CN}P_x$ normalized at the peak to the experimental points. The energy scales for the curves are displaced ΔE MeV relative to that of the Figure. Values for ΔE are given in Table I.



XBL 675 2046

Fig. 1

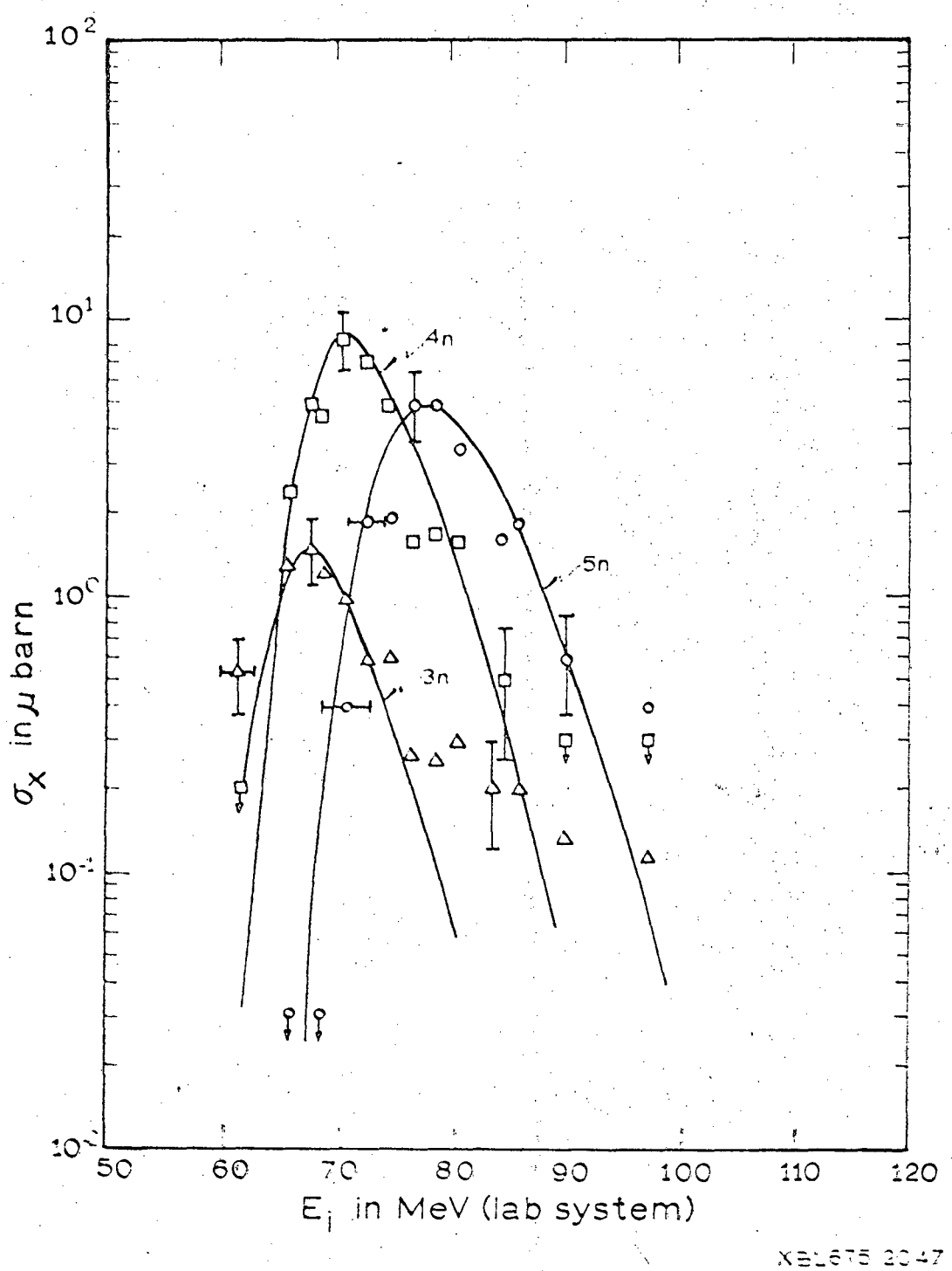
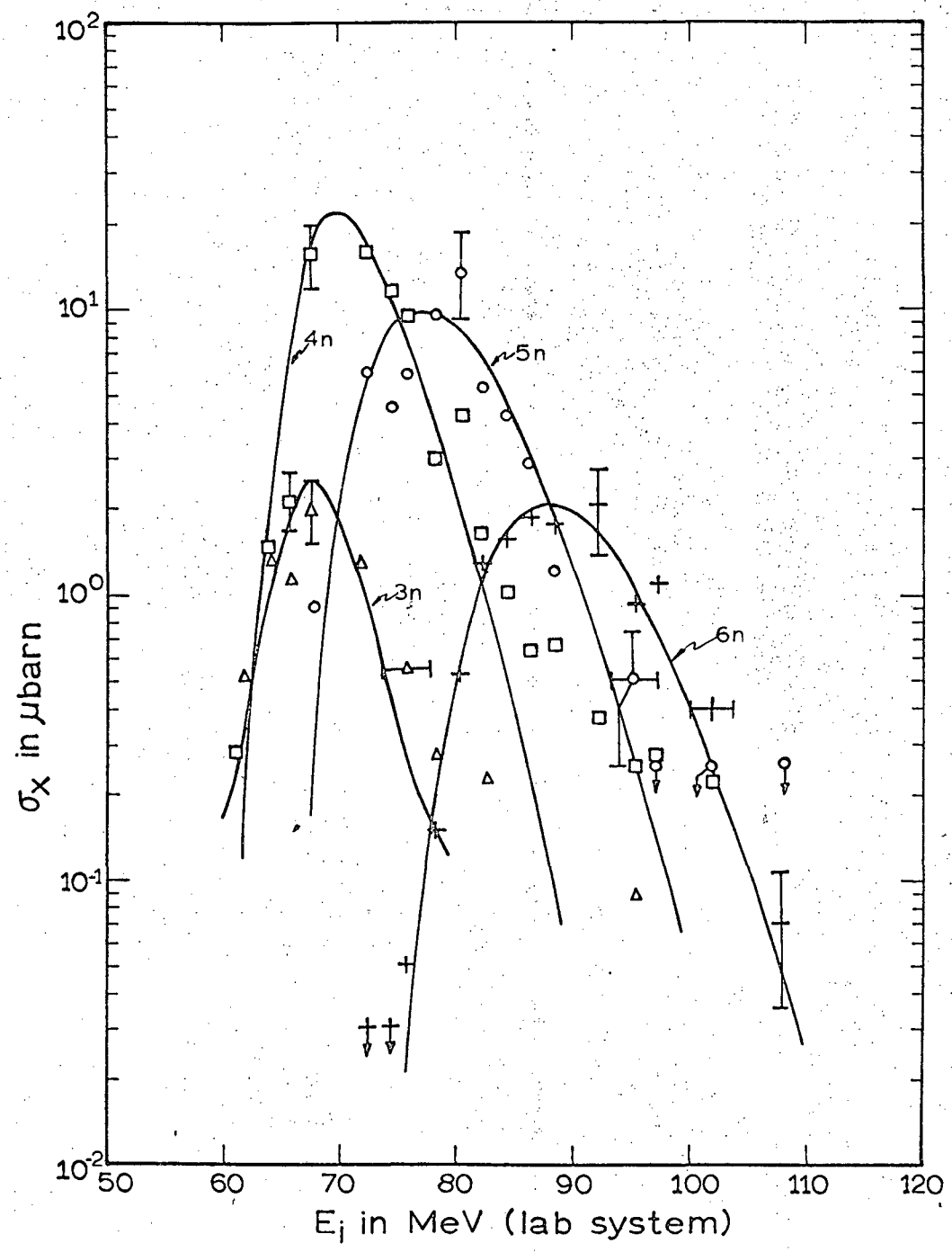
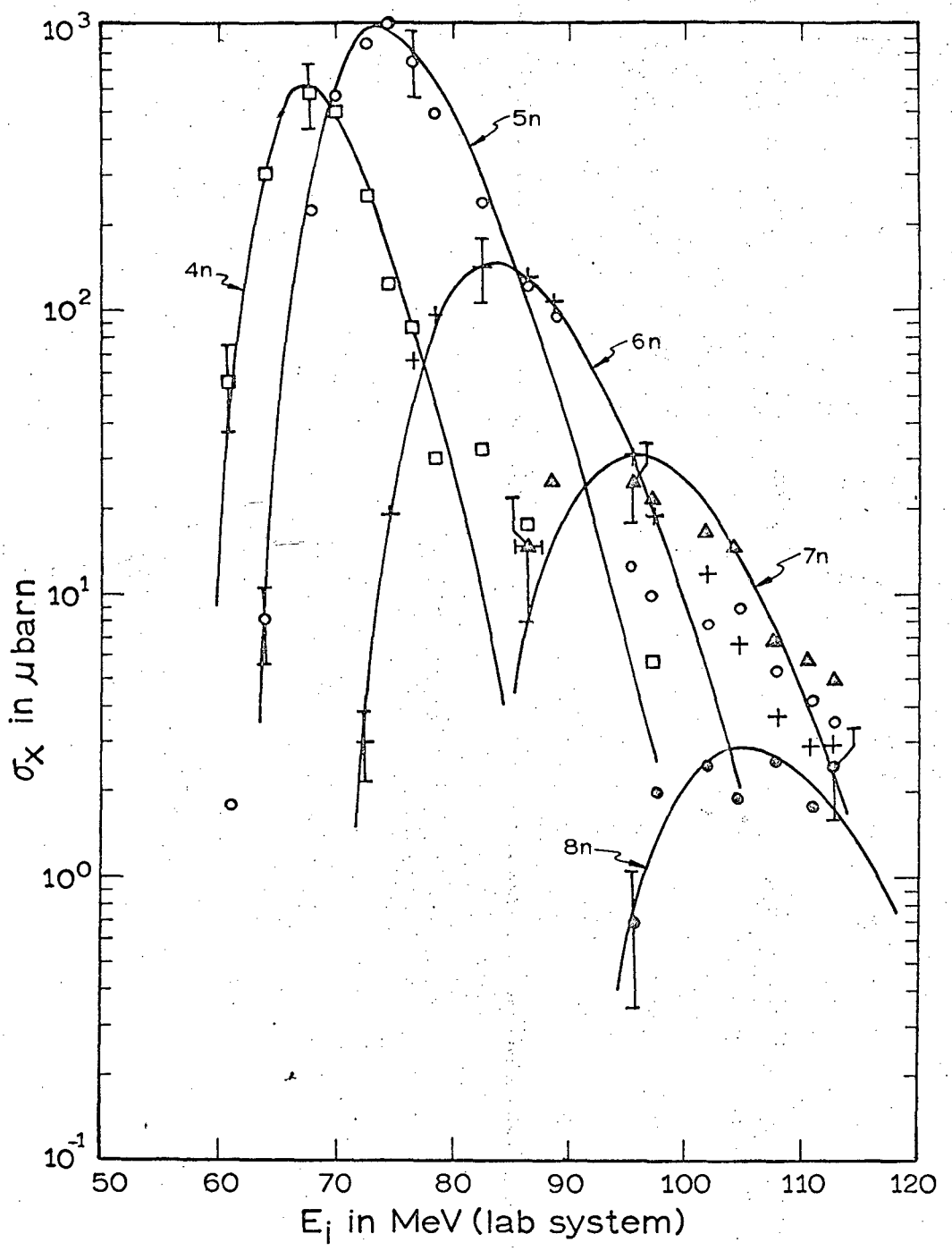

10^2
10^1
10^0
10^{-1}
10^{-2}
σ_x in μ barn
4n
5n
3n
50
60
70
80
90
100
110
120
E_i in MeV (lab system)
XBL675 3047

Fig. 2



XBL 675 2048

Fig. 3



XBL675 2049

Fig. 4

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.