AAEC/E304

AAEC/E304

AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

INVESTIGATION OF THE ENERGETICS OF BINARY AND TERNARY FISSION IN ^{252}Cf AND $^{236}U^*$

by

A. R. de L. MUSGROVE

March 1974

ISBN 0 642 99625 3

AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

INVESTIGATION OF THE ENERGETICS OF BINARY AND TERNARY FISSION IN ^{252}Cf AND ^{236}U*

by

A. R. de L. MUSGROVE

ABSTRACT

An attempt is made to calculate the total energy released in binary, neutron accompanied and α-particle accompanied fission of ^{236}U* and ^{252}Cf. Using measured values for the average kinetic energy released in fission, estimates are obtained for the average deformation-excitation energy of fission in each mode. The average number of neutrons emitted from the accelerated fragments in each fission mode is also evaluated and leads to estimates for the average energy required to emit a neutron in binary and ternary fission. Best values are found for the differential energetics between binary and ternary fission in ^{252}Cf and ^{236}U*. By comparing their electrostatic potential energies at the moment of scission, the mean extension of positive charge is found to be greater on average in α-particle accompanied fission, than in binary fission.

A number of experimentally determined parameters of interest in fission theory are also presented.

National Library of Australia card number and ISBN 0 642 99625 3

The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA–INIS–12 (INIS: Manual for Indexing) and IAEA–INIS–13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

ALPHA PARTICLES; CALIFORNIUM 252; DATA; EXCITATION; FISSION FRAGMENTS; KINETIC ENERGY; MEV RANGE 10–100; NUCLEAR DEFORMATION; NUCLEAR MODELS; TERNARY FISSION; URANIUM 236

CONTENTS

1. INTRODUCTION

Some years ago Feather (1968) investigated the differential energetics of binary and α-particle accompanied ternary fission of $^{236}U^*$ (U^{235} bombarded with thermal neutrons). The difference between the average total energy released in the two modes was calculated from mass tables to be:

$$\langle Q_b \rangle - \langle Q_{t\alpha} \rangle = 4.54 \pm 0.1 \text{ MeV}$$

which, when combined with the measured difference between the average energies converted into fragment kinetic energies in the two modes, yielded a difference of 6.5 ± 2 MeV between the mean deformation-excitation energies. It was shown from these results that the average potential energy at the scission point was the same (to within about 3 MeV) in binary and ternary α-particle accompanied fission. This result can be understood only if it is assumed that the charge distribution in binary fission is less extended than in the corresponding ternary mode.

More recently, Piekarz et al. (1970) calculated the energies involved in α-accompanied fission of ^{252}Cf. They found that the average fragment excitation energy in the ternary mode was comparable to that in binary fission. They assumed that the difference of the total energy of the fissioning system at the scission point was 15 – 17 MeV on the basis of the three point charge model calculation and using these results they calculated the average α- particle binding energy to the scissioning nucleus to be –3 ± 5 MeV.

The use of the three point charge model here appears open to question since it assumes that binary and ternary fission occur at the same inter-fragment separation. It seems far more reasonable to use experimental results to obtain information on this assumption as was done in Feather's (1968) calculation.

In the present report an attempt is made to give absolute values for the average excitation energies involved in binary and ternary fission of ^{252}Cf and $^{236}U^*$. In addition scission neutron accompanied fission will be examined as a separate mode of ternary fission. The occurrence of this mode of fission has been inferred from a detailed analysis of the angular distribution of prompt neutrons emitted in fission. Not all neutrons appear to have arisen by evaporation from the fully accelerated fragments: a residue appears to have been emitted isotropically in the laboratory system with somewhat greater energy, on average, than the neutrons evaporated from the fragments. For ^{252}Cf, Bowman et al. (1963) found that the scission neutron component comprised at least 10 per cent of the prompt neutrons while Skårsvag and Bergheim (1963) find a 15 per cent component of ternary neutrons for $^{236}U^*$. Since part of our aim here is to compare the average energy required to emit a neutron in each fission mode we first need estimates for the average number of neutrons emitted in binary and ternary fission of ^{252}Cf and $^{236}U^*$.

2. ESTIMATION OF $\bar{\nu}$ FOR BINARY AND TERNARY FISSION OF ^{252}Cf AND $^{236}U^*$

In the following calculation we assume the thermal $\bar{\nu}$ value for ^{252}Cf to be 3.782 and for $^{236}U^*$ to be 2.418 (Boldeman and Dalton 1967, Fillmore 1968). Both values contain contributions from pure binary fissions and from ternary neutron accompanied fission. Writing p_b and p_{tn} for the absolute probabilities for fission by these two modes and ν_b and ν_{tn} for the average number of neutrons evaporated from the moving fragments of the two fission modes, we have the following equation for the experimentally observed average neutron number:

$$p_b \; \nu_b + p_{tn}(1 + \nu_{tn}) = \bar{\nu} \text{ observed} \tag{1}$$

and

$$p_b = 1 - p_{tn} \; . \tag{2}$$

Here we have ignored fission accompanied by more than one central neutron to restrict the number of unknown parameters to manageable proportions. Now, assuming that 10 per cent of the prompt neutrons emitted in ^{252}Cf are scission neutrons we may estimate that $p_{tn} \doteq 0.38$ and hence $p_b \doteq 0.62$ for this nucleus. For $^{236}U^*$, assuming in this case 15 per cent of neutrons to be scission neutrons, we have $p_{tn} \doteq 0.36$ and $p_b \doteq 0.64$.

For the α-particle accompanied mode the following measurements of prompt neutron number have been made:

for ^{252}Cf (renormalising to a value of $\bar{\nu} = 3.782$) –

Piekarz et al. (1970)	3.11 ± 0.08
Nardi and Fraenkel (1968)	3.17 ± 0.06
Adamov et al. (1970)	2.83 ± 0.07

and for $^{236}U^*$ (renormalising to a value of $\bar{\nu} = 2.418$) –

Apalin et al. (1960)	1.75 ± 0.09
Ivanov et al. (1967)	1.73 ± 0.06 .

Taking a weighted mean of these measurements, we conclude that the best estimate for $\nu_{t\alpha}$ in ^{252}Cf is 3.05 ± 0.07 and for $^{236}U^*$ it is 1.74 ± 0.08. Here again, to be consistent with our assumption above, we assume that no central neutrons occur in α-particle accompanied fission. This opinion has also been expressed by Pik-Pichak (1967), but as yet the data relating to the angular distribution of neutrons emitted in α-particle accompanied fission are not sufficiently accurate to decide this point one way or the other. With this proviso, it is reasonable to assume that the number of neutrons evaporated from the fragments in ternary neutron-accompanied fission will, on average, be greater than for the α-particle accompanied mode. This is because more energy is required for the emission of an α-particle than for a neutron in ternary fission (Musgrove 1971b). Therefore, we take reasonable estimates for ν_{tn} to be 3.2 ± 0.2 for ^{252}Cf and 1.9 ± 0.2 for $^{236}U^*$ and obtain the following values of ν_b for these nuclei from Equation 1.

$$\nu_b\ (^{252}Cf) = 3.53 \pm 0.2$$

$$\nu_b\ (^{236}U^*) = 2.15 \pm 0.2\ .$$

We pass now to a calculation of the average total energy released in the three fission modes under consideration here for ^{252}Cf and $^{236}U^*$.

3. Q VALUES FOR BINARY AND TERNARY FISSION

Following Feather (1968) we identify the mean Q value in binary scission with the mean disappearance of mass:

$$\langle Q_b \rangle = M(A,Z) - \sum_{A_1} \sum_{Z_1(A_1)} P_b(A_1, Z_1)\ [M(A_1, Z_1) + M(A-A_1, Z-Z_1)] \quad (3)$$

where $P_b(A_1, Z_1)$ is the absolute probability that the fissioning nucleus (A,Z) divides in binary fission into the fragments (A_1, Z_1) and $(A-A_1, Z-Z_1)$. Similarly, for ternary fission where a further particle of mass number m and charge z appears, we have:

$$\langle Q_t \rangle = M(A_1Z) - M(m,z) - \sum_{A_1} \sum_{Z_1(A_1)} P_t(A_1,Z_1)\ [M(A_1,Z_1) + M(A-A_1-m, Z-Z_1-z)]\ . \quad (4)$$

To use Equations 3 and 4 to give average Q values in binary and ternary fission we require the probability factors P_b and P_t and a semi-empirical mass equation calculation of the nuclide masses. We have no data on the charge number distribution for a given mass in α-accompanied fission. Furthermore, the available data on the binary mode mass and charge distributions represent, as we have indicated, a weighted sum of two different fission modes which we are here interested in treating separately.

Consequently to proceed at all we use the measured mass yields as a function of A only, to evaluate an average Q value for both the even Z and odd Z fragment pairs which yield the maximum energy release for each mass number. We assume that the binary probabilities $P_b(A)$ are given sufficiently closely by the measured 'binary' mass distribution and for the ternary neutron accompanied mode we make the further assumption that:

$$P_{tn}(A) = P_b(A+1).$$

The experimental data on the binary mass distributions were taken from Schmitt, Neiler and Walter (1966), while the data relating to the α-particle accompanied fission mass distribution were taken from Nardi, Gazit and Katcoff (1969) for ^{252}Cf and from Asghar et al. (1970) for ^{236}U* fission.

The calculated mean Q values for even and odd Z fragments are given in Table 1 along with an adopted average Q value for each of the three fission modes under consideration. The nuclear masses were calculated from the mass formula of Myers and Swiatecki (1966,1968).

TABLE 1

Calculated Q values (<Q> (MeV)) for binary, ternary neutron accompanied and α-particle accompanied fission of ^{252}Cf and ^{236}U*

	Binary	Ternary n	Ternary α
		^{236}U*	
Z even fragments	194.6	190.1	190.5
Z odd fragments	192.5	188.0	188.3
Adopted	193.5±1	189.0±1	189.4±1
		^{252}Cf	
Z even fragments	219.1	214.3	214.1
Z odd fragments	217.0	212.3	212.0
Adopted	218.0±1	213.3±1	213.0±1

The following differences in total energy released in the various modes are found from Table 1:

^{236}U*

$$\langle Q_b \rangle - \langle Q_{tn} \rangle = 4.5 \pm 1 \text{ MeV}$$

$$\langle Q_b \rangle - \langle Q_{t\alpha} \rangle = 4.1 \pm 1 \text{ MeV}$$

^{252}Cf $\quad <Q_b> - <Q_{tn}> = 4.7 \pm 1$ MeV

$$<Q_b> - <Q_{t\alpha}> = 5.0 \pm 1 \text{ MeV}$$

Our value of $<Q_b> - <Q_{t\alpha}>$ for ^{236}U* of 4.1 ±1 MeV agrees quite closely with Feather's (1968) result of 4.54 MeV.

In the final state, before neutron evaporation occurs, the energy released in fission appears as kinetic energy and excitation energy of the fragments.

Writing $<T_b>$ for the mean fragment kinetic energy in binary fission averaged over the mass distribution and $<E_b>$ for the mean sum of deformation and excitation energy of the binary fragments, we have the following defining equation for $<Q_b>$:

$$<Q_b> = <T_b> + <E_b> \quad . \tag{5}$$

For ternary fission, where a third particle takes mean kinetic energy in amount $<T_p>$ we have similarly:

$$<Q_t> = <T_t> + <T_p> + <E_t> \quad , \tag{6}$$

where, as before, $<T_t>$ is the mean kinetic energy of the two heavy fragments in ternary fission.

Using experimental values for the average fragment kinetic energies in binary and ternary fission we are now in a position to estimate the mean excitation energy involved in each of the fission modes under consideration.

4. EXPERIMENTAL MEASUREMENTS OF $<T_b>$ AND $<T_t>$ FOR ^{252}Cf AND ^{236}U*

A number of points are worth making before an attempt is made to evaluate the experimental data we require. Firstly, of course, the 'binary' data are as before averaged over two separate fission modes. It is reasonable to assume that the emission of a scission neutron has little effect on the final fragment kinetic energies, so if the scission configuration in the two modes is closely similar on average, we are justified in assuming that the fragment kinetic energies in binary and in ternary neutron accompanied fission are the same. Secondly, it is impossible to measure the fragment kinetic energy in the pre-neutron emission state directly. However, methods have been devised whereby the true final state kinetic energies can be derived from measurements on the ultimate fission products (Schmitt et al. 1966, Fraenkel 1967).

Finally, in α-particle accompanied fission, experimental difficulties limit the useful data to those events where the α-particle energy is greater than about 10 MeV in ^{252}Cf and a somewhat lower energy in ^{236}U*. Since the final α-particle energy and final fragment energy are anticorrelated, neglect of low energy α-particles causes the measured mean fragment kinetic energy to be slightly lower than the true mean.

With these cautions in mind, we now examine the data relating to $<T_b> - <T_{b\alpha}>$, the difference between the mean fragment kinetic energy in binary and ternary α-accompanied fission. For ^{252}Cf, Nardi and Fraenkel (1970) have given the pre-neutron emission value for this quantity as:

$$<T_b> - <T_{t\alpha}> = 12.9 \pm 0.1 \text{ MeV} \quad ,$$

for α particle energies greater than 11.5 MeV. Using the value $\Delta <T_{t\alpha}>/\Delta T_\alpha = -0.45$ measured by Fraenkel (1967) and assuming a Gaussian shape for the α energy spectrum, they deduced a corrected value averaged over the entire α spectrum of:

$$<T_b> - <T_{t\alpha}> = 12.5 \pm 0.1 \text{ MeV} .$$

For the case of $^{236}U^*$, the following measurements of the uncorrected post-neutron emission quantity are available:

Dimitriev et al. (1961)	15.0 ± 0.5 MeV
Schmitt et al. (1962)	12 ± 2 MeV
Schröder (1965)	12.7 ± 0.5 MeV
Asghar et al. (1970)	12.38 ± 0.08 MeV
Gazit et al. (1971)	11.1 ± 0.4 MeV.

The measurement made by Gazit et al. (1971) quoted here was made for α-particles emitted at right angles to the fission axis. From these results we take as our estimate of the uncorrected difference $< T_b > - < T_{t\alpha} >$ for $^{236}U^*$ to be 13 ± 1 MeV. The two corrections to be made to this value (due to neutron emission from the fragments and to average over the whole α-particle spectrum) are largely compensatory being of the same order (approx. 0.3 MeV) and of opposite sign, hence we take 13 ± 1 MeV to be the best estimate we can make of the corrected difference between fragment kinetic energies in this case.

It remains now to estimate absolute values for the mean pre-neutron emission fragment kinetic energy in binary fission. For ^{252}Cf, the following measurements of this quantity are representative:

Whetstone (1963)	185.7 ± 1.8 MeV
Schmitt et al. (1966)	186.5 ± 1.2 MeV
Nardi and Fraenkel (1970)	187.5 ± 0.2 MeV.

We take as our estimate for $< T_b >$ in this nucleus to be 187 ± 1 MeV.

For $^{236}U^*$, the pre-neutron emission fragment kinetic energy has been measured by a number of groups, among them:

Schmitt et al. (1966)	171.9 ± 1.4 MeV
Maslin et al. (1967)	171.5 MeV
Boldeman et al. (1971)	170.8 MeV.

We estimate $< T_b >$ for this nucleus to be 171.5 ± 1 MeV. Using our previously obtained estimates for the difference $< T_b > - < T_{t\alpha} >$ in these two nuclei we can deduce the following values for $< T_{t\alpha} >$:

$$^{252}Cf \quad < T_{t\alpha} > = 173.5 \pm 1 \text{ MeV}$$

$$^{236}U^* \quad < T_{t\alpha} > = 158.5 \pm 1 \text{ MeV}.$$

Most experimenters agree that the most probable α-particle energy for both ^{252}Cf and $^{236}U^*$ ternary fission lies in the region 15.5 – 16.0 MeV (Dakowski et al. 1967, Carles et al. 1969, Gazit et al. 1971, Raisbeck and Thomas 1968, Cosper et al. 1968) and we take as our estimate of $< T_\alpha >$ for both these nuclei to be 15.7 ± 0.3 MeV. For ternary neutron accompanied fission, the scission neutron appears to have a greater energy on average than the neutrons emitted later from the fully accelerated fragments. Skårsvag and Bergheim (1963) find the best value of $< T_n >$ for $^{236}U^*$ to be 1.8 ± 0.1 MeV and we assume this value for both nuclei considered.

The information gathered in the preceding sections is in Table 2 to provide estimates for the mean excitation energy of the fragments and for $d < E > / d\bar{\nu}$, the mean energy required to emit a neutron in the three fission modes considered.

TABLE 2

Energetics of Binary and Ternary Fission in

$^{236}U^*$ and ^{252}Cf

$^{236}U^*$

Fission Mode	Binary	Ternary n	Ternary α
$< Q >$ (MeV)	193.5±1	189.0±1	189.4±1
Fragment Kinetic Energy (MeV)	171.5±1	171.5±1	158.5±1
Particle Kinetic Energy (MeV)	–	1.8±0.1	15.7±0.3
Excitation Energy (MeV)	22.0±2	15.7±2	15.2±2.5
ν	2.15±0.2	1.9±0.2	1.74±0.08
$d < E > / d\bar{\nu}$ (MeV/neutron)	10.2±2	8.3±2	8.2±2

^{252}Cf

Fission Mode	Binary	Ternary n	Ternary α
$< Q >$ (MeV)	218.0±1	213.3±1	213.0±1
Fragment Kinetic Energy (MeV)	187.0±1	187.0±1	173.5±1
Particle Kinetic Energy (MeV)	–	1.8±1	15.7±0.3
Excitation Energy (MeV)	31.0±2	24.5±2	23.8±2.5
ν	3.53±0.2	3.2±0.2	3.05±0.07
$d < E > / d\bar{\nu}$ (MeV/neutron)	8.8±1	7.7±1	7.8±1

Our calculated values for the average energy required to emit a neutron from the fission fragments can be compared directly with experiment in only one case: the binary fission of $^{236}U^*$. Here a number of groups have measured the energy dependence of $\bar{\nu}$ for neutron induced fission of ^{235}U. A linear fit to the data below 2 MeV bombarding energy by Boldeman and Walsh (1970) gave a value for $dE_b/d\nu$ of 9.35 ±0.4 MeV/ neutron. This is in good agreement with our appropriately weighted calculated values for binary and neutron-accompanied fission for this nucleus.

5. DIFFERENTIAL ENERGETICS AT THE SCISSION POINT

We now examine the energy balance conditions in our three fission modes at the moment of scission. For binary fission we can write the scission point energy balance equation as:

$$< Q_b > = < E_b > + < T_{0b} > + < V_b > ,$$

where $< V_b >$ is the average electrostatic potential energy, $< T_{0b} >$ the average fragment kinetic energy and $< E_b >$ the average energy of deformation-excitation of the fragments at the moment of scission. Similarly for ternary fission we write:

$$\langle Q_t \rangle = \langle E_t \rangle + \langle T_{0t} \rangle + \langle V_t \rangle .$$

We are interested here in the difference between the initial potential energy between binary and ternary fission:

$$\langle V_b \rangle - \langle V_t \rangle = (\langle Q_b \rangle - \langle Q_t \rangle) - (\langle E_b \rangle - \langle E_t \rangle) - (\langle T_{0b} \rangle - \langle T_{0t} \rangle).$$

From equations 5 and 6 we can further identify the quantity $\langle E_b \rangle - \langle E_t \rangle$ with the final state quantities:

$$\langle E_b \rangle - \langle E_t \rangle = (\langle Q_b \rangle - \langle Q_t \rangle) - (\langle T_b \rangle - \langle T_t \rangle - \langle T_p \rangle). \quad (7)$$

Hence:

$$\langle V_b \rangle - \langle V_t \rangle = (\langle T_b \rangle - \langle T_t \rangle - \langle T_p \rangle) - (\langle T_{0b} \rangle - \langle T_{0t} \rangle). \quad (8)$$

According to the model in which ternary fission develops exoergically out of a corresponding binary mode in a late stage of the fission process (Feather 1969) almost all of the kinetic energy difference ($\langle T_{0t} \rangle - \langle T_{0b} \rangle$) is concentrated on the third particle. This difference can therefore be identified to a good approximation with the initial average particle energy. From trajectory calculations for α-accompanied fission in ^{252}Cf, Musgrove (1971b) found a value of 2.75 MeV for the average initial α-particle energy while the recent calculations of Gazit et al. (1971) for ^{236}U* gave 3.4 MeV for the average α energy in this case.

Therefore, substitution of values already obtained into equation 8 yields for ^{252}Cf:

$$\langle V_b \rangle - \langle V_{t\alpha} \rangle = (12.5 \pm 0.1) - (15.7 \pm 0.3) + 2.75$$

$$= -0.45 \pm 0.4 \text{ MeV}$$

while for ^{236}U* we have:

$$\langle V_b \rangle - \langle V_{t\alpha} \rangle = (13 \pm 1) - (15.7 \pm 0.3) + 3.4$$

$$= 0.7 \pm 1.3 \text{ MeV.}$$

Because of our initial assumptions for the neutron accompanied fission fragment kinetic energies we would find $\langle V_b \rangle - \langle V_{tn} \rangle$ to be zero in both cases.

The results for α-particle accompanied fission can only be understood if the mean extension of positive charge in the nucleus proceeding to ternary fission is considerably more extended than that in binary fission. For a three point charge model of the fissioning nucleus Fraenkel (1967) and Musgrove (1971a) have calculated values for the difference in potential energy in the range 10–12 MeV assuming a constant heavy fragment separation distance.

From equation 7 we may also estimate the difference in excitation-deformation energy at the scission point between binary and ternary fission. For ^{252}Cf we obtain:

$$\langle E_b \rangle - \langle E_{t\alpha} \rangle = (5.0 \pm 1) + (3.2 \pm 0.4)$$

$$= 8.2 \pm 1.4 \text{ MeV}$$

$$\langle E_b \rangle - \langle E_{tn} \rangle = (4.7 \pm 1) + (1.8 \pm 0.1)$$

$$= 6.5 \pm 1 \text{ MeV}$$

and for ^{236}U*:

$$\langle E_b \rangle - \langle E_{t\alpha} \rangle = (4.1 \pm 1) + (2.7 \pm 1.3)$$
$$= 6.8 \pm 2.3 \text{ MeV}$$
$$\langle E_b \rangle - \langle E_{tn} \rangle = (4.5 \pm 1) + (1.8 \pm 0.1)$$
$$= 6.3 \pm 1 \text{ MeV}.$$

The value calculated here for $\langle E_b \rangle - \langle E_{t\alpha} \rangle$ in $^{236}U^*$ is in good agreement with that given by Feather (1968) of 6.5 ± 2 MeV.

In the following section a number of important fission parameters which have been experimentally determined are collected.

6. EXPERIMENTALLY DETERMINED FISSION PARAMETERS

(i) $\dfrac{d \langle T_{t\alpha} \rangle}{dT_\alpha}$.

The correlation between mean fragment kinetic energy and α-particle energy in ternary fission has been measured for both ^{252}Cf and $^{236}U^*$. This quantity is critically dependent on the initial conditions at the scission point. For ^{252}Cf the following measurements have been made for this quantity:

Fraenkel (1967): −0.445, for α-particle energies in the range 11–19 MeV,

Nardi et al. (1969): −0.41 ± 0.05, for α-particle energies in the range 17–24 MeV.

For $^{236}U^*$ the following results have been obtained:

Asghar et al. (1970): −0.45 ± 0.06, for α-particle energies in the range 7.5–26 MeV,

Gazit et al. (1971): −0.442 ± 0.04, for α-particle energies in the range 10–33 MeV.

Of these measurements, those by Fraenkel (1967) and Gazit et al. (1971) were made for a final α-particle direction at 90° to the fission axis only.

Trajectory calculations (e.g. Boneh et al. 1967, Gazit et al. 1971) have shown that the observed degree of anticorrelation between these two quantities can only be explained if, at the moment of scission, the heavy fragments have already acquired a considerable proportion of their final kinetic energy. This finding is directly contradictory to the assumptions of the statistical model of fission (Fong 1956) where the fragment kinetic energies at scission are assumed to be less than 0.5 MeV.

(ii) $\dfrac{d \langle T_\alpha \rangle}{dT_{t\alpha}}$

Measurements on $^{236}U^*$, have further demonstrated a weaker anticorrelation between $\langle T_\alpha \rangle$ and $T_{t\alpha}$. The value obtained by Asghar et al. (1971) for this quantity was −0.105 ± 0.01.

No measurement of this quantity has been made for ^{252}Cf ternary fission.

(iii) $\dfrac{d\bar{\nu}}{dT_\alpha}$

Three experimental measurements have been made for $d\bar{\nu}/dT_\alpha$ in ^{252}Cf.

These are:

Piekarz et al. (1970): -0.045 ± 0.010 MeV^{-1}

Adamov et al. (1970): -0.033 MeV^{-1}

Nardi and Fraenkel (1970): -0.026 ± 0.015 MeV^{-1}

In Figure 1, we have normalised the data points of these three groups to ν_b ^{252}Cf = 3.782 and the best straight line to all the data was found to be:

$$\bar{\nu}_{t\alpha} = 3.62\ (\pm 0.09) - 0.034(\pm 0.005)\ T\alpha .$$

We therefore take the most probable value of $d\bar{\nu}/dT_\alpha$ for ^{252}Cf to be -0.034 ± 0.005 MeV^{-1} .

No data relating to this quantity for the α-particle accompanied fission of ^{236}U* are available.

Using this value along with our previously calculated estimate for $d < E_{t\alpha} > /d\bar{\nu}$ in ^{252}Cf of 7.8 ± 1 MeV/neutron we deduce a value for $d < E_{t\alpha} >/dT_\alpha$:

$$\frac{d < E_{t\alpha} >}{dT_\alpha} = \frac{d < E_{t\alpha} >}{d\bar{\nu}} \cdot \frac{d\bar{\nu}}{dT_\alpha}$$

$$= -0.27 \pm 0.07 .$$

(iv) $\frac{dT_b}{d\bar{\nu}_b}$ and $\frac{dT_{t\alpha}}{d\bar{\nu}_{t\alpha}}$.

For binary fission of ^{252}Cf and ^{236}U*, which as we have commented contains an appreciable proportion of the ternary neutron accompanied mode, measurements to date have yielded:

for $dT_b/d\bar{\nu}_b$ in ^{252}Cf:

Bowman et al. (1962)	-6.6 MeV/neutron
Nardi and Fraenkel (1968)	-9.4 ± 0.4 MeV/neutron

and for $dT_b/d\bar{\nu}_b$ in ^{236}U*:

Maslin et al. (1967)	-18.5 MeV/neutron
Boldeman et al. (1971)	-16.7 MeV/neutron.

For α- particle accompanied fission the only measurement of $dT_{t\alpha}/d\bar{\nu}_{t\alpha}$ has been made for ^{252}Cf by Nardi and Fraenkel (1968) who obtained -10.9 ± 1.2 MeV/neutron for this quantity. It is interesting to note that in our calculations for $d < E >/d\bar{\nu}$ for ^{252}Cf we obtain a smaller value for ternary than for binary fission (7.8 against 8.8 MeV/neutron).

Both Maslin et al. (1967) and Boldeman et al. (1971) converted their measured values for $dT_b/d\bar{\nu}_b$ for ^{236}U* to the quantity $dE_b/d\bar{\nu}$ using energy releases calculated from semi empirical mass formulae. Maslin et al. (1967) obtained $dE_b/d\bar{\nu}$ = 15.2 MeV/neutron while Boldeman et al. (1971) give $dE_b/d\bar{\nu}$ = 9.5 MeV/neutron. The discrepancy here is puzzling but the value calculated by Boldeman et al. (1971) is in good agreement with the data relating $\bar{\nu}$ to the bombarding energy of the neutron incident on the ^{235}U nucleus (Boldeman and Walsh 1970).

If we accept for the moment, Nardi and Fraenkel's (1968) value for $dT_b/d\bar{\nu}_b$ in ^{252}Cf, and use a weighted average of our calculated values for $d<E_b>/d\bar{\nu}_b$ and $d<E_{tn}>/d\bar{\nu}_{tn}$ of 8.1 ± 1 MeV/neutron for this nucleus we find:

$$\frac{d<E_b>}{dT_b} \approx 0.86 \pm 0.14 \text{ for } ^{252}\text{Cf},$$

while for ^{236}U*, the calculation of Maslin et al. (1967) indicates a value of 0.82 and that of Boldeman et al. (1971) gives 0.57 for $d<E_b>/dT_b$.

For the α-particle accompanied fission of ^{252}Cf we deduce:

$$\frac{d<E_{t\alpha}>}{dT_{t\alpha}} = 0.71 \pm 0.16 \ .$$

This survey of experimental results has pointed to a number of gaps in the data particularly related to the measurement of $\bar{\nu}$ versus A for α-particle accompanied fission of ^{236}U*. Further data of interest would be measurements of the quantity $d<T_{t\alpha}>/dT_\alpha$ for restricted ranges of the mass ratio and excitation energy (or $\bar{\nu}_{t\alpha}$). This would provide information of valuable assistance in trajectory calculations as we have already mentioned.

7. REFERENCES

Adamov, V.M., Drapchinskii, L.V., Kovalenko, S.S., Petrzhak, K.A. and Tyutyugin, I.I. (1970). – Soviet J. Nucl. Phys. 11,557.

Apalin, V.F., Dobrynin, Yu.P., Zakharova, V.P., Kutikov, I.E. and Mikaelyan, L.A. (1960). – J. Nucl. Energy 13A,86.

Asghar, M., Carles, C., Chastel, R., Doan, T.P., Ribrag, M. and Signarbieux, C. (1970). – Nucl. Phys. A145,657.

Boldeman, J.W. and Dalton, A.W. (1967). – AAEC/E172.

Boldeman, J.W., Musgrove, A.R. de L. and Walsh, R.L. (1971). – Aust. J. Phys. 24,821.

Boldeman, J.W. and Walsh, R.L. (1970). – J. Nucl. Energy 24,191.

Boneh, Y., Fraenkel, Z. and Nebenzahl, I. (1967). – Phys. Rev. 156,1305.

Bowman, H.R., Milton, J.C.D., Thompson, S.G. and Swiatecki, W.J. (1963). – Phys. Rev. 129,2133.

Carles, C., Asghar, M., Doan, R.P. and Chastel, R. (1969). – Proc. 2nd Symp. on Physics and Chemistry of Fission, (IAEA, Vienna) p.119.

Cosper, S.W., Cerny, J. and Gatti, R.C. (1967). – Phys. Rev. 154,1193.

Dakowski, M., Chwaszczewska, J., Krogulski, T., Piasecki, E. and Sowinski, M. (1967). – Phys. Lett. 25B,213.

Dimitriev, V.N., Drapchinskii, L.V. Petrazhak, K.A. and Romanov, Y.F. (1961). – JETP 12,390.

Ivanov, O.I., Kroshkin, N.I. Nefedov, V.N. and Kharin, V.P. (1967). – Soviet J. Nucl. Phys. 5,523.

Feather, N. (1968). – Phys. Rev. 170,1118.

Feather, N. (1969). – Proc. Roy. Soc. Edinburgh, 68A,229.

Fong, P. (1956). – Phys. Rev. 102,434.

Fraenkel, Z. (1967). – Phys. Rev. 156,1283.

Fillmore, F.L. (1968). – J. Nucl. Energy 22,79.

Gazit, Y.,Katase, A., Ben-David, G. and Moreh, R. (1971). – Phys. Rev. C, 4,223.

Nardi, E. and Fraenkel, Z. (1968). – Phys. Rev. Lett. 20,1248.

Nardi, E. and Fraenkel, Z. (1970). – Phys. Rev. C, 2,1156.

Nardi, E., Gazit, Y. and Katcoff, S. (1969). – Phys. Rev. 182,1244.

Maslin, E.E., Rodgers, A.L. and Core, W.G.F. (1967). – Phys. Rev. 164,1520.

Musgrove, A.R. de L. (1971a). – AAEC/TM595.

Musgrove, A.R. de L. (1971b). – Aust. J. Phys. 24,129.

Myers, W.D. and Swiatecki, W.J. (1966). – Nucl. Phys. 81,1.

Myers, W.D. and Swiatecki, W.J. (1968). – UCRL 17070.

Pik-Pichak, G.A. (1967). – Soviet J. Nucl. Phys. 4,826.

Piekarz, H., Blocki, J., Krogulski, T. and Piasecki, E. (1970). – Nucl. Phys. A146,273.

Raisbeck, G.M. and Thomas, T.D. (1968). – Phys. Rev. 172,1272.

Schmitt, H.W., Neiler, J.H., Walter, F.J. and Chetham-Strode, A. (1962). – Phys. Rev. Lett. 9,427.

Schmitt, H.W., Neiler, J.H. and Walter, F.J. (1966). – Phys. Rev. 141,1146.

Schröder, I.G. (1965). – Ph.D. thesis, Columbia University (unpublished).

Skårsvag, K. and Bergheim, K. (1963). – Nucl. Phys. 45,72.

Whetstone, S.L. (1963). – Phys. Rev. 131,1232.

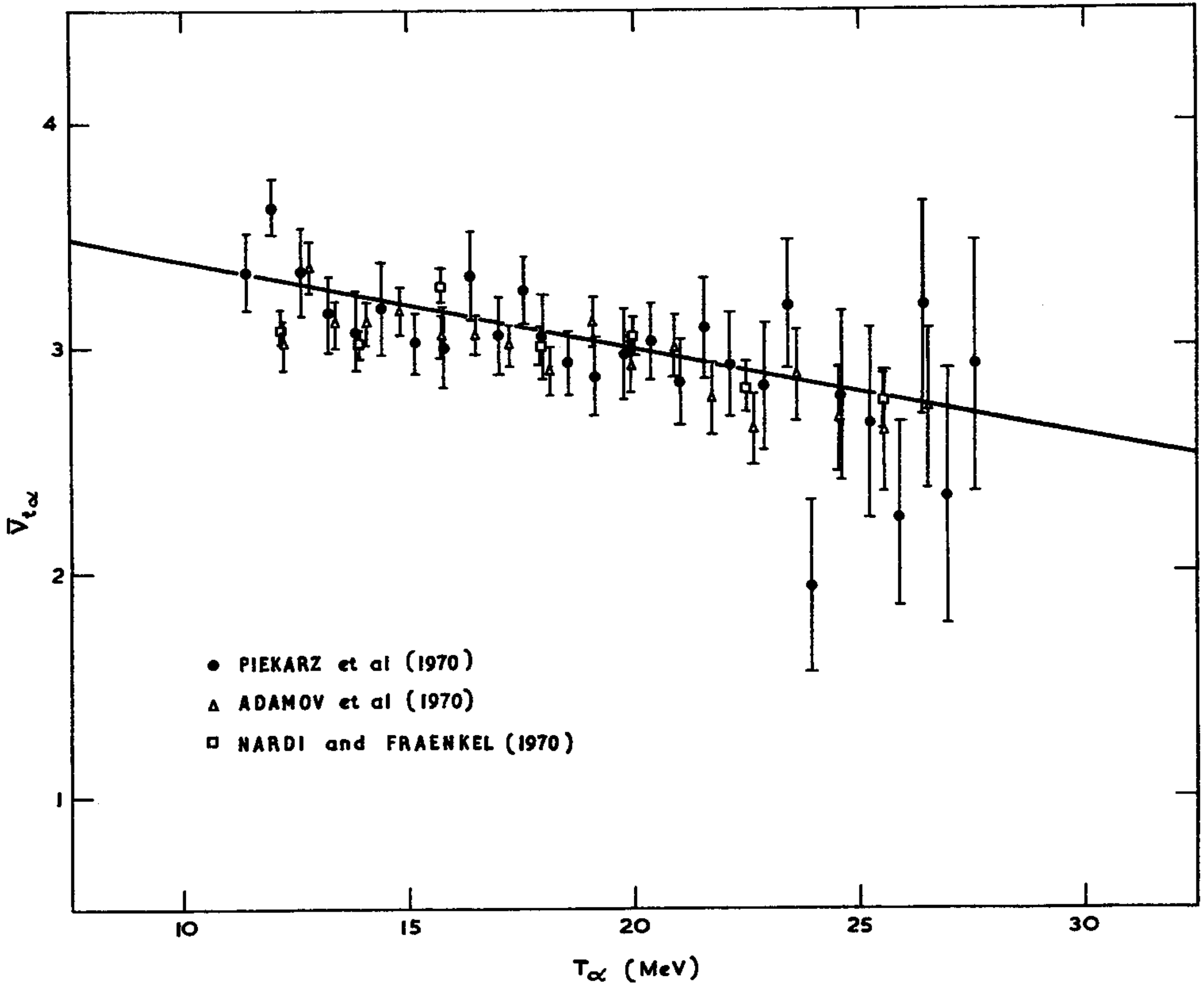

FIGURE 1. PLOT OF $\bar{\nu}_{ta}$ VERSUS ALPHA-PARTICLE KINETIC ENERGY (T_a) FOR ^{252}Cf TERNARY FISSION