V. COMPARISON OF THE LEVEL STRUCTURES OF 99-NEUTRON ISOTONES

It is instructive to compare the low-lying intrinsic states of the isotones ^{169}Yb, ^{165}Dy,[24,25] and ^{167}Er,[26,27] as shown in Fig. 6. With the exception of the $\frac{5}{2}^+[642]$ band, which has only been observed in the case of ^{169}Yb, there is a remarkable similarity in the energy spectra of these three nuclei. The fact that the negative-parity states in ^{167}Er are shifted upwards relative to those of the other iostones suggests that the $\frac{7}{2}^+[633]$ orbital has a comparatively higher binding energy in ^{167}Er. Also, we note that the energy differences between the complex vibrational states [i.e., $(K-2)$+single particle] and their corresponding base states are systematically greater in ^{169}Yb than in the other two isotones. This presumably mirrors the fact that the 2^+ one-phonon γ-vibrations in the even-even Yb nuclei lie higher in energy than those in the Er or Dy nuclei.

[24] O. W. B. Schult, B. P. Maier, and U. Gruber, Z. Physik **182**, 171 (1964).
[25] R. K. Sheline, W. N. Shelton, H. T. Motz, and R. E. Carter, Phys. Rev. **136**, B351 (1964).
[26] H. R. Koch, Z. Physik. **187**, 450 (1965).
[27] R. A. Harlan, thesis, Florida State University, 1966 (unpublished); R. K. Sheline and R. A. Harlan, Bull. Am. Phys. Soc. **11**, 752 (1966).

PHYSICAL REVIEW VOLUME 170, NUMBER 4 20 JUNE 1968

Comments on the Energetics of Ternary (Light-Particle-Accompanied) Fission

N. Feather
Department of Natural Philosophy, University of Edinburgh, Edinburgh, Scotland
(Received 9 October 1967)

A critical survey is given of the "differential energetics" of the binary and α-particle-accompanied ternary (thermal-neutron-induced) fission of ^{235}U. The Q value for such a fission process (in a particular mode) is defined as the sum of the kinetic energies T and the deformation-excitation energies E of the resulting particles at a time some 10^{-18} sec later than the instant of scission. It is found that for $^{235}\mathrm{U}(n_{\mathrm{th}},f)$ the difference of the mean kinetic energies is known more accurately than the difference of the mean deformation-excitation energies. However, on certain rather arbitrary assumptions, the difference of the mean Q values is calculable, using the mass tables, with considerably more accuracy than that with which either of the experimentally determined quantities is known. On this basis, the following best values are obtained for the thermal-neutron-induced fission of ^{235}U:

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=4.54\pm0.10\ \mathrm{MeV},$$
$$\langle T_b\rangle-\langle T_{t\alpha}\rangle=-2\ \pm2\ \mathrm{MeV},$$
$$\langle E_b\rangle-\langle E_{t\alpha}\rangle=6.5\ \pm2\ \mathrm{MeV}.$$

These values are discussed in relation to other evidence, and the importance of a detailed investigation of the secondary neutrons of α-particle-accompanied fission (with particular reference to the question of scission neutrons) is emphasized. The near equality of $\langle T_b\rangle$ and $\langle T_{t\alpha}\rangle$ implies no more than that the representative ("mean") event which is α-particle-accompanied ternary fission develops in time in such a way that at some stage it passes through the configuration which is the representative ("mean") configuration of binary scission. This conclusion in no way discriminates between the one-stage and two-stage descriptions of the ternary fission process.

GENERAL CONSIDERATIONS: DEFINITIONS OF Q VALUES AND "CORRESPONDING MODES"

FOR any well-defined nuclear transformation, the definition of a Q value can be formulated without ambiguity. In principle, and largely in practice, the initial and final states can be specified uniquely (the complication introduced by γ-ray emission is essentially trivial), and the Q value of the transformation is given unambiguously by the excess of the total kinetic energy of the final-state particles (together with the energy of any γ-ray quanta involved) over the corresponding quantity for the system in the initial state. This is not the case for nuclear fission. Though the initial state is unique, the end state can only be described statistically, even in relation to the particles concerned. Moreover, in respect of the over-all process, we recognize successive stages which are, at least conceptually, distinct. There is the stage of acceleration of the "primary fragments" produced at scission, and the generally later stage of the emission of particles (neutrons) and γ-ray quanta from the excited fragments whereby the ultimate "fission products" are produced. Obviously, the events of the second-stage process are merely consequential on the main phenomenon: Our aim should be to define a Q value characteristic of the primary event. Usually, this event is one of binary scission—in one of many possible "binary modes" of mass and charge division—but in a small fraction of cases it is a ternary event. In such a case a light particle is emitted, and the division of mass and charge between the residual primary fragments is in one of the possible ternary modes which the conservation laws allow. Clearly, we must define as many Q values as there are identifiable types of fission of a given nucleus.

We have said that the two stages of development of the over-all process of fission are "at least conceptually" distinct. They must, indeed, be physically distinct, or essentially so, if our definition of Q values is to be more than an academic exercise. It is of little use to define a Q value which is not open to experimental determination. In this connection only one conclusion is unassailable. It is certain that the first-stage process is essentially complete, dynamically, within a time of the order of 10^{-18} sec after scission. In that interval the primary fragments have separated through a distance of about 2×10^{-9} cm and have effectively acquired their full kinetic energy at the expense of the initial electrostatic potential energy of the scission state. Beyond that, it is generally believed[1] that the particle (as distinct from the γ ray) emission of the second-stage process is complete within less than 4×10^{-14} sec after scission. That belief is not in question here. What is in question is the associated belief that no "second-stage neutrons" are emitted within the first 10^{-18} sec after the instant of scission. Originally, it was concluded that the measured angular and energy distributions of the secondary neutrons of binary fission were consistent with the assumption that all these neutrons are emitted from fully accelerated fragments. Later, when more accurate experiments revealed discrepancies, the view was taken that the new distributions were consistent with the assumption that 80 or 90% of the neutrons are emitted from fragments that are fully accelerated, and the remainder of the neutrons from fragments essentially at rest. Certainly, this is the most reasonable interpretative assumption to make in the circumstances; making it, we recognize the category of "scission neutrons," and add neutron-accompanied ternary fission to the previously recognized types of light-particle-accompanied ternary fission. Still, there is an unproven element in this general picture which cannot be completely ignored. The best that can be said is that the picture cannot be grossly in error: It is more difficult to accept its categories as unique.

Having made this reservation, we accept the picture pragmatically: We assume that the first-stage processes of our conceptual scheme are in fact isolated in time, and we define our Q values. We say that the final-state configuration in fission is that configuration of energies existing between 10^{-18} sec and 2×10^{-18} sec after the moment of scission and we proceed to the definition of $\langle Q\rangle$, the mean energy-release in the primary process, having regard to the statistical description of the final state to which we have already referred.

Suppose, then, that $\langle T_b\rangle$ is the mean sum of the kinetic energies of the two fragments of binary fission in the final-state configuration, in which configuration $\langle E_b\rangle$ is the mean sum of the deformation-excitation energies of the fragments (energy of deformation is all the time being converted "slowly" into energy of excitation of the fragments). To be precise,

$$\langle T_b\rangle=\sum_{A_1}\sum_{Z_1(A_1)}P_b(A_1,Z_1)\langle T_b(A_1,Z_1)\rangle, \tag{1}$$

$$\langle E_b\rangle=\sum_{A_1}\sum_{Z_1(A_1)}P_b(A_1,Z_1)\langle E_b(A_1,Z_1)\rangle, \tag{2}$$

where $\langle T_b(A_1,Z_1)\rangle$ and $\langle E_b(A_1,Z_1)\rangle$ are, respectively, the average values of the sum of the kinetic energies and the sum of the deformation-excitation energies of the two fragments in the binary mode $(A_1,Z_1)/(A-A_1, Z-Z_1)$, and $P_b(A_1,Z_1)$ is the absolute probability of the occurrence of this mode. A and Z are the mass and charge numbers of the fissioning nucleus, and A_1 and Z_1 can be regarded with equal validity either as the mass and charge numbers of the light fragment or of the heavy fragment nucleus. In what follows, for the sake of precision, we shall assume, unless we specifically decide otherwise, that (A_1,Z_1) denotes the light fragment and that the fissioning nucleus is initially at rest. In terms of $\langle T_b\rangle$ and $\langle E_b\rangle$, the defining equation for $\langle Q_b\rangle$, the mean Q value for binary fission is then simply[2,3]

$$\langle Q_b\rangle=\langle T_b\rangle+\langle E_b\rangle. \tag{3}$$

Consistent with Eq. (3), we also have

$$\langle Q_b\rangle=M(A,Z)-\sum_{A_1}\sum_{Z_1(A_1)}P_b(A_1,Z_1)\times\{M(A_1,Z_1)+M(A-A_1,\, Z-Z_1)\}. \tag{4}$$

Equation (4) identifies the mean Q value of the transformation with the mean disappearance of mass (expressed in energy units) in the standard notation.

For α-particle-accompanied ternary fission, in a similar way, we have the two alternative defining equations,

$$\langle Q_{t\alpha}\rangle=\langle T_{t\alpha}\rangle+\langle E_{t\alpha}\rangle \tag{5}$$

and

$$\langle Q_{t\alpha}\rangle=M(A,Z)-M(4,2)-\sum_{A_1}\sum_{Z_1(A_1)}P_{t\alpha}(A_1,Z_1)\times\{M(A_1,Z_1)+M(A-A_1-4,\, Z-Z_1-2)\}, \tag{6}$$

where $P_{t\alpha}(A_1,Z_1)$ is the absolute probability that the mode of mass and charge division of the residual primary fragments is $(A_1,Z_1)/(A-A_1-4, Z-Z_1-2)$ in this case. We shall not, in our present discussion, be

[1] J. S. Fraser, Phys. Rev. **88**, 536 (1952).

[2] Essentially the same definition of $\langle Q_b\rangle$ has recently been given independently by Schmitt *et al.* (Ref. 3).

[3] H. W. Schmitt, J. H. Neiler, and F. J. Walter, Phys. Rev. **141**, 1146 (1966).

concerned with other types of light-particle-accompanied ternary fission; however, precisely similar defining equations could be set up in respect of them. In the equations that we have given, obviously, according to the terms of our formulation,

$$\sum_{A_1}\sum_{Z_1(A_1)} P_b(A_1,Z_1)=\sum_{A_1}\sum_{Z_1(A_1)} P_{t\alpha}(A_1,Z_1)=1. \quad (7)$$

Because our main object is to compare, as closely as possible, the final-state configuration of energies in α-particle-accompanied ternary fission with that characteristic of binary fission of the same nucleus, we are most directly interested in the energy difference $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$. From Eqs. (3) and (5) we have

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=\langle T_b\rangle-\langle T_{t\alpha}\rangle+\langle E_b\rangle-\langle E_{t\alpha}\rangle. \quad (8)$$

Similarly, from Eqs. (4) and (6),

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=M(4,2)+\sum_{A_1}\sum_{Z_1(A_1)} P_{t\alpha}(A_1,Z_1) \times\{M(A_1,Z_1)+M(A-A_1-4,\ Z-Z_1-2)\} -\sum_{A_1}\sum_{Z_1(A_1)} P_b(A_1,Z_1) \times\{M(A_1,Z_1)+M(A-A_1,\ Z-Z_1)\}. \quad (9)$$

Equation (8) provides the recipe for the determination of the difference of the mean Q values "by direct experiment"; Eq. (9) shows how one may evaluate the same quantity with the help of the tabulated values of nuclear masses calculated according to the semi-empirical mass equation. We shall be considering specifically, in what follows, the case of the binary and the α-particle-accompanied ternary fission of the compound nucleus ^{236}U produced by thermal-neutron capture by ^{235}U, and, in so doing, we shall survey both methods of evaluation of $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$. Over-all, we shall find that, in the present state of knowledge, the more accurate value of this difference is provided by Eq. (9) from the tabulated masses; however, use of the mass tables does not permit the evaluation of $\langle T_b\rangle-\langle T_{t\alpha}\rangle$ and $\langle E_b\rangle-\langle E_{t\alpha}\rangle$ separately, and we shall be interested to have this information also, which only direct experiment can provide.

Before we proceed to numerical details, firstly it will be useful to establish the formal bases from which we propose to discuss our results, and secondly, it may also be useful to expose certain possible misconceptions explicitly, and so to dismiss (albeit reluctantly) certain easy answers which do not stand criticism in the final analysis.

The concept most liable to misunderstanding in the context of fission is that of deformation-excitation energy as we have used it in Eqs. (2), (3), and (5). As we have defined the quantities $\langle E_b(A_1,Z_1)\rangle$ and $\langle E_t(A_1,Z_1)\rangle$, these refer to the intrinsic energies of the primary fragments, over and above their ground-state energies, in the final-state configuration which we have specified (and, by assumption, also, in the configuration existing immediately after scission has occurred). These quantities bear no direct relation to the similarly defined deformation-excitation energy of the fissioning nucleus immediately before scission. In spontaneous fission this quantity (if it is significant to define it) is zero at the instant of scission; in thermal-neutron-induced fission it is equal to the binding energy of the captured neutron in the compound nucleus concerned. In the same way, comparing the binary and α-particle-accompanied ternary modes $(A_1,Z_1)/(A-A_1,\ Z-Z_1)$ and $(A_1,Z_1)/(A-A_1-4,\ Z-Z_1-2)/(4,2)$ the quantities $\langle E_b(A_1,Z_1)\rangle$ and $\langle E_{t\alpha}(A_1,Z_1)\rangle$ are reckoned in relation to different zeros: Their difference cannot usefully be identified with any independently measurable parameter. This is immediately obvious if ternary fission is regarded as a one-stage process, the constituents of the α particle being assembled "indiscriminately" from the nuclear matter on each side of the incipient scission point; it is equally true on the basis of the extreme two-stage hypothesis which assumes that the α particle is emitted from the light (or, alternatively, the heavy) fragment in all cases,[4] as we shall now proceed to show. In respect of the (arbitrarily defined) "corresponding modes" $(A_1,Z_1)/(A-A_1,Z-Z_1)$ and $(A_1,Z_1)/(A-A_1-4,\ Z-Z_1-2)/(4,2)$, there is a necessary and simple relation involving $Q_b(A_1,Z_1)$ and $Q_{t\alpha}(A_1,Z_1)$ which is altogether independent of any hypothesis, but there is no such simple, verifiable relation involving $\langle E_b(A_1,Z_1)\rangle$ and $\langle E_{t\alpha}(A_1,Z_1)\rangle$ whatever hypothesis is espoused.

In order to derive the result which we are seeking, let us compare the configuration at binary scission with the configuration in the corresponding mode of ternary fission at the instant of α-particle release. In the former configuration (let us assume, for simplicity) the kinetic energy of the fragments is essentially zero, and their mean mutual potential energy is $\langle V_b(A_1,Z_1)\rangle$. In the latter configuration, in general, there is kinetic energy of the mean amount $\langle W_{t\alpha}(A_1,Z_1)\rangle$ distributed among the α particle and the residual fragments, and the mean mutual potential energy stored in the system is $\langle V_{t\alpha}(A_1,Z_1)\rangle$. Then, because the total energies of the two configurations are the same, and because we can develop one from the other by a suitable sequence of ideal operations, we can derive a significant result from their comparison.

Suppose that the fragments of binary fission are allowed to separate to rest at infinity and de-excite to their ground states. Energy in amount $\langle V_b(A_1,Z_1)\rangle+\langle E_b(A_1,Z_1)\rangle$ is released. If an α particle is now removed (to rest at infinity) from the fragment $(A-A_1,\ Z-Z_1)$, energy in amount $B_\alpha(A-A_1,Z-Z_1)$ is absorbed. At this stage the resultants of the corresponding mode of ternary fission have been isolated, and, if the residual fragments are endowed with the appropriate energies of deformation-excitation, and if the resultants

[4] H. W. Schmitt and N. Feather, Phys. Rev. 134, B565 (1964).

are then brought together into the configuration of α-particle release, a further amount of energy equal to $\langle E_{t\alpha}(A_1,Z_1)\rangle+\langle V_{t\alpha}(A_1,Z_1)\rangle+\langle W_{t\alpha}(A_1,Z_1)\rangle$ must be supplied. Over-all therefore,

$$\langle V_b(A_1,Z_1)\rangle+\langle E_b(A_1,Z_1)\rangle-B_\alpha(A-A_1,\,Z-Z_1)\\-\langle E_{t\alpha}(A_1,Z_1)\rangle-\langle V_{t\alpha}(A_1,Z_1)\rangle-\langle W_{t\alpha}(A_1,Z_1)\rangle=0.$$

In terms of our earlier notation, clearly,

$$\langle V_b(A_1,Z_1)\rangle=\langle T_b(A_1,Z_1)\rangle, \tag{10}$$

and

$$\langle V_{t\alpha}(A_1,Z_1)\rangle+\langle W_{t\alpha}(A_1,Z_1)\rangle=\langle T_{t\alpha}(A_1,Z_1)\rangle. \tag{11}$$

Finally, therefore,

$$Q_b(A_1,Z_1)-Q_{t\alpha}(A_1,Z_1)=B_\alpha(A-A_1,\,Z-Z_1). \tag{12}$$

We reemphasize the fact that the result expressed in Eq. (12) is independent of any hypothesis concerning the sequence of events leading to the separation of the α particle in the process of ternary fission: it issues directly from the meaning that we have attached to the symbols employed, and particularly from the meaning that we have given to the term "corresponding modes" in relation to two types of fission that we are comparing.

Equation (12) refers only to a single pair of corresponding modes. Realistically, we have to deal with the over-all average values $\langle Q_b\rangle$ and $\langle Q_{t\alpha}\rangle$ of Eqs. (8) and (9) rather than with the single-mode values $Q_b(A_1,Z_1)$ and $Q_{t\alpha}(A_1,Z_1)$. It will be instructive, therefore, to develop Eq. (9) into a form bearing direct comparison with Eq. (12), particularly as we shall be using the transformed equation, rather than Eq. (9) in its original form, for the direct evaluation of $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$ from tabulated data. In general, mass tables list values of binding energies, or values of mass excesses, or both: Our transformed equation, in fact, will involve both these quantities.

Taking account of the second of Eqs. (7), we first rewrite Eq. (9) in the form

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=\sum_{A_1}\sum_{Z_1(A_1)}P_{t\alpha}(A_1,Z_1)\\\times\{M(A_1,Z_1)+M(A-A_1-4,\,Z-Z_1-2)+M(4,2)\}\\-\sum_{A_1}\sum_{Z_1(A_1)}P_b(A_1,Z_1)\\\times\{M(A_1,Z_1)+M(A-A_1,\,Z-Z_1)\}.$$

Then, introducing the binding energy of the last α particle in a heavy fragment of binary fission in terms of the defining equation

$$B_\alpha(A-A_1,\,Z-Z_1)=M(A-A_1-4,\,Z-Z_1-2)\\+M(4,2)-M(A-A_1,\,Z-Z_1),$$

we have

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=\sum_{A_1}\sum_{Z_1(A_1)}P_{t\alpha}(A_1,Z_1)B_\alpha(A-A_1,\,Z-Z_1)\\+\sum_{A_1}\sum_{Z_1(A_1)}\{P_{t\alpha}(A_1,Z_1)-P_b(A_1,Z_1)\}\\\times\{M(A_1,Z_1)+M(A-A_1,\,Z-Z_1)\}.$$

Finally, taking account of Eqs. (7) again, we are able to replace the sum of the masses of the representative pair of complementary binary fragments in the last term of the equation by the sum of the mass excesses of the fragments. In this way we obtain

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=\sum_{A_1}\sum_{Z_1(A_1)}P_{t\alpha}(A_1,Z_1)B_\alpha(A-A_1,\,Z-Z_1)\\+\sum_{A_1}\sum_{Z_1(A_1)}\{P_{t\alpha}(A_1,Z_1)-P_b(A_1,Z_1)\}\\\times\{\Delta M(A_1,Z_1)+\Delta M(A-A_1,\,Z-Z_1)\}. \tag{13}$$

Equation (12), having reference specifically to a single pair of corresponding modes, gave a clear-cut result: It is perhaps not unexpected that Eq. (13), its counterpart when the whole spectrum of corresponding modes is in question, should lack the simplicity of the former expression. Only if the probability factors $P_{t\alpha}(A_1,Z_1)$ and $P_b(A_1,Z_1)$ were identical for each pair of corresponding modes would over-all simplicity be regained. This is an extremely unlikely eventuality in any case: In the one case that has been investigated in detail[4,5]—and to which our further considerations will now be devoted —it is known that this precondition is not fulfilled. The difference of the mean Q values, $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$, cannot be given simply in terms of the mean binding energy of the last α particle in the heavy fragment of binary fission of ^{236}U.

We pass, then, to the systematic consideration of the binary and α-particle-accompanied ternary fission of the compound nucleus ^{236}U, with initial excitation energy of 6.4 MeV, as formed by thermal neutron capture in ^{235}U. At various stages in our argument we shall be using Eqs. (8)–(11) and (13) as occasion demands.

INDIRECT EVALUATION OF $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$ FROM TABULATED DATA

Equation (13) has been developed in full generality, but before we can use it we have to admit to ignorance in relation to certain essential information, and make a reasonable adjustment in order to cover that ignorance. Unfortunately, present information concerning the division of charge in fission is very much less complete than the corresponding information concerning the division of mass. Indeed, in respect of ternary fission, such information is virtually nonexistent. In

[5] H. W. Schmitt, J. H. Neiler, F. J. Walter, and A. Chetham-Strode, Phys. Rev. Letters 9, 427 (1962).

this connection all that we have, and that only in the case of ^{236}U, is a set of (uncorrected) values of $\sum_{Z_1(A_1)} P_{t\alpha}(A_1,Z_1)$.[5] For practical use the effective form of any equation is necessarily determined by its weakest term. We therefore reformulate Eq. (13), specifically now in relation to the fission of the compound nucleus ^{236}U, writing

$$\sum_{Z_1(A_1)} P_{t\alpha}(A_1,Z_1)=P_{t\alpha}(A_1)\,, \quad \sum_{Z_1(A_1)} P_b(A_1,Z_1)=P_b(A_1)\,,$$

$$A=236\,,\quad Z=92\,,$$

as

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=\sum_{A_1} P_{t\alpha}(A_1)B_\alpha(236-A_1,\,92-Z_1) +\sum_{A_1}\{P_{t\alpha}(A_1)-P_b(A_1)\} \times\{\Delta M(A_1,Z_1)+\Delta M(236-A_1,\,92-Z_1)\}\,, \quad (14)$$

with

$$(92A_1/236)+0.1<Z_1<(92A_1/236)+1.1\,. \quad (15)$$

It should be clear that the physical content of Eq. (13) has been changed in the reformulation. The inequality (15) fixes the charge number Z_1 as the integer nearest to $(92A_1/236)+0.6$. This is the best simple representation that we have[6] for the charge number of the most probable light fragment of mass number A_1 in the binary fission of ^{236}U. In writing Eq. (14) as we have done, we are effectively replacing all the modes of binary fission in which the mass division is $A_1/(236-A_1)$ by the single mode $(A_1,Z_1)/(236-A_1,\,92-Z_1)$, and all the modes of ternary fission in which the fragment mass division is $A_1/(232-A_1)$ by the single ternary mode $(A_1,Z_1)/(232-A_1,\,90-Z_1)/(4,2)$. We have to admit that there is no direct indication from experiment that inequality (15) gives the charge number of the most probable light fragment of mass number A_1 in ternary fission, but we had to make some assumption in this respect in order to proceed at all—and this assumption (which does not appear altogether unreasonable) is the one that we have made. Obviously, we lose generality in making it, but until we have detailed experimental information regarding the probability factors $P_b(A_1,Z_1)$ and $P_{t\alpha}(A_1,Z_1)$ we cannot achieve that generality, anyway.

Taking the values of $P_b(A_1)$ and $P_{t\alpha}(A_1)$ for the thermal-neutron induced fission of ^{235}U from the published work of Schmitt *et al.*[5] (uncorrected for dispersion resulting from secondary neutron emission, and for instrumental resolution[3]) we have normalized them over the interval $80\leqslant A_1\leqslant 110$, and have used them in Eq. (14) together with values of B_α and ΔM taken directly from the mass tables of Seeger.[7] The crude results of this calculation (which we must now assess in relation to possible systematic and random errors) are as follows:

$$\sum_{A_1} P_{t\alpha}(A_1)B_\alpha(236-A_1,\,92-Z_1)=2.87\text{ MeV}\,,$$

$$\sum_{A_1}\{P_{t\alpha}(A_1)-P_b(A_1)\} \times\{\Delta M(A_1,Z_1)+\Delta M(236-A_1,\,92-Z_1)\}=1.87\text{ MeV}.$$

In respect of systematic errors, Wing and Fong[8] have critically investigated various semiempirical mass equations, using the experimentally determined masses of odd-A nuclides as reference material. For Seeger's equation, it appears that over the mass-number range $90\leqslant A\leqslant 154$ (with which we are almost exclusively concerned) the mass residuals $M_{\text{expt}}-M_{\text{calc}}$ are given as a function of A quite closely by the linear relation

$$M_{\text{expt}}-M_{\text{calc}}=(1/20)(A-130)\text{ MeV}\,, \quad (16)$$

being distributed randomly about this mean line with a standard deviation of some 0.4 MeV. The implications of this result for our present considerations can best be seen by reference to Eq. (9). Since, on the basis of Eq. (16)

$$\{M(A_1,Z_1)+M(232-A_1,\,90-Z_1)\}_{\text{expt}} -\{M(A_1,Z_1)+M(232-A_1,\,90-Z_1)\}_{\text{calc}} =(1/20)(232-260)\text{ MeV}$$

and

$$\{M(A_1,Z_1)+M(236-A_1,\,92-Z_1)\}_{\text{expt}} -\{M(A_1,Z_1)+M(236-A_1,\,92-Z_1)\}_{\text{calc}} =(1/20)(236-260)\text{ MeV}\,,$$

it is evident from Eq. (9) that the correction for this particular systematic error merely involves the subtraction of 0.20 MeV from the crude value of $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$ as deduced directly from the tables. Furthermore, a little consideration of the right-hand member of Eq. (14) will show that this error attaches to the crude value of the first term uniquely; the value of the second term remains unchanged when corrected on the basis of Eq. (16). We have, therefore, the corrected result $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=2.67+1.87=4.54$ MeV, and it merely remains to assign a probable error to it from a consideration of the random errors inherent in Seeger's tabulation.

In respect of random errors, detailed scrutiny with the help of Eq. (9) shows that, in effect, 79 independent mass values have been taken from the tables in our evaluation of $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$ on the basis of Eq. (14). Thirty-one of these values are those of the quantity $M(A_1,Z_1)$ entering into our calculations multiplied by the probability factor $\{P_{t\alpha}(A_1)-P_b(A_1)\}$; 17 values are those of the quantity $M(232-A_1,\,90-Z_1)$ which are multiplied by the factor $P_{t\alpha}(A_1)$; another 17

[6] L. E. Glendenin and J. P. Unik, Phys. Rev. **140**, B1301 (1965); S. S. Kapoor, H. R. Bowman, and S. G. Thompson, *ibid.* **140**, B1310 (1965); W. Reisdorf and P. Armbruster, Phys. Letters **24B**, 510 (1967).

[7] P. A. Seeger, Nucl. Phys. **25**, 1 (1961).

[8] J. Wing and P. Fong, Phys. Rev. **136**, B923 (1964).

values are those of $M(236-A_1, 92-Z_1)$ multiplied by $P_b(A_1)$; the remaining 14 values are those of the quantity $M(236-A_1, 92-Z_1)$ which are multiplied by $\{P_{t\alpha}(A_1+4)-P_b(A_1)\}$. [The emergence of four categories, rather than three, in this analysis, arises from the fact that for some values of A_1 both the nuclides (A_1,Z_1) and (A_1+4, Z_1+2) belong to the sequence specified in terms of Eq. (15), and for others they do not.] Over-all only 14 out of the 79 probability multipliers effective in the calculation proved to be greater than 0.04 in absolute magnitude. Taking the absolute magnitude of all 79 multipliers into account, and assuming a uniform probable error of 0.4 MeV for each mass value, we obtained in the end an estimated probable error of 0.1 MeV in the final result. We have ultimately, therefore, if our reasonable assumptions and adjustments are allowed, on the basis of Seeger's tables, with corrections derived from the analysis of Wing and Fong,

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=4.54\pm0.10 \text{ MeV} \qquad (17)$$

for the thermal-neutron induced fission of ^{235}U.

DIRECT DETERMINATION OF $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$ BY EXPERIMENT

The experimental determination of $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$ on the basis of Eq. (8) involves separate quantitative estimations of the mean kinetic energies and the mean deformation-excitation energies of the final-state particles in the two types of fission concerned. As we shall discover, surveying the present state of knowledge under these two heads, neither estimation is direct in any absolute sense, and in each case present knowledge is uncertain to an extent which is considerably greater than the probable error that we have attached to the result of the indirect determination quoted in Eq. (17). In respect of the difference of the mean energies of deformation-excitation, in particular, there remains a wide limit of uncertainty, if only direct experimental estimates of this quantity are considered.

In respect of the difference of the mean kinetic energies, $\langle T_b\rangle-\langle T_{t\alpha}\rangle$, the first point to make is that fragment energies cannot be measured in the final state of our definition but only at a later stage, after the secondary (prompt) neutrons and γ rays have been emitted. Fortunately, because the secondary neutron emission is isotropic about the moving fragment, the mean fragment kinetic energy is not greatly changed during the second-stage process, but some dispersion is necessarily introduced. It is only very recently that a method has been devised,[3] and information has become available, whereby the true spectrum of final-state kinetic energies can reasonably be deduced from detailed measurements on the ultimate products of binary fission. No comparable analysis has yet been attempted of the corresponding measurements on the ultimate residual products of ternary fission. We have already drawn attention to the fact that it has been necessary to use uncorrected values of $P_b(A_1)$ and $P_{t\alpha}(A_1)$; here, correspondingly, we are compelled to use uncorrected values of $\langle T_b\rangle$ and $\langle T_{t\alpha}\rangle$, for the same reason as before. There is no point in our using more refined methods for the estimation of $\langle T_b\rangle$ than for $\langle T_{t\alpha}\rangle$ when we are merely concerned with the difference of these two quantities.

Three groups[5,9,10] have determined the difference between the mean kinetic energies of the fragments of binary and α-particle-accompanied ternary fission following upon thermal-neutron capture by ^{235}U. (From this difference the mean kinetic energy of the α particles must be subtracted in order to give $\langle T_b\rangle-\langle T_{t\alpha}\rangle$ for this case.) The three published values of the (uncorrected) difference are as follows:

Dmitriev *et al.*[9]	15.0±0.5 MeV,
Schmitt *et al.*[5]	12 ±2 MeV,
Schröder[10]	12.7±0.5 MeV.

If we take 15.0±0.5 MeV[11] as the mean kinetic energy of the α particles, and accept 13±2 MeV as a reasonably conservative estimate of a corrected value for the mean difference of fragment kinetic energies, based on the evidence of the three determinations above quoted, we have, for the compound nucleus ^{236}U,

$$\langle T_b\rangle-\langle T_{t\alpha}\rangle=-2\pm2 \text{ MeV}. \qquad (18)$$

In respect of the corresponding difference of the mean energies of deformation-excitation, $\langle E_b\rangle-\langle E_{t\alpha}\rangle$, direct experimental evidence is meager in the extreme. It depends primarily on a single determination. In 1959, Apalin *et al.*[12] published the results of a comparison of the mean numbers of secondary neutrons emitted in binary and α-particle-accompanied ternary fission. With thermal-neutron-irradiated ^{235}U, they deduced a mean value $\langle\nu_{t\alpha}\rangle=1.77\pm0.09$ for the α-particle-accompanied events, assuming $\langle\nu_b\rangle=2.45$ for the events of binary fission. They concluded that "the excitation energy of the fragments of ternary fission is less than in binary fission by at least 4 or 5 MeV." This last figure was based on the then available information concerning the rate of increase of $\langle\nu\rangle$ in neutron-induced binary fission with incident neutron energy (see below). In fact, later investigations[13] have somewhat modified

[9] V. N. Dmitriev, L. V. Drapchinskii, K. A. Petrzhak, and Y. F. Romanov, Dokl. Akad. Nauk. SSSR **127**, 531 (1959) [English transl.: Soviet Phys.—Doklady **4**, 823 (1959)]; Zh. Eksperim. i Teor. Fiz. **39**, 556 (1960) [English transl.: Soviet Phys.—JETP **12**, 390 (1961)].

[10] I. G. Schröder, thesis, Columbia University, 1965 (unpublished); Nucl. Sci. Abstr. **20**, 30513 (1966).

[11] C. B. Fulmer and B. L. Cohen, Phys. Rev. **108**, 370 (1957); R. A. Nobles, *ibid.* **126**, 1508 (1962); M. Dakowski, J. Chwaszczewska, T. Krogulski, E. Piasecki, and M. Sowinski, Phys. Letters **25B**, 213 (1967).

[12] V. F. Apalin, Y. P. Dobrynin, V. P. Zakharova, I. E. Kutikov, and L. A. Mikaelyan, At. Energ. (USSR) **7**, 375 (1959) [English transl.: Soviet J. At. Energy **13A**, 86 (1960)].

[13] D. S. Mather, P. Fieldhouse, and A. Moat, Phys. Rev. **133**, B1403 (1964).

earlier accepted values of this particular parameter: With the newer value and on the same basis, the estimated excitation energy difference is more nearly 6±1 MeV.

Here, however, the assumptions underlying this estimate should be clearly exposed. The first tacit assumption is that the energy which is finally emitted from the excited fragments as γ radiation is, on the average, the same in binary as in ternary fission. This assumption is not unreasonable, in view of the very similar fragment mass distributions in the two cases, and of the generally accepted (though possibly too naive) view that no γ-ray quantum is emitted until the total energy of deformation-excitation of any fragment has fallen below the binding energy of the next available neutron. On the other hand, a much greater degree of doubt attaches to a second assumption. There is a hidden assumption underlying the conclusion of Apalin *et al.*, that the so-called scission neutrons are emitted along with the α particles of ternary fission with the same probability as they are in binary fission. If we accept that in binary fission the average number of scission neutrons is, say, 0.35 per fission,[14] then the value of $\langle\nu_b\rangle$ relative to the post-final-state development of the fission process is 2.10, not 2.45, in the thermal-neutron induced fission of ^{235}U. Because this is the case, if we were to assume that there are no scission neutrons accompanying the α particles of ternary fission (though the emission of ^{6}He nuclei[15] may be regarded as providing a contraindication to this view), we should compare 1.77 with 2.10 rather than with 2.45, and conclude (on the same basis as before) that the final-state deformation-excitation energy difference is more nearly 3 MeV than twice that amount.

The two assumptions that we have just discussed, in relation to the conclusion of Apalin *et al.*, are tacit (or even hidden) assumptions. These authors' primary and explicit assumption was that for any given binary fission mode the sum of the final-state mean energies of deformation-excitation of the two fragments [which sum we have represented by $\langle E_b(A_1,Z_1)\rangle$ in Eq. (2)] increases at the same rate as the energy of initial excitation of the compound nucleus from which they are derived. If this assumption were taken to its logical conclusion, it would imply that the sum of the final-state mean energies of deformation-excitation of the fragments in the (binary) spontaneous fission of ^{236}U is less than the corresponding sum for the fragments of binary fission of the compound nucleus ^{236}U formed by thermal-neutron capture in ^{235}U by 6.4 MeV, the value of the binding energy of the last-added neutron in ^{236}U. We shall return to this consideration in our final discussion; meanwhile we summarize the results of our survey of presently available information from direct experiment in respect of the quantities that interest us.

Having regard to the difficulties of interpretation of the results of Apalin *et al.* (and to their present lack of experimental confirmation) let us accept provisionally for the compound nucleus ^{236}U, at initial excitation of 6.4 MeV,

$$\langle E_b\rangle-\langle E_{t\alpha}\rangle=4.5\pm3.5\text{ MeV}. \tag{19}$$

Then, taking this result along with that of Eq. (18), we have, as our "experimental" estimate of the difference of the mean Q values,

$$\langle Q_b\rangle-\langle Q_{t\alpha}\rangle=2.5\pm4\text{ MeV}, \tag{20}$$

to be compared with the table-based estimate of Eq. (17).

DISCUSSION

The first, relatively trivial, comment to be made in relation to the estimates of $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$ set out in Eqs. (17) and (20) is that they agree with one another within the sum of the limits of probable uncertainty that we have assigned to each. If we regard this agreement as significant, we can take the more important step of combining the value of $\langle Q_b\rangle-\langle Q_{t\alpha}\rangle$ of Eq. (17) with $\langle T_b\rangle-\langle T_{t\alpha}\rangle$ of Eq. (18), thereby deducing a value of $\langle E_b\rangle-\langle E_{t\alpha}\rangle$ which is considerably "better known" than the direct value given by Eq. (19). Indeed, on this basis, we have

$$\langle E_b\rangle-\langle E_{t\alpha}\rangle=6.5\pm2\text{ MeV}. \tag{21}$$

In what follows we shall, in fact, base our discussion on the results of our over-all enquiry consolidated in this way, as given in Eqs. (17), (18), and (21).

We first discuss the implications of Eq. (18), using Eqs. (10) and (11) to provide the basis for our discussion. Generalizing these last mentioned equations to take account of the multiplicity of modes of binary (and ternary) fission, and taking in the experimental result, Eq. (18), we have

$$\langle V_b\rangle-\langle V_{t\alpha}\rangle-\langle W_{t\alpha}\rangle=-2\pm2\text{ MeV}. \tag{22}$$

Halpern,[16] among others, has discussed the difference in the kinetic-energy release in binary and ternary fission essentially in the same terms as we are using here. Adopting a one-stage view of the ternary fission process, in terms of our formalism he has effectively identified $\langle W_{t\alpha}\rangle$ with the initial energy of α-particle release and has variously suggested values of 4 MeV [16] and 2 MeV [17] for this quantity. We may accept these estimates (without attempting to decide between them) whether

[14] K. Skarsvag and K. Bergheim, Nucl. Phys. **45**, 72 (1963).
[15] M. Marshall and J. Scobie, Phys. Letters **23**, 583 (1966); J. Chwaszczewska, M. Dakowski, T. Krogulski, E. Piasecki, W. Przyborski, and M. Sowinski, Phys. Letters **24B**, 87 (1967).
[16] I. Halpern, *Physics and Chemistry of Fission* (International Atomic Energy Agency, Vienna, 1965), Vol. II, p. 369.
[17] I. Halpern (unpublished); see S. L. Whetstone and T. D. Thomas, Phys. Rev. **154**, 1174 (1967).

we adopt the one- or two-stage view. Accepting them, on the basis of the one-stage hypothesis, we should conclude from Eq. (22) that $\langle V_b \rangle$ and $\langle V_{t\alpha} \rangle$ are the same to within, say, 3 MeV; on the basis of the two-stage hypothesis, we could allow a smaller value of $\langle V_{t\alpha} \rangle$ provided that $\langle W_{t\alpha} \rangle$ (which would now include a contribution from the initial kinetic energies of the fragments) was correspondingly increased. Taking account only of the quantitative information provided by Eq. (22), there is no discrimination between these two hypotheses. This point having been established, we adopt the one-stage hypothesis for our further discussion.

First, note that the near equality of $\langle V_b \rangle$ and $\langle V_{t\alpha} \rangle$ (according to any hypothesis) is basically incomprehensible except against the background fact that the distributions of fragment mass and charge in binary and α-particle-accompanied ternary fission are so nearly the same. On the other hand, we cannot simply conclude that $\langle V_b(A_1,Z_1) \rangle$ and $\langle V_{t\alpha}(A_1,Z_1) \rangle$ in general differ by as little as 3 MeV just because $\langle V_b \rangle$ and $\langle V_{t\alpha} \rangle$ have the same value within these limits [compare Eqs. (12) and (13)]. No doubt individual differences for some modes of mass division are greater than 3 MeV. Yet it will simplify further argument and avoid considerable circumlocution if we use the particular case rather than the statistical ensemble of cases in our discussion. So this we shall do. We suppose, then, that for the corresponding modes of our previous definition, $(A_1,Z_1)(A-A_1,\ Z-Z_1)$ and $(A_1,Z_1)/(A-A_1-4,\ Z-Z_1-2)/(4,2)$, $\langle V_b(A_1,Z_1) \rangle$ and $\langle V_{t\alpha}(A_1,Z_1) \rangle$ differ by an amount which is very small indeed compared with the magnitude of either quantity (approximately 170 MeV in our case).

Provisionally, let us make the exploratory assumption that the mean distribution of positive charge in the fissioning nucleus at the moment of binary scission is essentially indistinguishable from the mean distribution of positive charge at the moment of α-particle release in the corresponding mode of ternary fission. Then, since $\langle V_b(A_1,Z_1) \rangle$ and $\langle V_{t\alpha}(A_1,Z_1) \rangle$ are calculated with respect to different reference configurations (one with respect to two deformed binary fragments, the other with respect to two deformed ternary fragments and an α particle, at "infinite" separation), we should expect $\langle V_{t\alpha}(A_1,Z_1) \rangle$ to be greater than $\langle V_b(A_1,Z_1) \rangle$ by the mutual potential energy of an α particle and the ternary fragment $(A-A_1-4,\ Z-Z_1-2)$ appropriately brought together (so that the α particle is repositioned in the scission configuration in the reconstituted binary fragment). This last quantity must be several times greater than the difference that experiment will allow in $\langle V_{t\alpha}(A_1,Z_1) \rangle - \langle V_b(A_1,Z_1) \rangle$. We conclude, then, that our exploratory assumption is untenable: The mean distribution of positive charge in the fissioning nucleus at the moment of binary scission must be less extended than is the mean distribution of charge at the moment of α-particle release in the corresponding mode of ternary fission.[18,19] We do not attempt to place any numerical value on this difference of (axial) extension (because any such estimate is obviously model-dependent), but it must be such as to correspond to a difference of, say, 8–15 MeV in $\langle V_{t\alpha}(A_1,Z_1) \rangle$. All this has been argued on the basis of the one-stage hypothesis, according to our intention. On the basis of the two-stage hypothesis, a precisely similar formal conclusion would result: Those events of binary scission from which events of ternary fission develop through the emission of an α particle from an already separated fragment must, on the average, be events in which the configuration at scission is more elongated than is the case, on the average, for binary scission events generally.

We summarize this part of the discussion in the statement (which does not discriminate between the one- and two-stage hypotheses) that the only valid inference from the quantitative information provided by Eq. (22) is that the representative (mean) event which is α-particle-accompanied ternary fission develops in time in such a way that at some stage it passes through the configuration which is the representative (mean) configuration of binary scission.

We now turn to a discussion of the quantitative information provided by Eq. (21). We note that this information is no longer provided directly through the interpretation which Apalin *et al.* gave to their experimental results on $\langle \nu_b \rangle - \langle \nu_{t\alpha} \rangle$ although it is not inconsistent with that interpretation in respect of its general approach to the problem. Following that general approach to its logical conclusion, as we have already pointed out, we should expect the mean number of secondary neutrons in the spontaneous (binary) fission of ^{236}U to be less than the $\langle \nu_b \rangle$ of our discussion by a deficit corresponding to a loss of 6.4 MeV of energy of initial excitation. It so happens that this is almost precisely the most probable value of $\langle E_b \rangle - \langle E_{t\alpha} \rangle$ indicated by Eq. (21). If, then, the interpretative approach of Apalin *et al.* can be justified, we conclude (coincidentally) that the difference between the mean numbers of secondary neutrons in the thermal-neutron induced (binary) fission of ^{235}U and the spontaneous (binary) fission of ^{236}U should be very closely the same as the difference $\langle \nu_b \rangle - \langle \nu_{t\alpha} \rangle$ which Apalin *et al.* determined in relation to the binary and α-particle-accompanied ternary fission in the former case.

Unfortunately, $\langle \nu \rangle$ has not been determined for the spontaneous fission of ^{236}U. It has been determined with considerable precision for the spontaneous fission of the four even-A isotopes of plutonium, ^{236}Pu, ^{238}Pu, ^{240}Pu, and ^{242}Pu;[20] and it would not be inconsistent with the

[18] On the basis of particular models, Halpern (Ref. 16) and Fraenkel (Ref. 19) have come qualitatively to similar conclusions.

[19] Z. Fraenkel, Phys. Rev. **156**, 1283 (1967).

[20] B. C. Diven, H. C. Martin, R. F. Taschek, and J. Terrell, Phys. Rev. **101**, 1012 (1956); D. A. Hicks, J. Ise, and R. V. Pyle, *ibid.* **101**, 1016 (1956).

results of these experiments to assign the same value $\langle\nu\rangle=2.26\pm0.10$ to all four isotopes. For the spontaneous fission of ^{238}U, $\langle\nu\rangle$ has been determined as 2.10 ± 0.08 by Shev and Leroy.[21] If we could argue by analogy, we might reasonably take $\langle\nu\rangle=2.10\pm0.25$ for the spontaneous (binary) fission of ^{236}U. This is less than the $\langle\nu_b\rangle$ of our discussion by 0.35 ± 0.25, whereas $\langle\nu_b\rangle-\langle\nu_{t\alpha}\rangle$ according to Apalin *et al.* is 0.68 ± 0.09. We cannot confidently conclude that the apparent discrepancy of these estimates is significant, but there is more than a suspicion that our previous suggestion that very few scission neutrons are emitted in α-particle-accompanied ternary fission should be taken seriously. We assume, of course, that the emission of scission neutrons is a feature of the binary spontaneous fission of ^{236}U as it is of the thermal-neutron induced fission of ^{235}U.

Very recently, an experimental multiparameter study of the secondary neutrons from the thermal-neutron induced fission of ^{235}U has been carried out by Maslin *et al.*[22] These authors have analyzed their results in such a way as to show how the mean number of secondary neutrons emitted by a primary fragment depends on the mass and kinetic energy of the fragment. In particular, they have shown that if the mean sum of the numbers of secondary neutrons emitted by complementary fragments is plotted against the sum of the kinetic energies of the fragments, without regard to the mode of mass division, then the curve falls linearly over the range of kinetic energy 145–205 MeV, with slope 0.054 neutron per MeV. They have also transformed these results, using Q values calculated by Milton[23] on the basis of the semiempirical mass formula of Cameron,[24] so that the independent variable becomes the sum of the deformation-excitation energies of the fragments (again without regard to the mode of mass division). When presented in this way, their results indicate that the mean number of secondary neutrons increases linearly with the sum of the deformation-excitation energies, over a considerable range, at the rate of 0.066 neutron per MeV.

[21] R. Shev and J. Leroy, J. Phys. Radium **21**, 617 (1960).
[22] E. E. Maslin, A. L. Rodgers, and W. G. F. Core, Phys. Rev. **164**, 1520 (1967).
[23] J. C. D. Milton, University of California Report No. UCRL-9883 (Revised 1962) (unpublished).
[24] A. G. W. Cameron, Can. J. Phys. **35**, 1021 (1957).

Though there are certain anomalous features of the results of Maslin *et al.* which the authors themselves do not profess fully to understand—and though no reference is made to the scission neutrons (which must have been counted along with the prompt neutrons, and arbitrarily assigned to the fragments, in the process of their analysis)—the results that we have quoted merit serious consideration. If we compare them with the results of Mather *et al.*,[13] a seeming discrepancy is revealed. Mather *et al.* determined the initial rate of increase, with bombarding neutron energy, of the mean number of secondary neutrons emitted in the neutron-induced fission of ^{235}U as 0.109 neutron per MeV. This is the figure that we used in "correcting" the original conclusion of Apalin *et al.* concerning the value of $\langle E_b\rangle-\langle E_{t\alpha}\rangle$ in the thermal-neutron induced fission of this nucleus. We raised the question, formally, whether it was justifiable to conclude that, in binary fission produced by neutrons of several MeV energy, the whole of the kinetic energy of the incident neutron which is taken up originally as energy of excitation of the compound nucleus is passed on as deformation-excitation energy to the primary fragments of fission. The results of Maslin *et al.* appear to give an unexpected (if oblique) answer to this question: To explain the rate of increase of secondary neutron emission with increasing bombarding neutron energy appears to require an even greater rate of increase of fragment excitation than the incident neutron is able to bring to the fissioning nucleus. It seems, then, that there is much still to be clarified in this aspect of the problem. Meanwhile we merely note that if we were to accept the result of Maslin *et al.*, in substitution for that of Mather *et al.* on which we have relied hitherto, we should have no difficulty in reconciling a (hypothetical) value of $\langle\nu\rangle$ for the spontaneous (binary) fission of ^{236}U of 2.03 with a value of 2.45 for $\langle\nu_b\rangle$ for the thermal-neutron induced fission of ^{235}U, nor in accepting the experimental results of Apalin *et al.* as consistent with the assumption that scission neutrons are not emitted in the α-particle-accompanied ternary fission in this case. Obviously, until the experimental results of Apalin *et al.* have been confirmed, and the question of the emission of scission neutrons in α-particle-accompanied fission has been decided by experiment, it will be unprofitable to carry this particular discussion further.