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ABSTRACT

The correlation between the angular anisotropy and the mass asymmetry of the fragments has been determined in the fission of U^{235} induced by 4 MeV neutrons. The kinetic energies of the pair fragments emitted parallel and perpendicular to the incident beam direction are measured by a three dimensional analogue to digital converter incorporated with the print-out arrangement. The anisotropy has been found to increase with the asymmetry in the region of mass ratios 1.2 to 1.7. The observed variation of the total kinetic energy E_k and the mean square deviation $\sigma^2_{E_k}$ are found to be different from that observed in the case of thermal fission. The various possibilities leading to the observed dependence of the anisotropy on the asymmetry are discussed.

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INTRODUCTION

To understand the mechanism of the mass division in fission, it is important to know whether the mass division depends on the quantum state of the fissioning nucleus at the saddle point. This dependence can be determined by a study of the correlation of the angular anisotropy and the mass asymmetry of the fission fragments, since the angular distribution is known[1] to be decided by the quantum numbers available at the saddle point. The anisotropy has been observed to be related to the asymmetry in the case of photo-fission[2] of Th^{232}, charged particle induced fission[3] of Th^{232} and 14.9 MeV neutron induced fission[4] of U^{238}. However, in all these cases the observed connection between the anisotropy and the asymmetry could arise because of fission taking place at various excitation energies due to the evaporation of neutrons, and, therefore, these observations are not sufficient to show any inherent dependence[5]. The direct dependence can be determined in the study of the fission of the compound nucleus excited below the binding energy of a neutron, so that fission takes place only at a single excitation energy.

In the experiments reported here, the relation between the anisotropy and the asymmetry has been studied in the fission of U^{235} induced by 4 MeV neutrons. The kinetic energies of the pair fragments emitted nearly along and perpendicular to the direction of the incident beam are measured by back to back solid state detector systems and recorded by a three dimensional analogue to digital converter with the print-out arrangement. The data have been analysed to obtain the distributions in the mass and the total kinetic energy of the fragments emitted at angles of 0° and 90° with respect to the direction of the incident beam. The results show that the angular anisotropy depends on the mass asymmetry of the fragments. The observed variation of the total kinetic energy with the mass ratio is also discussed.

EXPERIMENTAL ARRANGEMENT AND METHOD

A schematic diagram of the experimental arrangement is shown in Fig. 1. Neutrons of 4 MeV were produced by the $T(p,n)He^3$ reaction using the 5.5 MeV Van de Graaff generator. The uranium target was prepared by electro-spraying about 300 μg of U^{235} over an area of 1 sq.cm on to a VYNS foil coated with a thin layer of gold. The thickness of the VYNS foil and the gold layer was estimated to be about 10 $\mu g/cm^2$ and 15 $\mu g/cm^2$ respectively. The uranium foil and three identical solid state detectors were mounted inside a chamber which was evacuated to a high degree of vacuum (Fig.1). The distance between the surface of one of the detectors (referred to as common detector) and the foil was about 0.2 cm so that most of the fragments emitted in the backward hemisphere were detected by it. At each of the angles of 0^o and 90^o with the incident direction the fragments were detected with an angular resolution of about 18^o. The divergence of the incident neutron beam was calculated to be approximately 3^o.

Identical charge sensitive pre-amplifier-amplifier systems were used for amplifying pulses from the detectors. The coincidence between the pulses from the 0^o detector and the common detector (or the 90^o detector and the common detector) was used to gate the detector outputs. The gated output pulses were fed to three analogue to digital converters (ADC) each one employing a Wilkinson gate and a 88 Mc crystal controlled oscillator. The ADC systems were followed by an automatic print-out arrangement. The output pulse heights were transformed into energies by calibration of each of the detector systems using the kinetic energy distribution for the thermal fission of U^{235} as obtained by the time of flight technique[6]. To compare the kinetic energy distributions obtained by solid state detector to those obtained by the time of flight method, the latter was corrected[7] to represent the kinetic energy distribution after the neutron emission. As the peak positions in the kinetic energy distribution of single fragments are the same[8] for the fission induced by thermal neutrons and by medium energy neutrons, the above calibration procedure is justified. The fragment masses were calculated using the momentum conservation relation $M_L E_L = M_H E_H$, where M_L, E_L and M_H, E_H are the mass and the kinetic energy for the light and the heavy fragments respectively. The data were analysed using the computer TIFRAC. The total number of events recorded both in the 0° and 90° directions was about 40,000. The counts $N(0^\circ)$ and $N(90^\circ)$ from the 0° and 90° detectors respectively, were also separately monitored to determine the anisotropy of the fragments.

EXPERIMENTAL RESULTS

The ratio $\{N(0^\circ)/N(90^\circ)\}$ as determined from the monitor counts of the 0° and 90° detectors has been found to be equal to (1.147 ± 0.027). This value, uncorrected for geometrical resolution, compares favourably with the value of (1.13 ± 0.020) obtained by Simmons and Henkel[9]. From the calculated mass distributions, the following results are obtained:

$$\{N_L(0^\circ)/N_H(0^\circ)\} = (1.01 \pm 0.01); \quad \{N_L(90^\circ)/N_H(90^\circ)\} = (0.99 \pm 0.01)$$

where N_L and N_H are the total number of the light and the heavy fragments respectively. It can be seen that within the statistical accuracy of one percent the numbers of the light and heavy fragments emitted in the 0° direction are equal. This shows that the angular distributions are symmetric about 90°, implying that the light and the heavy fragments have identical angular distributions. This is in agreement with the results of the previous work[4, 10, 11, 12] but in disagreement with the work of Brolley et al[13] on the fission of Np^{237} by 14.3 MeV neutrons where the light and heavy fragments were found to have different angular distributions.

The results of the measurements are summarised compactly in the contour plots of Fig. 2 (a & b) which have been drawn from the $E_L - E_H$ matrix by interpolations between two points and represent the probability distribution $N(E_L, E_H)$. The number labelled on each of the contours gives the relative frequency of occurrence of the events defined by the contour. The mass distributions of the fragments emitted at angles of 0° and 90° to the incident beam, as obtained from the analysis of the data, are shown in Fig. 3 (a). These distributions have been corrected for the systematic effects of the emission of neutrons as described by Terrell[14] and Britt et al[15]. The error ΔM_H in the calculated mass M_H is given by

$$\Delta M_H = M_H - M_H^* = \nu_H - \{(M_H^* \nu_T) / (M_H^* + M_L^*)\} \quad (1)$$

where M_H^*, M_L^* are the corrected masses of the light and heavy fragments respectively and ν_H and ν_T are the number of neutrons emitted from the fragment of mass M_H and the total number of neutrons from both fragments respectively.

The variation of ν_T with the fragment mass division was calculated using the measured values of the total kinetic energy $\bar{E}_k$ for each mass division, on the energy balance considerations, as described later. Since there exists no information on the variation of number of neutrons with the fragment mass in the case of the fission of U^{235} by 4 MeV neutrons by direct measurements, it was assumed that $\nu_L = \nu_H = \nu_T/2$. This assumption may not be fully justified at medium excitation energies, especially in the region of the symmetric mass divisions. As the corrected values appear to be closely dependent on the nature of the variation of $\nu(M)$, the applied corrections can be considered only approximate. The corrected distributions are shown in Fig. 3 (b). For comparison, the uncorrected mass distribution of the fragments emitted in the 0° direction is also shown in the same figure. The values $\bar{M}_H$ of the average heavy fragment mass are found to be (139 $\pm$ 0.2) and (138.6 $\pm$ 0.2) for the fragments emitted in the 0° and 90° directions respectively. The variances σ_M^2 of the observed mass distributions for the 0° and 90° fragments are found to be same and equal to 65.3. The value of the variance for both the mass distributions corrected for the systematic effects of neutron emission is 61.9. This value includes a variance of about 2.0 due to the dispersion[14] resulting from the varying directions and number of emitted neutrons, and an estimated variance of about 0.8 due to the experimental energy resolution of the semi-conductor detectors.

The anisotropy$\{N(0^{\circ})/N(90^{\circ})\}$for the various mass ratios as calculated from Fig. 3 is shown in Fig. 4. This plot is independent of the effects of the neutron emission on the mass distributions, if it is assumed that the characteristics of the neutron emission are the same for emission from the fragments emitted along the 0° and 90° directions. The variation of the average kinetic energy with the fragment mass ratios for the two cases as observed in the present experiment supports this assumption. From

Fig. 4 it is seen that the anisotropy increases with the mass ratio in the region of mass ratios between 1.2 to 1.7. Further, in the regions of lesser statistical accuracy the anisotropy seems to decrease for mass ratios greater than 1.7 and to increase for mass ratios less than 1.2. Earlier measurements for the fission of U^{238} by 3 MeV neutrons using a double ionization chamber by Baranov et al[12] do not show the increase in the anisotropy between the mass ratios of 1.25 and 1.65, but the anisotropy was found to be higher for the mass ratio of 1.0 than for 1.25. The variance of the mass distributions obtained by Baranov et al[12] is about 85 which is significantly higher than the value obtained in the present work. This shows that the mass resolution obtained in their work is poorer, probably due to the use of a thicker source and gridded ionization chamber as compared to solid state detectors. This might have been responsible for masking the dependence of the anisotropy on the asymmetry in their experiment. A larger anisotropy for the symmetric fragment group was also found by Manley[16] in the study of fission of U^{238} induced by neutrons of energy from 1.2 to 1.7 MeV, using the photographic emulsion technique but the mass resolution in this work is not sufficient to obtain detailed information about the variation of the anisotropy with the asymmetry.

The average values of the total kinetic energies of the fragments are found to be as follows:

$$\bar{E}_k(0^\circ) = (165.4 \pm 1.1) \text{ MeV}; \; \bar{E}_k(90^\circ) = (166.0 \pm 1.1) \text{ MeV}.$$

The values of the average total kinetic energies $\bar{E}_k(0^\circ)$ and $\bar{E}_k(90^\circ)$ for the fragments emitted at angles of 0° and 90° respectively are the same within the experimental error showing that the scission configurations in the two cases are identical. The variation of the average total kinetic energy $\bar{E}_k$ with the fragment mass ratio after correcting for the effects of neutron emission is shown in Fig.5 (a) along with that for the case of thermal fission[6]. For the calculation of the correction ΔE_k to the measured total kinetic energy $\bar{E}_k$ the following approximate expression[15] was used:

$$\Delta E_k = \left\{ \bar{\bar{E}}_k/(A-\nu_t) \right\} \left\{ \nu_L R + (\nu_H/R) \right\} \qquad (2)$$

where $R = (M_H/M_L)$

The correction to the measured values of $\bar{E}_k$ has been applied on the assumption of $\nu_L = \nu_H = \nu_{T/2}$.

The calculated error ΔE_k is only weakly dependent on the nature of variation of ν (M) and, therefore, the erros in the values ΔE_k calculated on the assumption of $\nu_L = \nu_H = \nu_T/2$ are very small. From the observed values of $\bar{E}_k$, uncorrected for the neutron emission effects, the total number of neutrons ν_T emitted for each mass ratio is calculated on the energy balance consideration, and are shown in Fig. 4 (c). However, the values of ν are not appreciably changed if the corrected values of $\bar{E}_k$ are used in the calculations. In these calculations, the values of the energy released and the neutron binding energies have been taken from Milton[17], and it has been assumed that for each mass division the average energy emitted as gamma rays is 7.5 MeV and the average emission energy of the neutrons is 1.2 MeV. It can be seen from Fig. 5 (a) that the variation of $\bar{E}_k$ with the fragment mass ratios is nearly the same for the fragments emitted parallel and perpendicular to the incident neutron beam indicating that the characteristics of the neutron emission for various mass ratios are the same for the two cases. The mean square deviations $\sigma^2_{E_k}$ of the total kinetic energy distributions as obtained by eye fit is shown inFig. 4(b). The observed variation of $\sigma^2_{E_k}$ is different than that observed by Milton and Fraser[6] for the thermal fission of U^{235} but agrees with recent experiments[18] in the medium energy fission and the trend calculated by Fong[19].

DISCUSSION

The average separation of the effective charge centres at the scission point for the various mass divisions can be obtained from the measured variation of $\bar{E}_k$ with fragment mass ratios as the kinetic energy arises from the Coulomb repulsion between the fragments at scission. The elongation of the fissioning nucleus at scission for the various mass divisions can be expressed in terms of a parameter β which can be defined as the ratio of the actual distance between the charge centres to the distance if the fragments were formed spherical, and is given by the relation

$$\beta = Z_L^p Z_H^p e^2 / \{ \bar{E}_k \, r_o (A_L^{1/3} + A_H^{1/3}) \} \quad (3)$$

where Z_L^p, Z_H^p are the most probable charges for the fragments of mass numbers A_L and A_H respectively. The values of β calculated for different mass ratios using the measured values of $\bar{E}_k$ and the tabulated values[17] of Z_L^p and Z_H^p, are shown in Fig. 6 for thermal and 4 MeV neutrons induced fission.

For thermal fission the occurrence of the minimum value of β at the mass ratio of 1.27 can be explained on the shell effects, as the heavy fragment in this case is doubly magic. A higher value of β in the region of mass ratios 1.19 to 1.48 for the case of 4 MeV neutron induced fission than for thermal fission signifies that the shell effects are less predominant at higher excitation energies. For all the other mass divisions, the value of β is higher for the thermal fission than for the 4 MeV neutron induced fission, showing that at higher excitation energies the nucleus undergoes lesser stretching upto the scission indicating that the "tensile strength" of the nucleus decreases with the increase in the excitation energy. The largest difference in the values of β for the two cases occurs in the case of symmetric fragments showing that the symmetric fragments are formed in a significantly more stretched configuration in the thermal fission. For this reason, the symmetric fragments produced in the thermal fission emit more neutrons than those produced in the medium energy induced fission {Fig.4(c)}. These differences in the characteristics of the symmetric fragments with regard to their kinetic and excitation energy suggests that these are produced by different mechanisms in the two cases.

Strutinski[20] has suggested that the dependence of the anisotropy on the asymmetry may arise through the spin dependence of the level densities of the fragments at scission. In such a case, the different moments of inertia of the fragments formed in the various mass divisions can lead to different anisotropies. On this basis, a higher anisotropy in those divisions where the fragments are magic or near magic is expected as these fragments have lower moments of inertia. However, the above explanation assumes that the anisotropy depends on the properties of the fragments at scission which is contrary to the results of later investigations. Further, in the present work lower values of the anisotropy are observed for the mass ratios leading to the magic fragments. However, a dependence of the anisotropy on the asymmetry can arise if the final mass division depends on the saddle point shapes and each saddle point shape has a different sequence of the quantum numbers. From the results of the present experiment, a dependence of the final mass division on the saddle point shapes, in at least the medium energy induced fission, can, therefore, be inferred. The dependence of the saddle point quantum numbers on the different shapes can arise due to different reasons. On the basis of the analysis of Halpern and Strutinski[20] and Griffin[21], the anisotropy increases with the decrease in the value of K_o^2, where K_o^2 is the mean square of the projection of the total angular momentum $\vec{I}$ on the nuclear symmetry axis. On the statistical arguments it has been shown that $K_o^2 = J_{eff}T/\hbar^2$, where J_{eff} and T are the effective moment of inertia and the nuclear temperature respectively of the nucleus at the saddle point. For low excitation energies, K_o^2 is given by

$$K_o^2 = \text{Const.}\; J_{eff}\,(E_{exc} - \bar{E}_{th})/\hbar^2 \qquad (4)$$

where E_{exc} is the excitation energy of the nucleus and E_{th} is the fission threshold and is equal to the deformation energy at the saddle point. The observed correlation can, therefore, be associated either with the variationof J_{eff} or T or both with the saddle point shape of the nucleus. However, the evaluation of J_{eff} for the various mass divisions requires a detailed knowledge of the corresponding saddle point shapes about which at present very little is known. If the variation of J_{eff} with the saddle point shapes is small, the observed dependence suggests that the average nuclear temperature T decreases with the increasing asymmetric shapes in the region of mass ratios 1.2 to 1.7. This would imply that the saddle point deformation energy increases with the asymmetry in the saddle point shape. On the other hand, if one generalises that the variation of β for various mass ratios as seen inFig. 6, is due to the same reason as the observed difference in β for the case of thermal and 4 MeV fission, one expects different starting nuclear temperatures leading to various mass divisions. The variation of (1/T) can, therefore, be thought to be similar to the observed variation of β with themass ratio. On this picture, the increase inthe anisotropy in the mass ratio region of 1.2 to 1.7 should be due to the decrease of J_{eff} with increasing mass ratio, as the variation of T is expected to be small in accordance with the variation of β.

The purpose of the present discussion on the observed variation of the anisotropy with the asymmetry has only been to point out the various possibilities leading to the observed dependence. A quantitative estimate of the various factors effecting the dependence of the anisotropy for the various saddle point shapes is necessary for more detailed discussion.

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FIGURE CAPTIONS

Fig. 1 Schematic diagram of the experimental arrangement.

Fig. 2 Contour plots of the data for the 4 MeV neutron induced fission of U^{235} in cases when the fragments are emitted (a) parallel, and (b) perpendicular to the incident beam direction. The number labelling each contour represents the frequency of occurrence of the events defined by the contour. The total number of events is about 4×10^4.

Fig.3(a) Mass yields of the fragments emitted in the 0^o and 90^o directions plotted against the heavy fragment mass. These distributions are the observed yields uncorrected for the effects of the neutron emission.

Fig. 3(b) Mass yields of the fragments emitted in the 0^o and 90^o directions plotted against the heavy fragment mass after correcting for the systematic effects of the neutron emission onthe assumption that the pair fragments emit equal number of neutrons. For comparison the uncorrected mass yield of the 0^o fragments is also shown as crossed points.

Fig. 4 Angular anisotropy $\{N(0^o)/N(90^o)\}$ versus mass asymmetry (M_H/M_L), calculated from the observed mass yields shown in Fig. 3 (a).

Fig. 5(a) Plot of the average total kinetic energy $\bar{E}_k$ of the fragments against mass ratios. The values of $\bar{E}_k$ have been corrected for the effects of neutron emission. The observed variation of $\bar{E}_k$ with the fragment mass ratios, as observed[6] in the thermal neutron fission of U^{235} is also shown.

Fig. 5(b) The variance $\sigma^2_{E_k}$ of the total kinetic energy E_k of the fragments plotted against fragment mass ratios.

Fig. 5(c) Total number ν_T of the neutrons emitted for the various mass divisions as calculated on the energy balance considerations using the measured values of $\bar{E}_k$.

Fig. 6 Variation of the calculated β with the fragment mass ratios for the thermal and 4 MeV neutron induced fission of U^{235}. β is the ratio of the actual distance between the effective charge centres of the fragments at the scissionpoint to the distance if the fragments were formed spherical.

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