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GOVERNMENT OF INDIA
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EMISSION OF LONG RANGE ALPHA PARTICLES IN FISSION

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I. INTRODUCTION

The emission of long-range alpha particles in fission, though discovered some 20 years ago, has not been fully understood. Due to the low probability of emission of the long-range alpha particles, extensive experimental studies could be undertaken only recently with the availability of high flux reactors and high current machines. Several experimental techniques such as the photo-emulsion method, double ionization chamber and recently, semi-conductor detectors have been employed in these investigations which give a clear indication that the emission process is a complicated one. The following is a survey of the experiments as well as the various theories that have been put forth to explain this phenomenon.

II. EXPERIMENTAL WORK

The first published work on the subject was by Tsien et al(1) in 1947, although the long-range alpha particles were observed by Alvarez as early as 1943 as reported by Farwell et al(2). Alvarez observed, using a double ionization chamber, that the maximum range of the light charge particle associated with fission was about 20 cm in air. Tsien et al using the emulsion technique were able to establish the nature of the particle. The probability of emission of particle per fission of U^{235} and Pu^{239}, its nature and energy were measured by Farwell et al. with an ionization chamber. Similar work has also been reported by other workers but probably the most accurate results have been due to Fulmer and Cohen(3) who used the magnetic

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spectrometer to obtain the alpha particle spectrum emitted in the pile neutron fission of U^{235}, which has a peak at about 15 MeV with a full width at half maximum of 10 MeV and the high energy tail extending upto 29 MeV. They found that the high energy part of the spectrum corresponds to a Maxwallian distribution with a nuclear temperature of 1.4 MeV and the probability of emission of alpha particle to be 1 in 310 binary fissions. In Table 1 below are given the results of these early investigations[1-9]

Since the study of the phenomenon could lead to a better understanding of the fission process itself, interest in this field has been revived in recent years and considerable experimental work of varied nature has been reported from various laboratories of the world. The vast amount of data collected[10] is probably best presented under the following heads:

(a) Relative probability of binary to ternary fission.

(b) Energy spectrum of long range alpha particles.

(c) Kinetic energy distribution of fission fragments in ternary fission.

(d) Emission of other charged particles.

(e) Angular correlation of alpha particles

(f) Mass distribution of fission fragments internary fission

(a) Relative Probability of Binary to Ternary Fission

The reported values of relative probabilities of binary to ternary fission are not in good agreement with each other because of the poor statistical accuracies involved and the dependence of the detection efficiency on the method employed. In the thermal neutron induced fission of U^{235} the values reported are in the range 250 to 550:1. Perfilov and Solov'eva[11] measured the probabilities for fast neutron induced fission to be 600:1 and 1050:1 for 2.5 MeV and 14 MeV neutron energies respectively. The various results for different nuclides are shown in Fig. (1). Nobles [12] plotted the relative probability of ternary fission against Z^2/A of various nuclides.

This indicated that the probability of ternary fission increases with the increasing of Z^2/A and decreases with increasing excitation energy in a given nuclide. Furthermore, Coleman et al[13] measured the ratio of probability of binary to ternary fission of different nuclides at different excitation energies and found that the ratio increases with excitation energy up to 20 MeV. These measurements indicate a dependence of the ratio on the target nuclide, excitation energy and probably on the angular momentum of the fissioning nucleus. Recent measurements [14] of the ratio of binary to ternary fission of Np^{239} at an excitation energy of 22.7 MeV indicate a higher value than that of Coleman et al.[13] They concluded that the variation of ratio of binary to ternary fission cannot be the result of some simple angular momentum dependence. Experiments carried out at this Laboratory on the ternary fission of U^{235} induced by thermal and 3 MeV neutrons [15] showed that the ratio of binary to ternary fission increases with the excitation energy, indicating that the emission of long range alpha particle and prescission neutrons are competing modes of de-excitation of the fissioning nucleus. In resonance neutron induced fission of U^{233} Panov [16] found the relative probability of binary and ternary fission to be constant within statistical error of less than 8% which was later found to be true in the case of Pu^{239} fission also. Schroder et al[17] measured the ratio of binary to ternary fission of U^{235} in neutron energy region .003- .3 eV and found that the ratio of binary to ternary fission is constant in this energy region of neutrons.

On the other hand, it was found[18] that there is a variation in the ratio of ternary to binary fission probability from resonance to resonance in the neutron energy of .06 to 10 eV. Measurements[19] in the neutron energy region .005 to 0.2 eV with a high statistical accuracy (1%) showed a small and smooth variation of binary to ternary ratio with neutron energy. Comparing these results on ternary fission with those of Faler and Tromp, [20] they concluded that the increase of probability of ternary fission is correlated with the decrease of asymmetric mass ratio. It means that a higher symmetric fission yield results in a higher probability of ternary fission. The variation of probability of ternary fission seems[21] to be correlated with the spin of the excited levels of fissioning nucleus. The measurement of probability of ternary fission as a function

----- of neutron

energy is intersting as it may be possible to identify the energy levels of fissioning nucleus. Melkonian and Mehta[22] found some indication of variation of the relative yield of alpha particles from level to level.

(b) The Energy Spectrum of Long-range Alpha Particles:

The energy spectrum of long-range alpha particles extends from 6 to 30 MeV with a broad peak around 15-17 MeV and the full width at half maximum about 10-12 MeV. Muga et al[23] measured the spectrum of long-range alpha particles in spontaneous fission of Cf^{252}, the spectrum extending upto 34 MeV had a peak at about 19 MeV with a half width of 10 MeV; but Watson[24] and Nobles[12] found the peaks to be at 16 MeV and 17 MeV respectively. In spontaneous fission of Pu^{238} and Pu^{240} Perfilov et al[25] observed the peak of the spectrum at about 17.3 and 17.0 MeV respectively and the spectrum of alpha particles from all plutonium nuclides seems to be shifted towards greater energies but have smaller half widths compared to those of the alpha spectrum from uranium nuclides. They concluded that the spectrum is in good agreement with a Gaussian distribution. The apparent shift of the peak of energy spectrum of long-range alpha particle emitted in Pu^{239} thermal fission compared to that in U^{235} is probably connected with the different deformations and charges involved in the two cases. In thermal neutron induced fission of U^{235}, Hill[26] investigated the energy spectrum and compared it with a gaussian distribution curve;

$I(E) = K\ \text{Exp.}\ \dfrac{-(E - 15.15)^2}{(6.05)^2}$. The high energy part of the alpha spectrum[3] can be fitted with a Gaussian, but the low energy part deviates considerably from this. The variation of Coulomb barrier penetration factor for a spherical nucleus as a function of energy of alpha particle has been plotted for different Z values[3]. It is seen that the Coulomb barrier penetration factor calculated for different Z-values differ from that required to fit the observed energy spectrum. The spectrum of long range alpha particles in 3 MeV neutron induced fission of U^{235} (15) shows a broad peak at 15-17 MeV; it seems to be slightly shifted toward the higher energy side compared with the spectrum obtained in reference[3]. As seen in fig.(2), the high energy part of the spectrum falls down rapidly which might be due to a higher nuclear temperature. On the basis of the statistical theory the temperature of the spectrum was found to be 0.76 MeV and 0.66 MeV for 3 MeV neutrons and pile neutron induced fission of U^{235} respectively in fig.(3).

Schmitt et al [27] have measured the total kinetic energy of fission fragments in coincidence with various energy intervals of alpha particle spectrum. It is seen that the total kinetic energy of fission fragments accompanying high energy alpha particles is diminished. Also, the most probable kinetic energy is shifted towards symmetric region. This indicated that high energy alpha particles are emitted preferentially in those ternary fission events which result in near symmetric fragments.

(c) Kinetic Energy Distribution of Fission Fragments in Ternary Fission

Allen and Dewan [8] were the first to measure the kinetic energy distribution of fission fragments in ternary fission of U^{235}. The spectrum was plotted together with the spectrum of fission fragments in binary fission and it was found that the peaks of the spectrum were shifted to the lower energies compared to those of the binary fission spectrum. The peak of the spectrum is shifted by about 10 MeV and 7 MeV for the light and heavy fragments respectively. Dmitriev et al [28] found that the peak is shifted towards lower energy side by about 9 MeV and 6 MeV for the light and heavy fragments respectively and that the half widths of the ternary spectrum are less than those for the binary fission spectrum. They suggested that the narrower width may be due to more symmetric fission in ternary fission. The relation between kinetic energy of the fission fragments in binary and ternary fission can be written as

$$E_b = E_t + E_\alpha$$

Solov' eva and Filov [29] confirmed this result and concluded that this equation remains valid for all portions of the alpha particle spectrum. However recently Dmitriev et al [30] investigated the kinetic energy distribution of fission fragments in the thermal neutron fission of U^{235}; they measured the energy spectrum of fission fragments for different energy intervals of alpha particles spectrum. They found that the shifts in the peaks of light and heavy fragment kinetic energies from the binary fission values vary with the energy of the emitted alpha particles. For the energy

of alpha particles greater than 15 MeV, the shifts in the heavy and light peaks remain constant; thus the equation of $E_b = E_t + E_\alpha$ can be applied only for the alpha particle in the region below 15 MeV. They concluded that the internal excitation energy of ternary fission fragments decreases due to the emission of the high energy alpha particles (E 15 MeV), so that the number of emitted neutrons in ternary fission should be smaller than that in binary fission. Apalin et al[31] measured the number of neutrons emitted in ternary fission and obtained the value for the mean number of neutrons to be 1.77 ± 0.09. As the relation $E_b = E_t + E_\alpha$ remains approximately valid, this shows that the Coulomb energy in both ternary fission and binary fission remains the same. On the basis of evaporation theory, the excitation energy of compound nucleus is decreased due to the emission of alpha particles before scission has taken place in those cases where high energy alpha particle are emi
It is found[31] however that the number of neutrons per fission does not critically depend on the energy of emitted alpha particles. This probably implies that the yield of γ-rays in ternary fission depends on the energy of alpha particle.

(d) <u>The Emission of Other Charged Particles:</u>

There are various other charged particles accompanying fission, apart from alpha particles. Albenesius[32] reported the value of probability of emission of one triton in $(1-2) \times 10^4$ binary fissions when the natural and enriched uranium were irradiated in nuclear reactor. Andreev and Sirotkin[33] considered the emission of other isotopes of hydrogen, helium and other light nuclei associated with fission. The results obtained by them are shown in the table below:

Element	No.of fissions per particle.
H^3	$(2.4 \pm 0.7) \times 10^5$
H^5	7×10^6
H^3	6×10^5
He^4	$(1.6 \pm 0.2) \times 10^3$

In spontaneous fission of Cf^{252}, Watson[24] measured the energy spectrum of tritons, the peak of spectrum was found to be at about 8 MeV, with a half width of 7 MeV and a relative probability of fission with the emission of a triton to binary fission to be about 1.4500 $\pm$ 900. Wegner[34] has reported a measurement of the relative yield of light charged particles in spontaneous fission of Cf^{252}. The measured values are given in the following table:

Particles	Relative yield (compared with the yield of alpha particles)
He^4	100
He^3	1
He^3	6
d	0.5
p	2.2 $\pm$ .5

Muga[35] investigated triple fission of Cf^{252} and U^{236} in to 3 fragments of comparable masses. It was found that the probability of triple fission to be 1:1.1x10^6 and 1:6x10^6 fissions for Cf^{252} and U^{236} respectively. The average kinetic energy of the fission fragments in triple fission is higher than that in binary fission of both the nuclei, the average kinetic energy of Cf^{252} is 206 MeV and U^{236} is 180 MeV. He suggested it may be divided into two classes for mass distribution:-

Type 1: the events that have two low mass fragments and one heavier fragment. The lowest mass peak is about 56 amu. For Cf^{252} triple fission is considered to have this type of mass distribution.

Type 2: the events that have one light fragment mass peak are found to be about 38 amu. The mass distribution in triple fission of U^{236} was found to consist of both types of division. It seems that shell effects appear to restri the resultant mass disvision.

(e) Angular Correlation of Alpha Particles

The angular distribution of alpha particles with respect to the fission fragment motion and incident neutron direction have been investigated.

(i) Angular Correlation of Alpha Particles with Fission Fragments

From a previous investigation(10) it was reported that the angular correlation of alpha particles is strongly peaked at about 80° - 90° with respect to the light fission fragments. In fast neutron induced fission of uranium nuclei, Perfilov and Soloveva(36) plotted the angular distribution of alpha particles by breaking up the range of alpha particle into 3 portions; and found that in almost all cases no angle greater than 90° was observed for alpha particles of range less than 100/u. Investigation of this correlation of spontaneous ternary fission of Cf^{252} has been made(37) and the angular distribution of alpha particles for different mass ratios has been plotted. It was shown that the shift of the most probable angle of alpha particles is towards the direction of heavy fragments when the mass ratio increases; the peak is at 72° and 99° with respect to the direction of motion of the light fragment. The experimental data of angular distribution of alpha particles show that the alpha particle is emitted in a region between the two heavier fragments. The observed shift of the the peak of the angular distribution is due to the variation in Coulomb potential between the two fragments and alpha particle as the mass division becomes more asymmetric.

ii) Angular Correlation of Alpha Particles with Incident Neutron Direction

In 14 MeV neutrons induced fission of U^{238}(38) the angular distribution of alpha particles with respect to the incident neutron direction has been found to be forward backward peaked, symmetric about 90° as shown in Fig. (4). This spectrum is a characteristic of evaporated particles from a compound nucleus with a large angular momentum. Recently an investigation on ternary fission of U^{235} by 3 MeV neutrons has been carried out(15) at Trombay, the anisotropy of alpha particles $[N_\alpha(0°)/N_\alpha(90°)]$ was measured to be about 32 ± 12% and this is in quantitative agreement with the predicted value on the basis of the statistical theory of evaporation. As the excitation energy of the compound nucleus is less than the threshold for second chance fission there are no complications caused due to such events. Work on 17.5 MeV protons induced fission of U^{238} (14) indicates that the angular distribution of alpha particles with respect to incident protons is nearly isotropic. However, the results show a trend toward peaking at 0° within the statistical error ($>30\%$). However, in 3 MeV neutron fission of U^{235} the anisotropy was found to be about $30 \pm 12\%$. In case of 14 MeV neutron fission U^{238} the anisotropy is larger than the expected value. The angular distribution of fission fragments in binary fission[39] induced by 3 MeV neutrons is found to be peaking in the forward direction with anisotropy of about 18%, fission fragment anisotropy in ternary fission is therefore expected to be small ($\sim 10\%$). The results of reference[14] do not however rule out the existence of ternary fission fragment anisotropy.

(f) Mass Distribution of Fission Fragments in Ternary Fission

Mass distribution of fission fragments has been measured[14] in thermal neutron fission of U^{235} using ionization chambers and solid state detectors. It is assumed that the change in the momentum along the fragment direction due to alpha particle emission is small and hence the relation $M_1 E_1 = M_2 E_2$ is assumed in binary fission as well as in ternary fission. It was found[40] that the mass distribution for ternary and binary fission agree within the statistical errors. However, Schmitt et al[27] found that the peaks in the mass distribution in ternary fission are shifted towards low mass values compared with those in binary fission and that low mass sides of the heavy and light fragment distributions are almost identical, but the high mass sides of both the fragment distributions are shifted to lower values when compared with binary mass distribution as shown in Fig. 5. Furthermore, the mass yield was obtained for various energy intervals of alpha particle spectrum and it is observed that for high energy alpha particles the peak to valley ratio is reduced. This shows that the mass distribution of fragments in coincidence with high energy alpha particles shows a higher symmetric yield than that in coincidence with low energy alpha particles. The fragment kinetic energy averaged over all alpha particle energies was found to be about 155 MeV. It is less than the averaged total kinetic energy in binary fission which is found to be about 167 MeV.[41].

III. Theories of Alpha Particle Emission in Fission

Though the emission of long-range alpha particles in fission was discovered over 20 years ago, its mechanism has no tyet received a satisfactory explanation. Much experimental data has been obtained so far in connection with the emission of long-range alpha particles in fission. There are many hypotheses put forward to describe this phenomena. We discuss some of them briefly below:

1. Liquid Drop Model

Present[42] has extended the liquid drop model to predict that the division of liquid drop into three fragments of comparable masses is dynamically possible. On the basis of his calculation, the dynamical course of fission follows a path over a potential energy surface in the configuration space whose dimensions represent the amplitudes of n^{th} harmonic deformations of the liquid drop. A large positive amplitude deformation of the fourth harmonic type creates a pair of tropical furrows, which deepen as the drop elongates, forming three colinear droplets connected by liquid necks. The relative size of the droplets depends on the amplitudes and phase of the second and fourth harmonic deformations. Hill and Wheeler[45] also show the possibility of ternary fission by picturing the nuclear drop at scission; the drops leads to the formation of tiny droplets in the region between two big drops in the case of nuclear fission. This small droplet will be formed as an alpha particles as it is a saturated particle. The direction of alpha particles will be in the direction of resultant Coulombic force of the two heavy fission fragments. Tsien et al[44] proposed the following hypothesis based on their experimental results. The excitation energy of the nucleus due to the capture of a neutron is transformed into deformation energy of the compound nucleus. The deformed nucleus will form a dumbell shape; the neck part of this dumbell shape will come off as a charged particle. All these three fragments touch each other up to the instant of scission. At scission all of the three fragments will be separated and get accelerated due to the mutual Coulomb repulsion. They postulated that the light charged particle emitted from the neck of the dumbell shaped nucleus does not have a unique mass; its mass number varies from 1 to 9 at least. On the basis of their calculations they found that the charged particle has two probable masses, one about 5 mass units and the other about 9 mass units. According to this hypothesis, the direction of emission of the light charged particle will be decided by the net Coulomb force due to the two heavy fragments. This explains the angular distribution of the alpha particles as observed. But the hypothesis is incapable of explaining the observed probability of ternary fission and the other correlations.

2. "Two-step Process" Hypothesis

The two step process[45] proposes that the alpha particle is emitted from one of the fragments shortly after scission, when the fragment nucleus has not yet gained a considerable velocity. Feather[45] has analysed the ternary mass distribution data and evaluated the alpha emission probability for various fragment masses and concludes that the lowest alpha emission probability is for those fragment masses with A   130. In order to explain the observed angular distribution of alpha particles it is necessary to suppose in this picture, that the alpha particles are emitted opposite to the direction of motion of the parent fragment.

Recently, the probability of emission of alpha particle has been calculated from a simple equation[46] as

$$P_{\alpha}(M) = \frac{Y_T(236-M)}{Y_B(236-M)}$$

where $P_{\alpha}(M)$ is the probability of alpha particle emission from a fragment of mass M,

$Y_T(M)$ is the yield in ternary fission of mass M, and Y (M) is the yield in binary fission of mass M.

In calculating $P_{\alpha}(M)$, it was assumed that $P_{\alpha}(M) = 0$ for $M > 118$ in one set and $P_{\alpha}(M) = 0$ for $M < 118$ in another set. The cluster model was applied in this hypothesis[46] and it was pointed out that $P_{\alpha}(M)$ is smaller in the closed shell regions. It is concluded that the alpha particle is emitted entirely from the heavy fragment (A   130) because it is proton rich compar to the light fragment.

3. Snapping Process

A recent hypothesis of alpha particle emission describes this phenomena as a snapping process[47]. Halpern has calculated energy required to remove an alpha particle from one of the fragments and place it in the region between them, this value is about 25 MeV. The excitation energy of the fragments at scission is not sufficient to account for the energy of the emitted alpha particle. But during the fission process, the distortion energy of the stretched nucleus is converted to deformation energy of the fragments just after scission and due to the sudden sucking in of the neck of the large deformed fragment, in rare case an alpha particle may be left behind in the region between the two fragments. The Coulomb force due to two charged fragments then accelerates the alpha particle. The probability of emission of alpha particle depends on the fissioning nucleus, fragment mass division, fragment kinetic energy and excitation energy of the fissioning nucleus. Assuming that the alpha particle is at the center of distance from the two fragments, the calculated kinetic energy will increase by 13%; the kinetic energy is to remain constant, the distance between the two fragments should be larger by 13%. He concluded that the alpha particles are not evaporated from the fissioning nucleus because in the usual events, the available energy for evaporation of alpha particle is not enough. But the calculation of excitation energy presented in the next section seems to over rule this objection. Assuming that the alpha particles start at the scission point in the Coulomb potential at the fragment axis, he computed the energy and angular distribution of alpha particle. The computed angular distribution of alpha particle starting isotropically from a point off axis between the fragments with an initial kinetic energy of 4.4 MeV and at a time of 1.7×10^{-21} second after scission is in agreement with the observed angular spectrum. But the energy spectrum of alpha particle depends on the time at which scission is assumed to occur. If the scission time is long enough the computed mean final energy spectrum of alpha particle can be in agreement with the mean energy of the observed energy spectrum. However, the theory cannot explain the angular anisotropy of alpha particle with respect to the incident neutron direction in fast fission satisfactorily.

4. Evaporation Process

It is proposed that the alpha particles in fission is the result of evaporation of these particles from the excited and deformed compound nucleus having a large angular momentum (38). The emission of alpha particles takes place at the neck of the distorted nucleus where the barrier is depressed so that they come off preferentially in a plane perpendicular to the line of flight of the fragments. The charge polarisation will reduce the barrier at the neck for all types of distortion. In the case where the symmetric axis is perpendicular to angular momentum vector, azimuthal directions of emission of alpha particles other than about perpendicular to neck are less probable because the potential barrier is high in other directions (Fig.6a) For the case where symmetric axis is parallel to angular momentum vector, all the azimuthal directions of emission of alpha particles are more favourable due to lower potential barrier at the neck (Fig.6(b).) Also it has been observed experimentally that the alpha particles have a forward-backward peaking with respect to the incident neutron direction and this is a characteristic of evaporation from a compound nucleus having a large angular momentum. In 14 MeV neutron induced fission of U^{238}, the anisotropy of alpha particles was found to be much larger than predicted by the statistical theory but this discrepancy may be ascribed to second and higher chance fissions. In the case of 3 MeV neutron induced fission of U^{235}, the anisotropy of alpha particles has been measured(15) to be 32 $\pm$ 12%. In this case neutron emission does not complicate the picture because the excitation energy is less than the neutron emission threshold. The anisotropy is in agreement with the predicted value of the statistical theory which is of the order of 10 -25% and depends very sensitively on the value of τ_0 . In this calculation, the value of K_0^2 was used from the angular distribution of fission fragments in 3 MeV neutron fission of U^{235} (39). It seems that the emission of alpha particle is connected to the saddle point levels.

The high energy part of energy spectrum of alpha particles is found to fit very well with the evaporation spectrum (Fig. 3). Because the barrier penetration factor at high energy approaches unity, the $\sigma_c(\epsilon)$ for the deformed nucleus is practically the same as that for the spherical nucleus.

Observation of Fulmen and Cohen(3) also confirmed this. Fig. 3 is a plot of $\ln \frac{N(E_\alpha)}{E_\alpha \sigma_c(E_\alpha)}$ against E_α, the energy of alpha particles for 3 MeV neutron(15) and pile neutron(3) induced fission of U^{235} respectively. The value of σ_c (E) was calculated numerically assuming a spherical compound nucleus and using r_0 = 1.2 fermis. It is found that the nuclear temperatures are 0.76 ± 0.04 MeV and 0.66 ± 0.03 MeV for 3 MeV and pile neutron fission of U^{235} respectively. The temperature of the pile neutron induced fission spectrum is in agreement with the distribution temperature T_D which is 0.63 MeV in reference(3.8).

The decrease in probability of ternary fission with increase of incident neutron energy can be accounted for as follows: alpha particle and pre-scission neutron emission are competing modes and depend on the excitation energy of the compound nucleus. The neutron emission is more favourable at higher excitation energy than the alpha particle emission. On the other hand the emission of alpha particles take place at the neck region, so that the probability of occurrence of alpha particle cluster there will decrease as the excitation energy increases. Halpern(47) pointed out that, the ratio of alpha emission to neutron emission is given by the function exp.$\left[\frac{1}{T}(E_n - E_\alpha)\right]$. He estimated the energy required for releasing an alpha particle to be about 25 MeV and for releasing neutron is about 5 MeV. If both particles are produced by evaporation, the ratio of alpha particle to neutron should be of the order of 10^{-9}, but the observed value is 10^{-3}. If one takes the minimum kinetic energy of particle emission into account, the total required energy will be 21 MeV and 28 MeV for neutrons and alpha particles respectively(47). Using a similar approach as Halpern, the ration of the number of alpha particles to neutrons emitted is found to be of the order of 10^{-3}. As the observed value of pre-scission neutron is 10% of the total number of emitted neutrons (48,49) and the ratio of alpha particles emitted in thermal neutron induced fission of uranium to the number of neutrons emitted is about 10^{-2} which is in qualitative agreement with the predicted value. Kapoor et at(48) calculated the ratio of $\frac{\Gamma_\alpha}{\Gamma_n}$ for the nuclear temperature of 1 MeV, using the values of $\sigma_c(E)$ as in reference(38) and they obtained a value which is consistent with the experimental value.

The other important consideration about the evaporation theory is, whether there is enough excitation energy for evaporation of alpha particles from the compound nucleus. One can calculate the excitation energy of the compound nucleus just before scission, in binary fission from the relation of $E = E_R - E_K - E_d^L - E_d^H$. Fong[50] has calculated E_K, E_d^L, E_d^H by minimising the potential energy at scission configuration, assuming α_2 deformation for the fragments. The results are plotted against fragment masses in Fig. 7. It is found that in the symmetric region, the excitation energy is of the order of 25 MeV; if the binding energy of alpha particle is taken into account, the maximum excitation energy is about 30 MeV which is the same as the maximum energy of the observed alpha particle. It has been experimentally observed in ternary fission that the average kinetic energy of fission fragments is about 150 MeV[51] and average number of neutrons emitted is 1.7 neutrons[31], The kinetic energy of the fission fragments in ternary fission is less than that in binary fission by about 10 MeV which will increase the excitation energy of the fissioning nuclei resulting in ternary fission. Also the number of neutrons emitted is less. In evaporation process, alpha particle is considered to be evaporated before scission so that most of the excitation energy will be carried out by alpha particle and the remaining energy will go to deformation energy. As the excitation energy at symmetric fission is large, the high energy alpha particles can be associated with this region. Schmitt et al (27) measured the mass distribution in ternary fission of U^{235} and found that for events associated with high energy alpha particles the peak to valley ratio of the mass distribution is small.

The main objection to the evaporation model of alpha emission in fission has been that it is (1) unable to explain the (n,f) angular correlations, (2) there is not enough energy for the process and (3) the time involved for evaporation is much longer than one expects in the fission process. None of these seem to be serious in view of the above discussion as it seems that there is sufficient energy and the angular distributions of the alpha particles of the fission fragment can be explained by assuming charge polarisation for which sufficient reasons exist. There is also no definite proof that the fission process is a fast one, certainly not to exclude the possibility of a thermodynamic evaporation process. On the contrary the theory of the process by considering it as given by Markov system[52] shows that at least 500 steps take place before scission occurs. This approach to fission is so general that the time of fission as predicted by this theory can be given its due importance in showing that low energy fission is a slow one. The kinetic energy data indicates charge polarisation and the X-ray emission data also indicates the same. If this was not the case, some violent emission of X-ray due to rearrangement of electronic shells could have been observed.

In the survey, it is clear that though there is much controversy, connected with the emission of alpha particles, the evaporation model however emplains most of the facts without invoking any new nuclear process. As it is essential that one should not introduce new processes in this, it is absolutely necessary to try as much as possible to connect the fission process with the rest of the low energy nuclear physics. More experiments in angular correlation are required before one can have a complete understanding of the process.

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FIGURE CAPTIONS

Fig. 1 The relative probability of binary and ternary fissions as a function of the excitation energy of compound nucleus. The data taken from references 10, 12 and 15. The crossed points represent data from Ref. 15.

Fig. 2 The energy distribution of long-range alpha particles in the 3 MeV neutron and pile neutron fission of U^{235} as in reference 15 and 3.

Fig. 3 A plot of en $\frac{N(E\alpha)}{E\alpha\,\sigma_c(E\alpha)}$ versus $E\alpha$ in 3 MeV neutrons (15) and pile neutrons (3) induced fission of U^{235}, $\sigma_c(E\alpha)$ was calculated numerically assuming a special compound nucleus and using r_0 = 1.2 fermis.

Fig. 4 The angular distribution of long-range alpha particles with respect to incident neutron direction (38).

Fig. 5 A plot of mass distribution in binary and ternary fission of U^{235} as in reference 27.

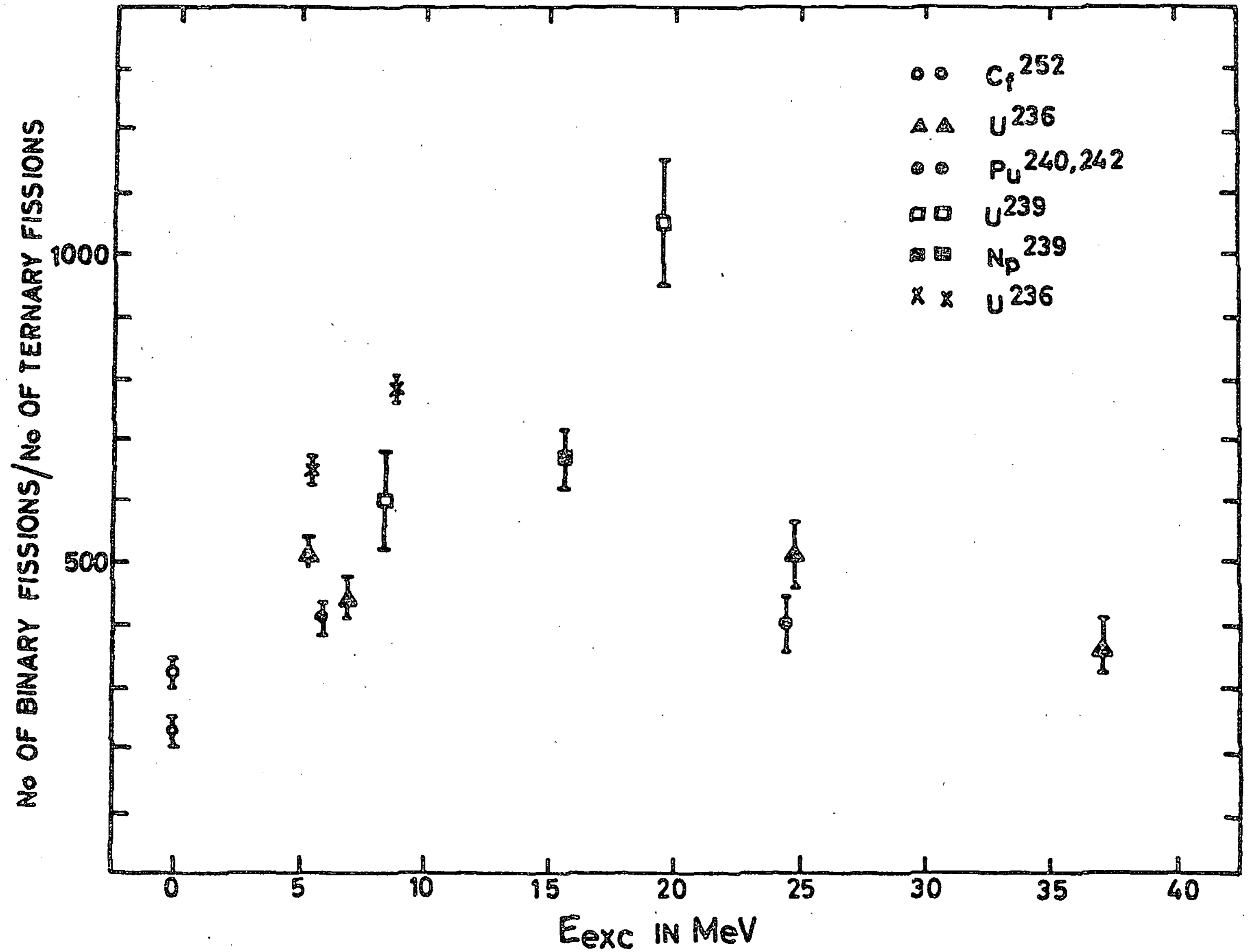
Fig. 6 The relative direction of emission of fission fragments and alpha particles with respect to incident neutron direction.

Fig. 7 The excitation energy of compound nucleus is plotted versus fragment masses, the kinetic energy of fission fragments and deformation energy has taken from reference 50.

No.	Name	Method of investigation
1.	Alvarez 1944	Thermal neutron fission of U-235; ionization chamber was used.
2.	Tsien[1] et al	Using photo-emulsion technique for detecting emitted particles from slow neutron fission of Uranium.
3.	Farwell[2] et al.	Employing ionization chamber to investigate the changed particle emission in fission of U-235 and Pu-239.
4.	Green and[4] Livesey	Using photo emulsion method; Fission fragment tracks in the ternary fission of U^{235} with thermal neutrons were scanned.
5.	Demers[5]	Using photo-emulsion technique in the fission of Uranium.

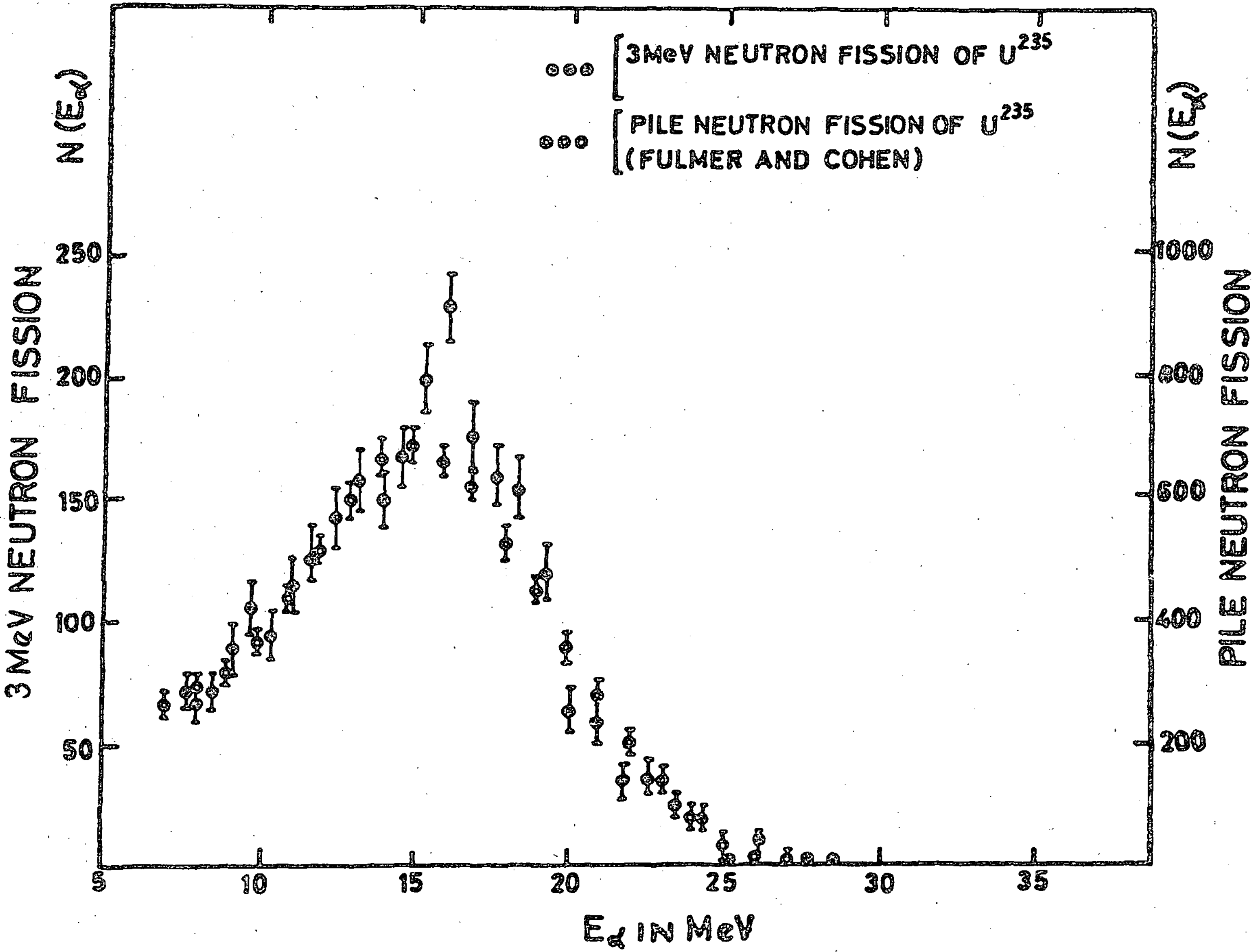
Range of the particle	Frequency of emission	Remarks
Maximum of range is about 20 cm in air		
Maximum range observed to be about 44 cm in air	1/300 of binary fission	A theory of emission of particle in fission, was proposed.
Maximum range was about 23 cm in air (16 MeV) for both targets.	1/250 in U^{235} target and 1/500 in Pu-239	
Range up to 55 cm of air-equivalent	1/340 ± 40	a) The interval of time elapsing between fission process and emission of particle is less than 2×10^{-14} sec. b) The angular distribution of alpha particles has a maximum at nearly 90° to the fission fragments.
Maximum energy was about 19 MeV	1/250	He calculated the time of alpha particles emitted after fission to be less than 2×10^{-14} sec.

No.	Name	Method of investigation	Range of the particle	Frequency of emission	Remarks
6.	Wallan et al [6]	Photoemulsion technique has been applied in the fission of Uranium	Maximum range observed was about 40 cm of air		From the observed angular distribution of alpha particles, the authors concluded that alpha ~~x~~ particles are released as a part of fission process.
7.	Marshall [7]	Photo emulsion technique was used in fission of U-235	Maximum energy is 26.4. MeV	1/230	There is ~~ak~~ a slight tendency for alpha particle of the highest energy to be emitted at an angle greater that 90° with respect to the heavy fragment.
8.	Allen and Dewan [8]	Employing a double ionization chamber in fission of U-233, U-235 and Pu-239.	Maximum range observed is about 26 MeV	1/405± 30 for U-233 1/505± 50 for U-235 1/445± 35 for Pu239	The energy spectrum of fission fragments in ternary fission of U-235 indicated that the peaks are shifted to-ward the low energy relative to binary fission spectrum; by 10 and 7 MeV for light and heavy fragments respectively.
9.	Titterton [9]	Using photo-emulsion technique in the fission of U-235.	Maximum energy is 29 MeV	1/422±50	a) The energy spectrum of alpha particle has a peak at 15 MeV. b) The angular distribution of alpha particle is peaked at 80°-90° with respect to light fission fragment.



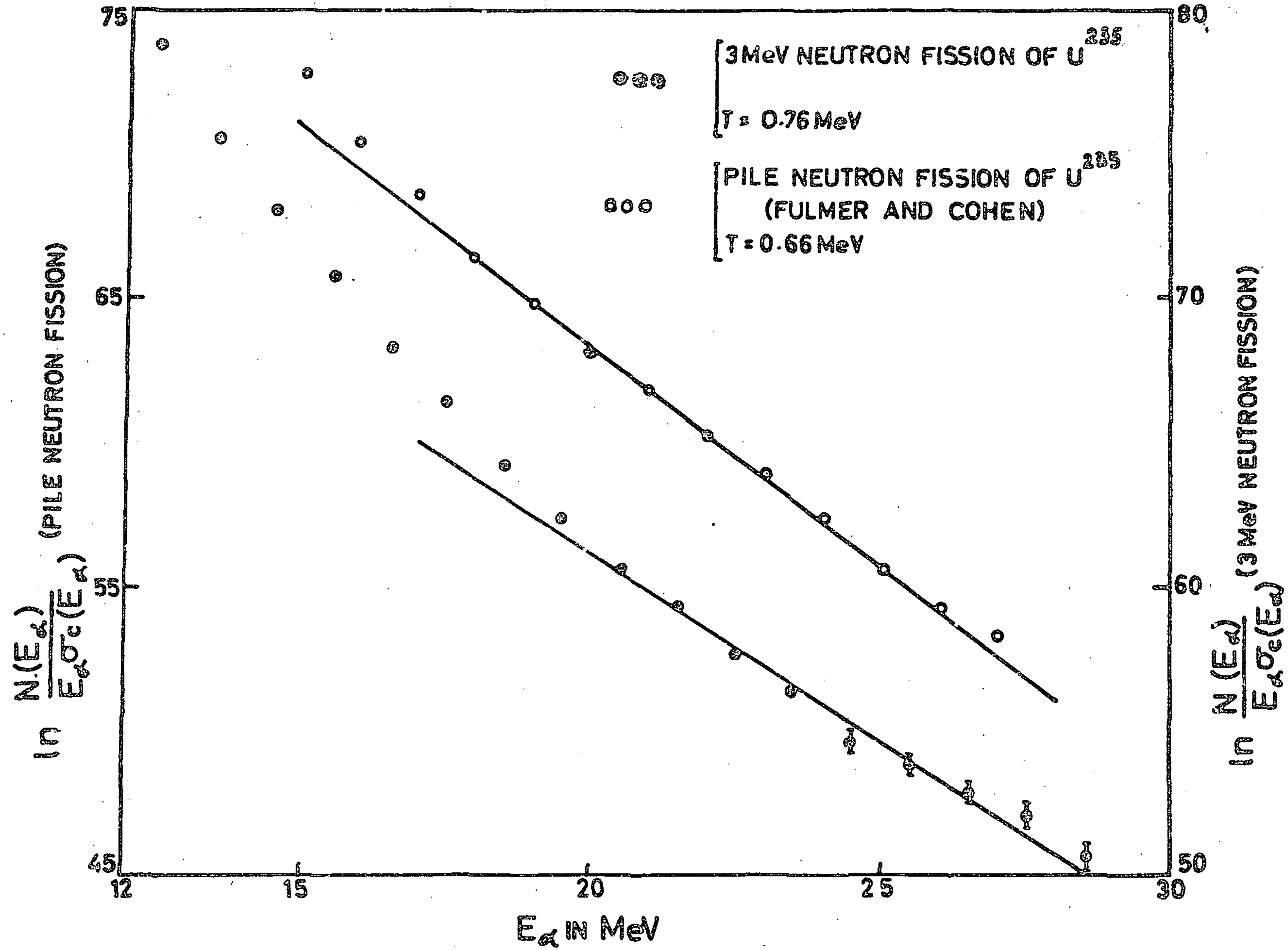
C_f^{252}
U^{236}
$P_u^{240,242}$
U^{239}
N_p^{239}
U^{236}
No OF BINARY FISSIONS/No OF TERNARY FISSIONS
1000
500
0
5
10
15
20
25
30
35
40
Eexc IN MeV

FIG-1

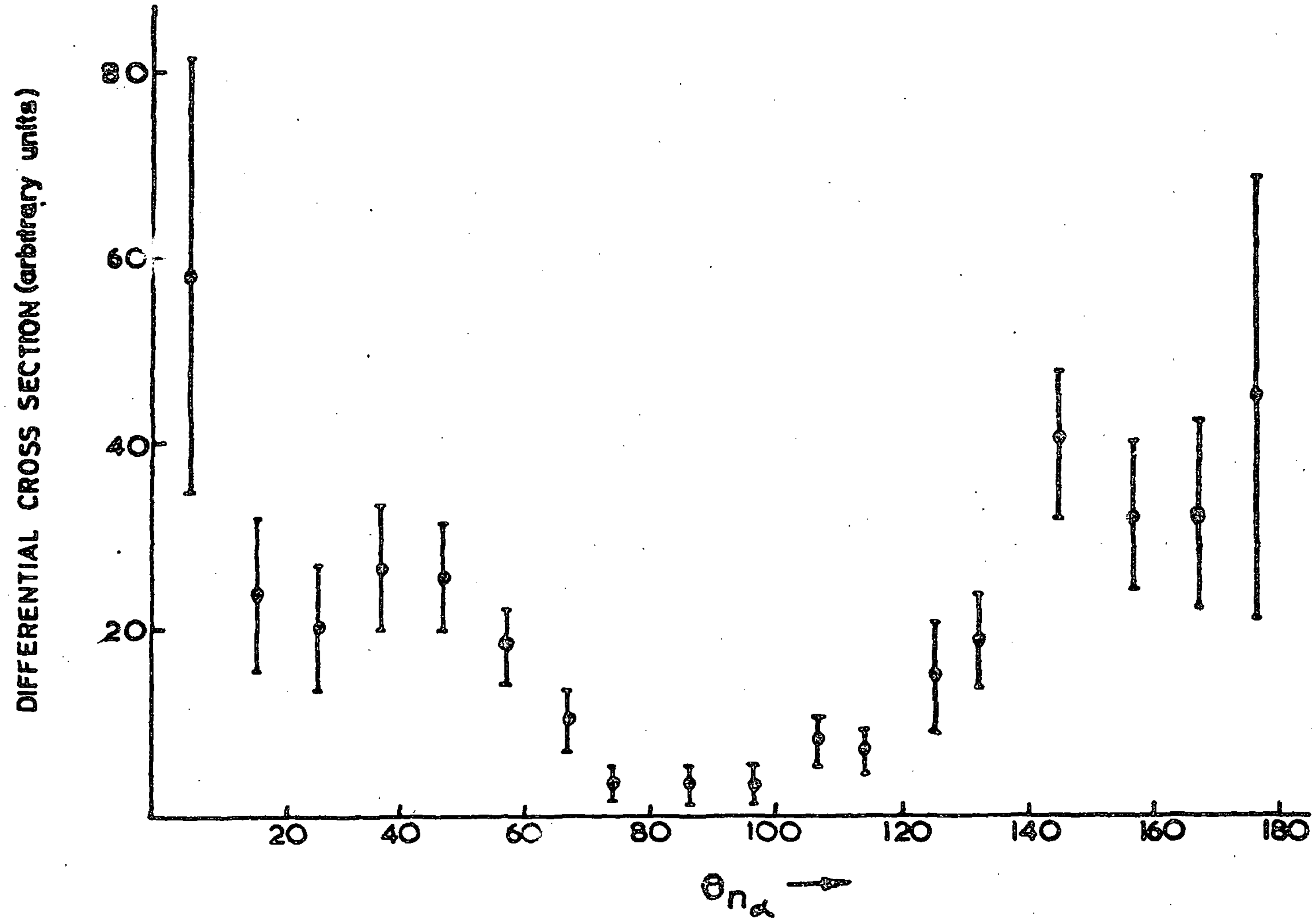


3MeV NEUTRON FISSION OF U235
PILE NEUTRON FISSION OF U235
(FULMER AND COHEN)
N(Eα)
3 MeV NEUTRON FISSION
PILE NEUTRON FISSION
250
200
150
100
50
1000
800
600
400
200
5
10
15
20
25
30
35
Eα IN MeV

FIG. 2

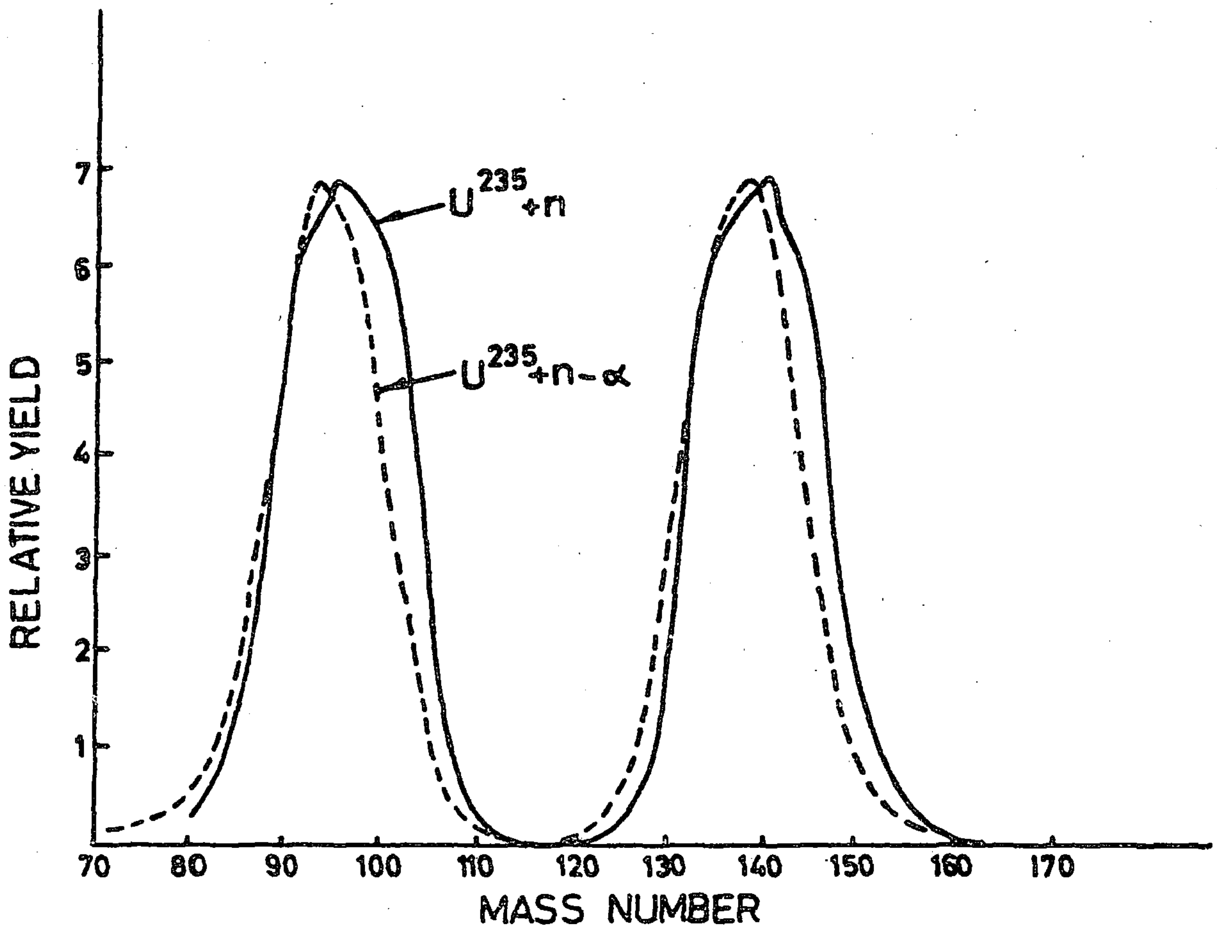

3MeV NEUTRON FISSION OF U235
T = 0.76 MeV
PILE NEUTRON FISSION OF U235
(FULMER AND COHEN)
T = 0.66 MeV
ln N(Eα)/Eα σc(Eα) (PILE NEUTRON FISSION)
ln N(Eα)/Eα σc(Eα) (3 MeV NEUTRON FISSION)
Eα IN MeV
75
65
55
45
80
70
60
50
12
15
20
25
30

FIG·3



DIFFERENTIAL CROSS SECTION (arbitrary units)
80
60
40
20
20
40
60
80
100
120
140
160
180
$\theta_{n\alpha}$ →

FIG-4



RELATIVE YIELD
7
6
5
4
3
2
1
70
80
90
100
110
120
130
140
150
160
170
MASS NUMBER
$U^{235}+n$
$U^{235}+n-\alpha$

FIG-5

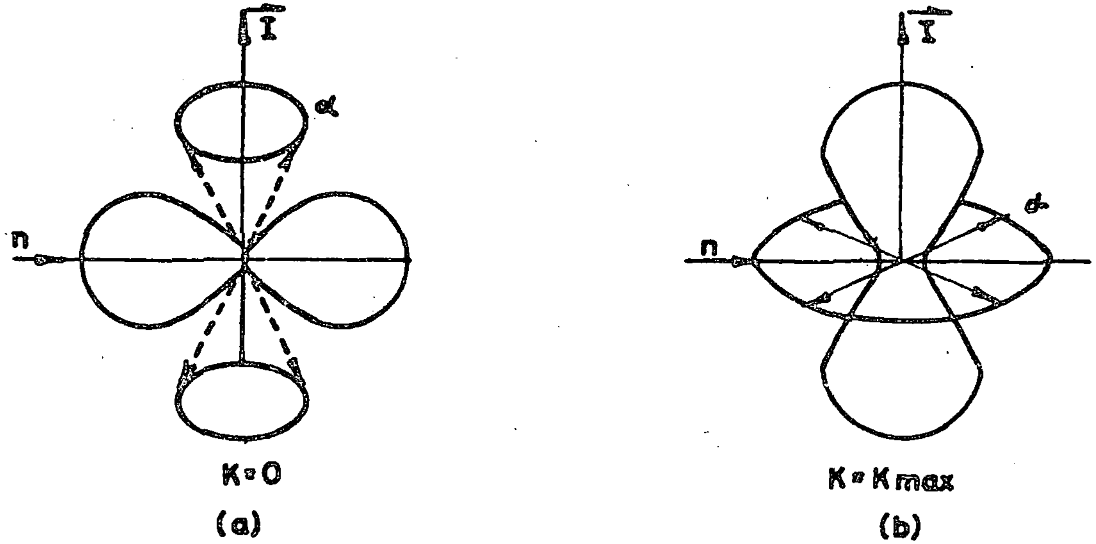


FIG-6

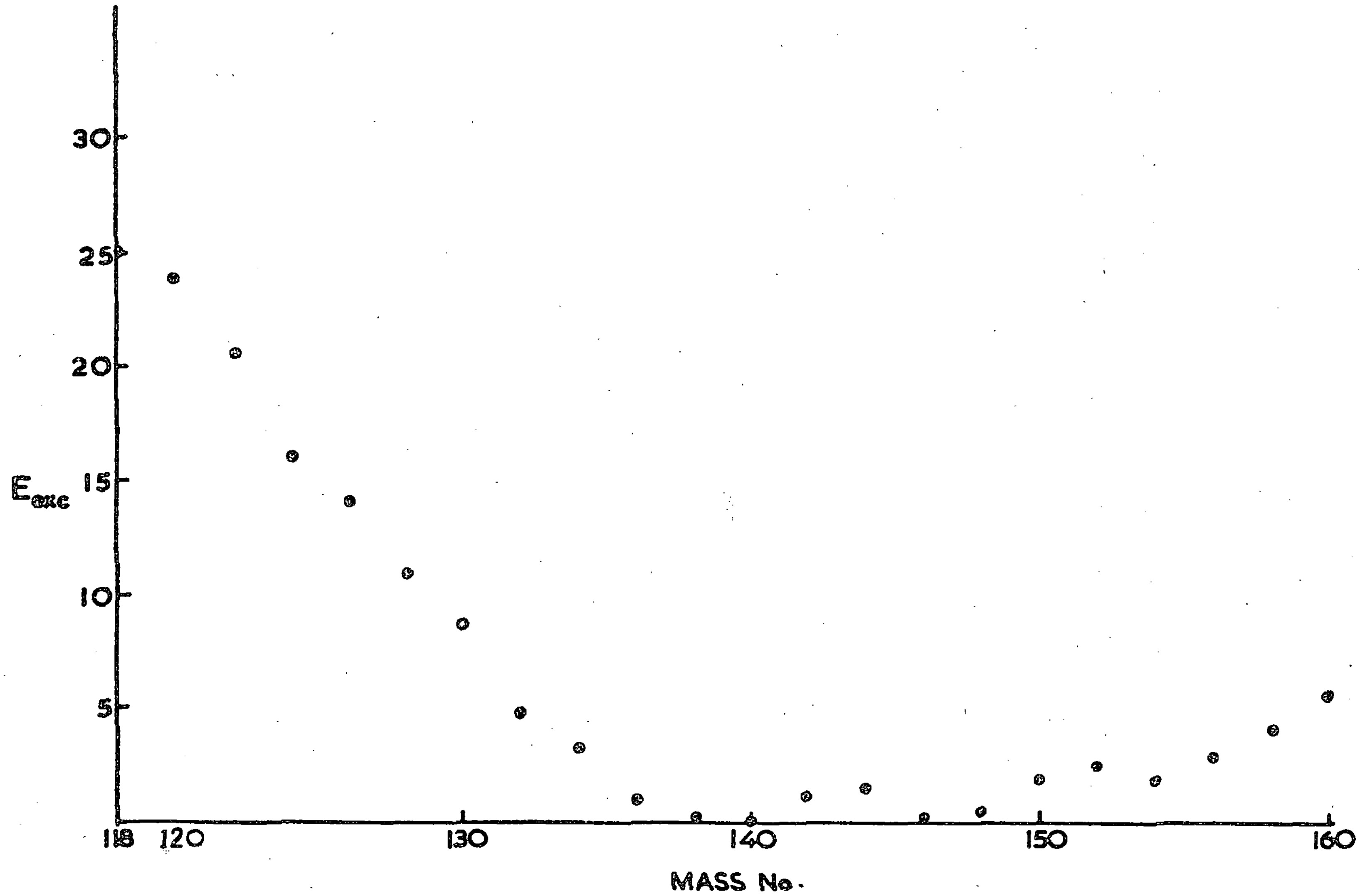


FIG-7