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Angular distribution in ternary fission

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Abstract. The angular distribution of long-range alpha particles emitted in keV-neutron induced fission of ^{235}U has been measured using a technique which employs only a particle telescope to derive the angular information. The neutron energy region investigated is 100 keV–1 MeV. The angular distribution of LRAs has been found to be peaked perpendicular to the neutron-direction with a substantial amount of anisotropy near 200 keV.

Keywords. Fission; LRA-fission; angular distribution.

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1. Introduction

Light-charged particle (LCP) accompanied fission represents an interesting phenomenon in the study of the fission process. It is a potential source of information on the configuration of the fissioning nucleus at scission and the subsequent dynamics of the process till the last stage of rupture. The striking feature of the LCP-emission is that their angular distribution is strongly peaked perpendicular to the fission-fragment direction. This has led to the belief that they are born in the vicinity of the scission point from the neck of the compound nucleus. Several hypotheses on the emission mechanism of the LCPs *viz* the pre-scission evaporation model (Ramanna *et al* 1963), Carjan's model (1975) of pre-scission emission, the post-scission emission model by Feather (1969), the sudden-snap model (Halpern 1965) and the statistical model (Fong 1970) are in vogue. However, it is not yet established whether the LCPs are emitted before or after the scission. The experiments on the angular distribution of the light-charged particles (LCPs) about the fission axis have yielded some information on the configuration of the nucleus at the scission point with the help of trajectory calculations. However, there is always an uncertainty in locating the scission point in trajectory calculations which reflects in the non-uniqueness of the information derived about the dynamical variables at scission. The angular distribution of the LCPs about the space-fixed axis (incident neutron direction) could provide valuable information on the emission mechanism of these LCPs. This aspect of the LCPs is not studied well and the existing experiments have yielded conflicting results. The present paper is an effort to understand the LCP-emission mechanism by studying the anisotropy of LCPs about the incident projectile direction.

The angular distribution of the binary fission fragments in neutron-induced fission near the fission threshold exhibits a forward peaking about the incident neutron direction. On the other hand, the trend of the fragment angular distribution in ternary fission (fission accompanied by a third particle (LCP)) is unclear. The behaviour of the LCP angular distribution should depend on the fact whether the LCP emission takes place before or after the scission. The angular distribution of the fragments and the LRAS (long-range alpha particles, the most predominant LCP) in 14 MeV neutron-induced fission of ^{235}U was measured by Ramanna *et al* (1963). They observed that the LRA angular distribution was peaked fore and aft along the beam direction, and the associated fragments (referred to as ternary fragments) were peaked at 90° to the beam. This behaviour of ternary fragments was opposite to the behaviour of fragments in binary fission. This result implied that the ternary fission process is distinctly different from the binary process notwithstanding that all the other characteristics of the fission process, such as kinetic energy distribution, mass distribution etc are known to be very similar in the two cases of the binary and ternary fission. However, in another measurement, 17·5 MeV proton-induced fission of ^{238}U, Atneosen *et al* (1965) observed that the ternary fission fragments have nearly the same (0°-peaked) angular distribution as the binary fission fragments. The results of Ramanna *et al* (1963) and Atneosen *et al* (1965) are contradictory to each other. In both these experiments there is substantial contribution from second and third chance fissions, and the observed angular distribution arises from contributions due to a number of nuclides fissioning at different excitation energies. Nadkarni (1968) measured the angular distribution of ternary fission fragments and LRAS about the neutron-beam direction in 3 MeV neutron-induced fission of ^{235}U. The ternary-fragment anisotropy was found to be opposite to that of binary fragments, in agreement with the results of Ramanna *et al* (1963). The results were interpreted by assuming that the LRA emission takes place as a result of evaporation before the scission point. However, it was not understood as to why in this particular characteristic, the ternary fragments behave in a completely different way than the binary fragments whereas in all other characteristics they are similar. In view of the unclear picture of ternary-fission angular distribution as stated above, we have measured the angular distribution of LRAS in the neutron-induced fission of ^{235}U for several energies in the region 100 keV to 1 MeV.

2. Experimental technique

The low probability of occurrence of the ternary fission, particularly in fast-neutron induced fission, makes it difficult to investigate the angular distribution of the LRAS using conventional techniques. We have developed a method (Sharma *et al* 1984) for determining the angular distribution using a $\Delta E - E$ particle telescope. This allows simultaneous identification of the particle and determination of its angular distribution. The energy loss in the ΔE-detector is proportional to thickness Δx of the detector for the normal incidence. However, if the particle is incident at an angle θ with the telexcope axis, it suffers an energy loss proportional to the slant thickness traversed in the ΔE-detector and therefore, ΔE-signal carries an information on the angle θ. Using the range-energy tables, the angular distribution is extracted, from the relation

$$\cos \theta = \Delta x / \Delta x', \tag{1}$$

where Δx and $\Delta x'$ refer to the normal thickness and the slant distance traversed by the particle in ΔE-detector respectively.

3. Experimental details

The experiment used a 97 % enriched ^{235}U source of thickness 5 mg/cm^2 with an active area 4 cm^2 and a semi-conductor detector particle telescope consisting of 50 μm thick ΔE-detector and a 500 μm thick E-detector. An aluminium foil was placed between the ^{235}U source and the particle telescope to stop the natural alpha particles and the fission fragments from reaching the detectors. The space-fixed axis (neutron-beam direction) coincided with the telescope axis. The distance of the ^{235}U source from the neutron producing target was such that the neutron divergence was $\approx 10°$. The neutrons were produced using $^7Li(p, n)$ and $^3H(p, n)$ reactions with 2 MV Van de Graaff accelerator at Indian Institute of Technology, Kanpur. The data were recorded at the following neutron energies: thermal, 140 ± 30 keV, 170 ± 25 keV, 200 ± 25 keV, 400 ± 200 keV, 600 ± 180 keV and 1000 ± 170 keV. The large spread at higher energies was owing to the use of 6 Ci tritium target. The data were recorded event-by-event on a magnetic tape using a 3-parameter data-acquisition system and the analysis was done off-line on DEC-1090 computer.

4. Data analysis and results

The added advantage of our technique is that it allows the use of broad area source which helps in overcoming the count-rate problem. However, with broad source the contribution to the angular distribution arises from every point of the source, thereby causing a smearing in the measured angular distribution. The actual angular distribution is disentangled from the experimental one by Monte-Carlo simulation with the given geometrical constraints. Figure 1 shows the calculated (Monte-Carlo) and experimental angular distributions for thermal-neutron induced fission. The calculated distribution has been obtained for isotropic emission in thermal neutron-induced fission. The calculated and experimental distributions show excellent agreement. The curves can be fitted to straight lines for angles beyond 10°. The points upto 10° have been excluded because of large errors due to $(\sin\theta)^{-1}$ factor near $\theta = 0°$ while calculating $d\sigma/d\Omega$. The least-square fitted straight lines to the calculated and experimental curves give identical values of slopes. The slopes of the straight lines

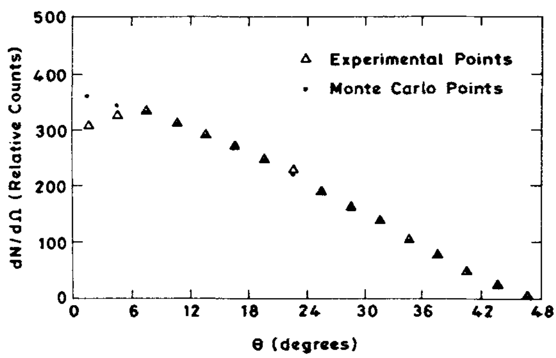

Figure 1. Calculated (Monte-Carlo) and experimental angular distributions of LRAs emitted in thermal-neutron induced fission.

depend upon the anisotropy of the angular distribution. Monte-Carlo calculations for various anisotropic distributions were carried out. The distributions were assumed to go as

$$W(\theta) = 1 + \alpha \cos^2 \theta, \tag{2}$$

where α represents the anisotropy, the positive value indicating a fore and aft peaking and a negative one showing perpendicular peaking. Figure 2 shows the variation of slopes with negative values of α, as all the experimental curves in the fast-neutron fission showed a decrease in the slope compared to thermal-neutron fission. This corresponds to a negative value of α and the perpendicular peaking. For quantitative determination of anisotropy, figure 2 served as a calibration curve. The anisotropies thus determined are shown in table 1. Our anisotropy results lead to the conclusion that the LRA angular distribution is peaked perpendicular to the neutron-beam direction at all neutron energies from 140 keV to 1 MeV (figure 3). Assuming that the alpha-fragment angular

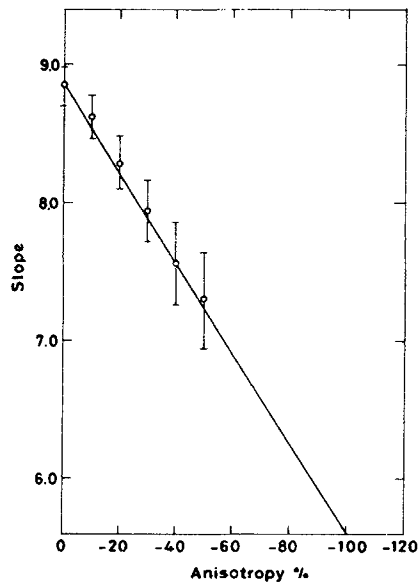

Figure 2. Slope of the least-squares fitted straight lines as a function of anisotropy (α).

Table 1. Anisotropy for several incident neutron energies.

Energy of incident neutron (keV)	Anisotropy (α) (%)
140 ± 30	(-85 ± 28)
170 ± 25	(-87 ± 32)
200 ± 25	(-94 ± 31)
400 ± 200	(-10 ± 28)
600 ± 180	(-25 ± 19)
1000 ± 170	(-50 ± 27)

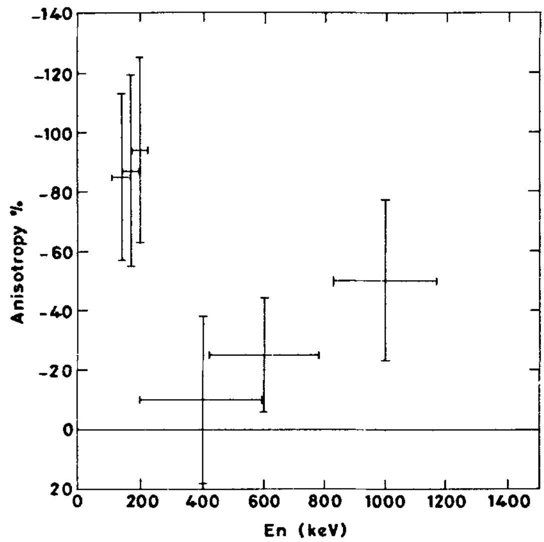

Figure 3. Anisotropy of the LRAs at different neutron energies.

correlation does not undergo any change from thermal to fast fission, the ternary-fragment angular distribution in our experiment will be peaked forward and backward to neutron direction as does the binary-fragment angular distribution. We find that the LRA anisotropy is very high near 200 keV neutron energy. The error bars indicated in anisotropy in figure 3 are due to statistical origin only as the angular resolution due to our technique is only $\approx \pm 3°$ and better above angle 15°.

5. Discussion

The angular distribution of the long-range alpha particles (LRAs) emitted in ternary fission is observed to be peaked perpendicular to the incident neutron direction. This implies that the ternary fission fragments are forward-peaked which is similar to the case in the binary fission. Thus it is concluded that the characteristics of the fission fragments are similar in both binary and ternary fission in all aspects. The similarity in angular distribution suggests that the K-distributions at the saddle point are the same whether a third particle accompanied the fission or not. Earlier measurements of Ramanna *et al* (1963) and Nadkarni (1968) do not agree with our results. However, these angular-distribution measurements were for higher energy neutron-induced fission. They had proposed that the LRA emission takes place as evaporation before the scission point. Our results on ternary fission in the neutron energy range of 100 keV to 1 MeV lend credence to the assertion that the LRA emission takes place near the scission point. The models which can predict the angular distributions in conformity with our results are the sudden-snap model (Halpern 1965) and the statistical model (Fong 1970).

We find that the anisotropy is very high near 200 keV neutron energy and then reduces at higher energies. In the region around 200 keV, the interaction of p-wave neutrons is predominant and the states $2^+, 3^+, 4^+$ and 5^+ are accessible to the fissioning nucleus at the saddle point. The increased anisotropy seems to be due to these positive parity states at the transition point. At higher neutron energy, other partial waves also contribute significantly and thus one observes the angular distribution averaged over states of both parities. This may be the reason for decrease in anisotropy at higher energies.

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