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Long-range alpha emission in *P*-wave neutron induced fission of ^{235}U

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Abstract. The yield and energy distribution of long-range alpha-particles (LRA) emitted from neutron-induced fission of ^{235}U have been measured at neutron energies; thermal, 125 ± 12, 155 ± 11, 185 ± 10, 210 ± 9, 240 ± 9, 365 ± 50 and 480 ± 45 keV. The long-range alpha-particles were detected in cellulose nitrate track detector foils. Results showed an increase of about 50% in the yield at neutron energies in the region 150 keV $\leqslant E_n \leqslant$ 220 keV as compared to that of thermal neutrons. A calculation has been carried out to extract the LRA to binary fission ratio for *p*-wave neutron induced fission.

Keywords. *p*-wave neutron induced fission; long-range alpha particle yield.

1. Introduction

The light-charged-particles emitted in spontaneous and neutron induced fission have been investigated for about 25 years. However, there is still a lack of adequate results, particularly on the dependence of this process on the excitation energy of the fissioning nucleus. Recently, some measurements (Krishnarajulu *et al* 1977, 1979; Sharma *et al* 1981) indicated an increase of about 20% in the yield of long-range alpha-particles emitted from neutron-induced fission of ^{235}U at neutron energies around $E_n = 200$ keV as compared to that of thermal neutrons. In these measurements, thick neutron targets were used for neutron production and therefore the observed yields were averaged over appreciable neutron energy window. The motivation for the present work was to see whether there is any fine structure in the variation of the LRA yield in the neutron energy region studied earlier. The measurements were carried out in the neutron energy range from 125 keV to 500 keV using thin neutron targets.

In the previous measurements, silicon surface-barrier detectors were used to detect the long-range alpha-particles. Since these detectors are very sensitive to neutrons and high neutron fluences are required to get statistically significant data for low probability LRA emission experiments, the use of semiconductor detectors poses difficulties. Solid state nuclear track detectors (SSNTDs) are well suited for such measurements. Due to the better sensitivity in alpha detection and reasonably good energy resolution (Sharma and Mehta 1980), the cellulose nitrate track detector (CNTD) foils were used in the present measurements.

The measurements were carried out at neutron energies; thermal 125 ± 12, 155 ± 11, 185 ± 10, 210 ± 9, 240 ± 9, 365 ± 50 and 485 ± 45 keV. The yield and energy spectrum of long-range alpha-particles emitted from ^{235}U fission were determined. The rear-etching technique (Sharma and Mehta 1980) was employed to determine the alpha-particle energy distributions.

2. Experimental

The measurements were carried out with 2 MV Van de Graaff accelerator at Indian Institute of Technology, Kanpur. The ^{235}U fission source (area ~ 4 cm^2 and thickness 5 mg/cm^2) acted as the cathode of the ionization chamber used to detect the fission fragments. An aluminium foil of thickness ~ 7 mg/cm^2 was used as the collector of this chamber. The chamber was filled with pure argon gas at one atm. pressure. The amplified fission fragment pulses were passed through a single channel analyser (SCA) and were counted. The fission pulses were used to normalise the LRA yield. The cut-off in the fission channel was set to cut the natural alpha-particles (about 6 MeV). The thickness of the aluminium collector was chosen such as to stop the natural alpha particles and fission fragments and to allow only long-range alpha-particles to pass through and get registered in the stack of five CNTD foils placed close to the collector.

Figure 1 shows the schematic diagram of the ionization chamber. A stack of five CNTD foils was mounted on the back of the aluminium collector. Each detector foil was of size 3 cm × 3 cm and of thickness 100 μm. The solid angle subtended by the foils at the fission source was close to 2π. The uranium source was bombarded with neutrons of known energy until about 10^7 fission events were recorded in the ionization chamber. Thus a set of five CNTD foils was irradiated for each run. ^{7}Li (p, n) ^{7}Be reaction was used to produce neutrons of energies, thermal, 125, 155, 185, 210 and 240 keV. Thermal neutron flux was obtained by interposing a 5 cm thick paraffin block in between the neutron producing target and the chamber. Neutrons of energies 365 and 480 keV were produced from $T(p, n)$ ^{3}He reaction.

Each of the irradiated foils was etched from the rear in several steps using the rear-etching technique. The energy range that can be covered in a single etching depends on the size of the range in which the linearity between the track pit radius and the residual thickness is preserved. A separate experiment was carried out to

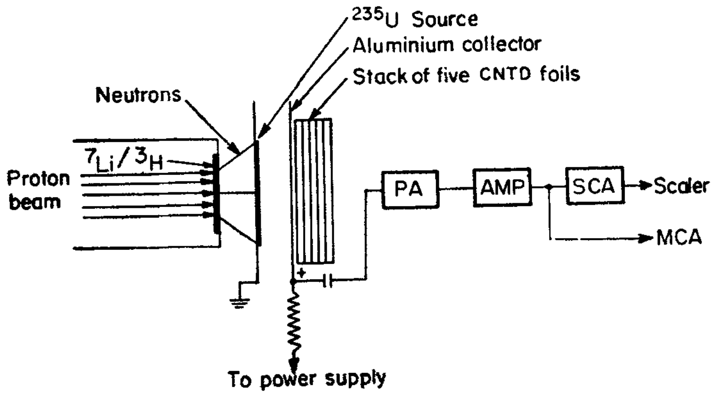

Figure 1. Schematic diagram of ionization chamber and electronics.

determine this energy range. We irradiated two samples of CA 80-15 (size: 3 cm × 3 cm) by ^{241}Am ($E_\alpha = 5{\cdot}48$ MeV) alpha source. The particles were collimated and allowed to enter the detector foils vertically. The samples were etched from the rear by floating them on the surface of 6*N* NaOH solution maintained at 57 ± 0·5°C for varying periods of time. After each interval of etching, the average track-pit radius over the area of interest was determined. The variation of the track-pit radius as a function of the residual thickness of the sample is shown in figure 2. The curve remains linear upto a track-pit radius of about 14 μm and hence the particles having range difference of about 14 μm can be evaluated in a single etching. Thus a layer of about 14 μm can be removed from the rear of the sample in a single etching to determine the range of the particles accurately. The details of etching and counting of the track-pits is described by Sharma and Mehta (1980).

3. Results and discussion

The long-range alpha-particle energy spectra at different incident neutron energies are shown as histograms in figure 3. The energy cut-offs in these spectra are at 10·5 MeV. These cut-offs are due to the energy loss of alpha particles in the aluminium collector and ionization chamber gas. The continuous curves in figure 3 are the least-squares Gaussian fits to the observed energy spectra. The average energy ($\bar{E}_\alpha$) and the standard deviation (σ_{E_α}) at various incident neutron energies, determined from the Gaussian fits, are plotted in figure 4. No significant variation of $\bar{E}_\alpha$ and σ_{E_α} with neutron energy was observed. These results confirm the earlier findings (Krishnarajulu *et al* 1977; Sharma *et al* 1981).

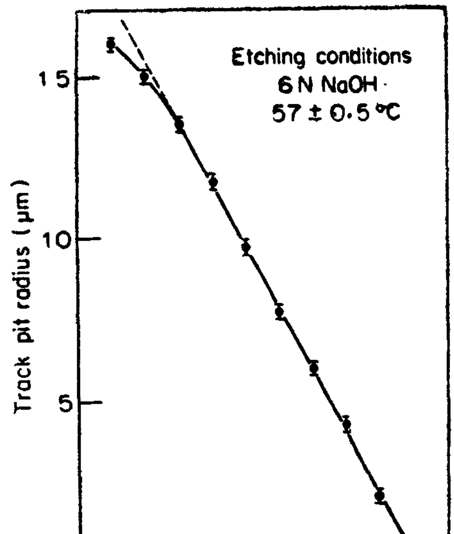

Figure 2. Variation of track-pit radius with the residual thickness.

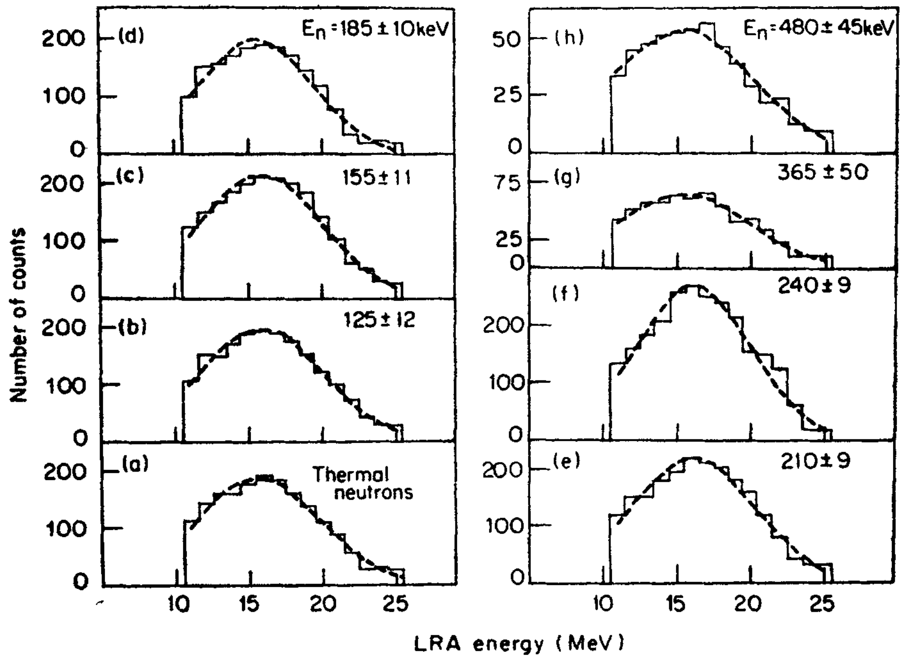

Figure 3. The LRA energy spectra for various incident neutron energies.

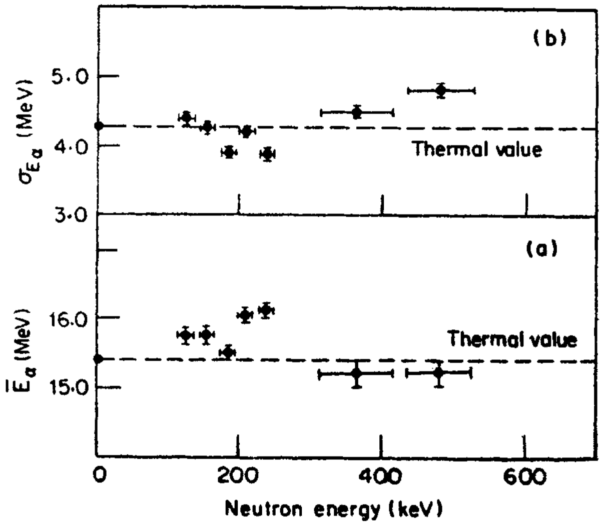

Figure 4. Variation of (a) the most probable LRA energy (E_α) and (b) standard deviation (σ_{E_α}) with incident neutron energy.

The variation of the yield with neutron energy is shown in figure 5. The yield increases with neutron energy above 120 keV and at neutron energies in the region 150 keV $\leqslant E_n \leqslant$ 220 keV the yield is about 50% higher as compared to thermal neutron fission. The enhancement in the effect of increase in LRA yield around 200 keV was, in fact, expected from the earlier measurements (Krishnarajulu *et al* 1977;

Sharma *et al* 1981) where reasonably thick neutron targets were used. Thick neutron targets gave rise to an averaging over an appreciable neutron energy window as compared to that in the present measurements. At higher neutron energies ($E_n > 220$ keV), the yield decreases slowly towards its thermal value. The yield variation is quite smooth and no fine structure is seen in the yield at neutron energies around 200 keV.

The contribution of various partial waves ($l = 0, 1, 2, \ldots$, etc.) to the fission cross-section vary with the incident neutron energy. The p-wave contribution increases rapidly in the energy region below 200 keV and at $E_n = 200$ keV it becomes about 60% of the total fission cross-section (Cuninghame *et al* 1961, 1966). The contribution due to higher partial waves ($l > 2$) is negligible in the energy region studied here. To see the effect of p-wave neutrons on the LRA yield, the contributions due to s-wave and d-wave neutrons were calculated and were subtracted from the total observed LRA yield. The contribution due to d-wave was calculated assuming the LRA to binary fission ratio for d-wave neutrons to be the same as that for s-wave neutrons. The

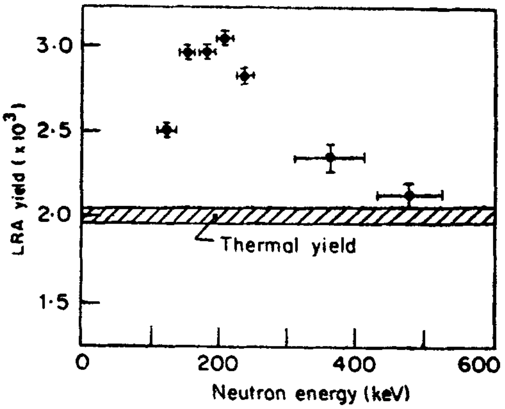

Figure 5. Variation of total LRA yield with incident neutron energy.

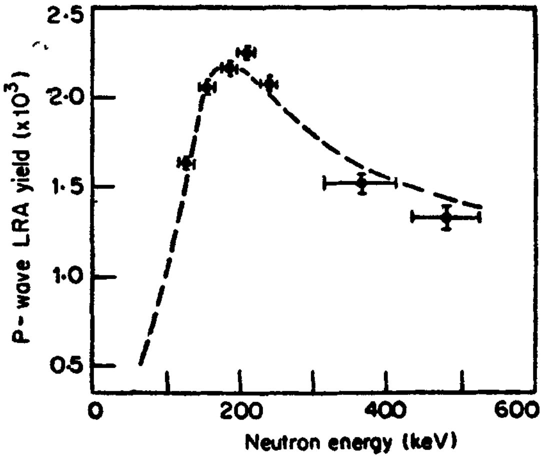

Figure 6. Variation of p-wave LRA yield with incident neutron energy.

variation of p-wave LRA yield with the incident neutron energy is shown in figure 6. The yield can be expressed as

$$P\text{-wave LRA yield} = b\,\frac{\sigma_f\,(l=1)}{\sigma_f\,(\text{total})}$$

where b represents the LRA to binary fission ratio for p-wave neutrons, σ_f $(l = 1)$ is the partial fission cross-section for p-wave neutrons and σ_f (total) is the total binary fission cross-section. The dotted curve, shown in the figure, gives the value of $b = 3{\cdot}6 \times 10^{-3}$. This indicates that LRA to binary fission ratio in the p-wave neutron fission is about two times that in the s-wave fission (2×10^{-3}).

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