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PROPERTIES OF THE NEUTRONS EMITTED IN THE LONG-RANGE ALPHA FISSION OF Cf^{252}

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We have investigated the long-range alpha (LRA) fission neutrons of Cf^{252} in a four-parameter correlation experiment and found the behavior of the average number of neutrons as a function of fragment mass and total fragment kinetic energy to be very similar in binary and LRA fission. We concluded that binary and LRA fission have essentially the same scission configuration and discuss the mechanism of alpha emission and the fragment stiffness coefficients also.

Neutrons emitted in the spontaneous fission of Cf^{252} accompanied by long-range α particles (LRA) particles have been investigated in a four-parameter correlation experiment. A schematic representation of the experiment is presented in Fig. 1. Four fixed solid-state counters, two for fission-fragment detection and two for α-particle detection, were placed inside an aluminum vacuum chamber of 30-cm diam and 5-mm wall thickness. The fission counters were locally made 300-Ω-cm surface-barrier detectors. Both detectors subtended an angle of 44° with respect to the source. The α-particle detectors were surface-barrier counters, manufactured by ORTEC, of 300-μ depletion layer. They were placed opposite each other at 90° to the fission-counter axis and each subtended an angle of 60° with respect to the source. The source consisted of Cf^{252} on a 100-$\mu g/cm^2$ Ni backing. Its strength was about 2×10^5 fissions/min. The source plane was at 45° to the four detectors. In order to prevent fission fragments and 6.1-MeV α particles from the Cf^{252} α decay from reaching the α-particle detectors, 17-mg/cm^2 gold foils were placed between the Cf^{252} source and the α counters.

The neutrons were detected by means of the time-of-flight method with the aid of two identical NE102 plastic scintillators of 5 in. diam and

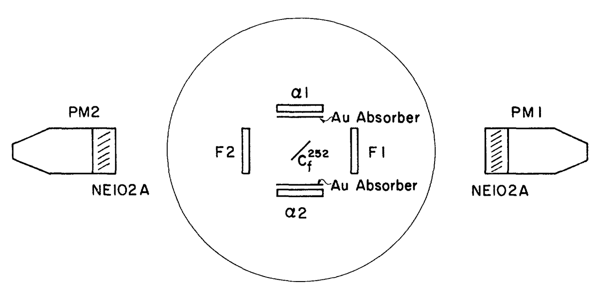

FIG. 1. Experimental arrangement.

10 cm length mounted on 58AVP photomultiplier tubes. The scintillators were situated outside the chamber at a distance of 30 cm from either side of the source on the fission-detector axis. The start signal for the time-of-flight measurement was furnished by one of the fission detectors.

The large opening angles subtended by fission, alpha, and neutron detectors as well as the substantial length of the scintillator (as compared with the relatively short flight path) were necessary in order to obtain a reasonable counting rate. However, they resulted in large experimental dispersions in the data.

The events were recorded by a four-dimensional analyzer and stored on magnetic tape. A total of 8500 LRA-fission neutrons in coincidence with both fission fragments and the α particle were recorded.

The data were analyzed with the aid of a computer. The weighting factor attached to each event involved the detection efficiency of the scintillator as well as the transformation of the neutron velocity vector from the laboratory to the center-of-mass system. The neutron detection efficiency was obtained by comparing the neutron energy spectrum obtained from Bowman et al.[1] for binary fission of Cf^{252} with the energy spectrum obtained with our experimental arrangement for neutrons emitted in binary fission. The comparison involved suitable corrections for the differences in the opening angles of the fission detectors and scintillator geometry in the two experiments.

We present here some of the main results of the experiment. A more detailed discussion of the experiment, including other experimental results, will be published elsewhere.

Assuming that 3.71 neutrons are emitted in the binary fission of Cf^{252},[2] we found that 3.11 ± 0.06 neutrons are emitted in LRA fission. (The errors quoted in this paper consist of the statistical error only.) These numbers are to be compared with the values $\tilde{\nu}_{\text{binary}} = 2.45$ and $\tilde{\nu}_{\text{LRA}} = 1.77 \pm 0.09$ obtained by Apalin et al.[3] for the thermal neutron fission of U^{235}. It is seen that in both cases the absolute decrease in the average number of neutrons in LRA as compared with binary fission is the same within the experimental error.

The ratio of neutrons emitted from the light fragment to those emitted from the heavy fragment obtained in this experiment for the binary fission of Cf^{252} is 0.985 ± 0.004, as compared with the value of 1.14 obtained by Bowman et al.[1] from the small-angle data only. The discrepancy in the values of $\tilde{\nu}_{\text{light}}/\tilde{\nu}_{\text{heavy}}$ may be due to an underestimation of high-energy neutrons or an overestimation of low-energy neutrons, i.e., an incorrect estimation of the neutron detection efficiency at either end. In the LRA fission of Cf^{252} we obtained for this ratio 0.98 ± 0.02, indicating no change in this value between binary and LRA fission.

Figure 2(a) shows the average number of neutrons $\tilde{\nu}$, as a function of fragment mass A, for both binary and LRA fission. The great similarity between the curves is evident. The $\tilde{\nu}(A)$ results for binary fission are in satisfactory agreement with those of Bowman et al.[4]

The function $(\partial\tilde{\nu}/\partial E_K)_A$, the derivative of the average number of neutrons $\tilde{\nu}$ with respect to the total kinetic energy E_K of the two fragments (for a given fragment mass), is plotted in Fig. 2(b) for both binary and LRA fission. These curves are also seen to be similar. The weighted average (over all mass divisions) of

$$\left(\frac{\partial\tilde{\nu}}{\partial E_K}\right)_L + \left(\frac{\partial\tilde{\nu}}{\partial E_K}\right)_H$$

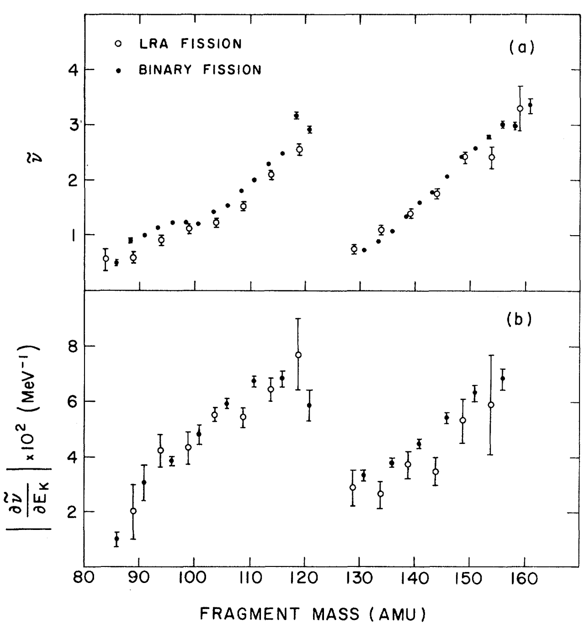

FIG. 2. (a) The average number of neutrons as a function of fission fragment mass in binary and LRA fission. (b) The derivative of the average number of neutrons with respect to the total kinetic energy of the two fission fragments as a function of fragment mass for both binary and LRA fission.

(L and H denoting light and heavy fragment, respectively) is equal to the weighted average (over all fragment masses) of $2(\partial\bar{\nu}/\partial E_K)$, i.e., twice the weighted average of the function shown in Fig. 2(b). It is -0.106 ± 0.004 MeV^{-1} for binary fission, while for LRA fission this value is -0.092 ± 0.011 MeV.

The similarity of Figs. 2(a) and 2(b) indicates that any additional excitation energy [over the average described by Fig. 2(a)] of the fissioning nucleus is divided between the two fragments in roughly the same proportion as that of their average excitation energy [Fig. 2(a)]. In both Figs. 2(a) and 2(b) the excitation energy of a given fragment mass is shown in the form of the number of neutrons emitted from it.

It is generally assumed that the excitation energy of a fragment in low-energy fission results from the deformation energy of the fragment immediately following scission. Figures 2(a) and 2(b) therefore indicate that the behavior of the deformation energy of the fission fragments as a function of fragment mass and fragment kinetic energy is very nearly the same for both binary and LRA fission. The similarity in the deformation energies of the fragments furnishes further direct evidence in support of the hypothesis[5,6] that binary and LRA fission have essentially the same scission configuration. This hypothesis was first based on the great similarity between binary and LRA fission in the mass-ratio distribution, in the kinetic energies of the fragments as a function of mass ratio, and in the total fragment kinetic-energy distribution.[6] In addition to those just mentioned, the results of this experiment strongly support the belief that information on the scission configuration of binary fission may be obtained from the study of the α-particle characteristics of LRA fission.[7]

In the following, the problem of the mechanism of α-particle emission will first be dealt with; subsequently, the possibility of obtaining the fragment stiffness coefficients with the aid of the results of this experiment will be discussed.

The results of Fig. 2(a) do not support the view that the α particles are always emitted from the heavy fragment as proposed by Feather.[8] If indeed the α particles were always emitted from the heavy fragment, we would not expect the $\bar{\nu}(A)$ curve for LRA fission to resemble so closely the curve for binary fission for the heavy fragment region. Nor would we expect the $\bar{\nu}(A)$ curve for LRA fission to be lower than that of binary fission for the light fragment region. Indeed, in view of our results it seems very unlikely that the α particle is emitted in a two-stage process consisting of (a) the scission of the nucleus into two separate fragments, and (b) the emission of the α particle from one of the fragments. While it is not at all clear that such a separation into two distinctive steps is physically meaningful in view of the very short times involved, our data seem to indicate that the α particle is not emitted from one of the fragments.

Briefly our argument goes as follows: If indeed the α particle is emitted from one of the fragments, we would conclude from Figs. 2(a) and 2(b) that very rarely will the fragments in the mass ranges $A < 105$ and $130 < A < 145$ have sufficient excitation energy to emit an α particle. (The energy required for the emission of a LRA has been estimated to be 23-25 MeV.[6,9]) It would therefore be expected that in LRA fission in which a fission fragment is in the above mass ranges, it would be the complementary fragment that would emit the α particle. In view of the fact that the final excitation energy of these "α-emitting" fragments is seen to be only slightly lower [Fig. 2(a)] than in binary fission, we find that prior to the emission of the LRA, the excitation energy of these fragments would have been considerably higher than the average excitation energy in binary fission. It would follow that the fragments in the mass ranges $A < 105$ and $130 < A < 145$ (since they do not emit α particles) should have a higher excitation energy in LRA fission than in binary fission. (This should be the case unless we are willing to postulate that the higher-than-average excitation energy of the "α-emitting" fragment is actually complemented by a lower-than-average excitation energy in the other fragment, implying a negative correlation between the excitation energies of the two fragments.) The results of Fig. 2(a) do not indicate that the excitation energies of the fragments in the intervals $A < 105$ and $130 < A < 145$ are higher in LRA fission than in binary fission.

The results of this experiment may therefore be taken as evidence that α-particle emission does not follow scission as a separate step. It follows that the $\bar{\nu}_{\mathrm{LRA}}(A)$ curve provides us with a measure of the deformation energy of the fragments in LRA fission immediately following scission. In addition, the distance between the scission point and the centers of the two fragments at the moment of scission in LRA fission were determined by Boneh, Fraenkel, and Nebenzahl[7] on the basis of trajectory calculation of the LRA fission process. (We assume here that the point of α-particle emission as obtained by Boneh, Fraenkel, and Nebenzahl[7] from the experimental data of Fraenkel[5,6] coincides with the point of scission.)

Based on a given assumption with respect to the shape of the nucleus at the point of scission and knowing the deformation energy of the two fragments, we may calculate a nuclear "stiffness parameter" which relates the deformation energy to the deviation of the fragment shape from that of a sphere.

Vandenbosch[10] and Terrell[11] assumed the scissioning nucleus to consist of two touching spheroids, whereas Fong[12] assumed that the radius vectors of the two touching fragments have the form $R = R_0[1+\beta_2 P_2(\cos\theta)]$. In the Fong formulation the deformation energy of the fragment is given by

$$E^*(A) = \tfrac{1}{2}C_2(A)\beta_2^2, \qquad (1)$$

where C_2 is the stiffness parameter. $E^*(A)$ in LRA fission can be calculated directly from the results of Fig. 2(a), whereas $\beta_2(A)$ of the Fong model can be obtained from the scission point values of Boneh, Fraenkel, and Nebanzahl.[7] The resulting values for $C_2(A)$ may then be compared with the values for $C_2(A)$ obtained from the Coulomb-excitation studies of Alder et al.[13] This comparison shows that the values of $C_2(A)$ obtained from the scission configuration are much lower than those obtained from Coulomb excitation. This may result from the fact that for the large deformations associated with the scission configuration, the quadratic approximation for the deformation energy [Eq. (1)] is not valid, and higher order terms result in a larger value for the parameter $C_2(A)$.

On the other hand, the low values of C_2 may indicate that the parametrization of the scissioning nucleus in the form of two touching spheroids does not seem to be valid for a nucleus as heavy as Cf^{252}. Indeed, the dynamical-liquid-drop calculations of Nix[14] show the nuclear configuration at scission to differ substantially from the two-spheroid model. The results of these liquid-drop calculations are in good agreement with the results of Boneh, Fraenkel, and Nebanzahl[7] for the scissioning configuration.

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