Table II. Dispersion of hypersonic velocity in CCl_4 at 3 GHz.

Source and method	$(V/V_0)-1$
Authors–direct	4 %
Fabelinskii–optical[a]	6 %
Pellam and Galt–ultrasonic absorption[b]	11 %

[a]Fabelinskii's value of $V = 1040 \pm 27$ m/sec, measured optically at 5 GHz, has been extrapolated to 3 GHz; see reference 11.

[b]Pellam and Galt's value for the excess absorption, $\alpha/f^2 = 510 \times 10^{-17} \pm 1\%$, was measured at 15 MHz; see reference 8 for the computation of V/V_0.

velocity of hypersound in other liquids.

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PROPERTIES OF THE ALPHA PARTICLES EMITTED IN THE SPONTANEOUS FISSION OF Cf^{252} †

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The properties of the alpha particles emitted in the spontaneous fission of Cf^{252} have been examined in a three-parameter correlation experiment. The experimental apparatus consisted of a fission chamber containing two fixed semiconductor detectors (for the two fission fragments), one movable semiconductor detector (for the alpha particle), and a 1.5×10^7-fission/min Cf^{252} source on a 100-μg/cm^2 Ni foil backing. A 16-mg/cm^2 Au foil was placed in front of the alpha-particle detector in order to prevent the 6.1-MeV alpha particles from the alpha decay of Cf^{252} and fission fragments from reaching the detector. The Au foil could be replaced by a thick Es^{253}-Am^{241} source which served for the energy calibration of the alpha-particle detector. The energy calibration of the two fission-fragment detectors was done by comparing the single-fragment energy distribution with that obtained by a time-of-flight method by Fraser et al.[1] The opening angle subtended by each detector (±5°) was large enough to make negligible any corrections in the counting efficiency for different values of the alpha-particle energy and angle and the fission-fragment mass ratio (all affecting the angle between the two fission fragments). Triple-coincidence events were processed by a multidimensional analyzer and stored on tape. The data were then analyzed in various ways with the aid of a computer. A total of 2×10^5 triple-coincidence events were analyzed in this fashion. In our experiment we only detected alpha particles of energy greater than 10 MeV. This cutoff was chosen so as to exclude from our analysis accidental coincidences of binary-fission events with 6.1-MeV alpha particles from Cf^{252} contamination of the alpha counter assembly. Such events would be indistinguishable from true triple-coincidence events involving 9.5-MeV alpha particles which have traversed the Au foil. The angle of the alpha-particle detector was varied between 60° and 120° with respect to either fission counter. We present here first a brief summary of our main results. A more detailed description of the apparatus and experimental results will be published elsewhere.

The angular distribution (corrected for finite detector size and finite extension of the source) of the alpha particles is peaked at an angle of 81° with respect to the direction of the light fragment. It is approximately symmetric with respect to this angle and we obtain for this distribution a width of 32° (full width at half-maximum). (The true width may be somewhat narrower. See below.) The energy spectrum of the alpha particles when measured at an angle of 90° with respect to the two fission-fragment counters is peaked at 14 MeV and falls to one-half its peak value at 20 MeV. When the alpha-particle spectrum is measured without regard to its angle with the direction of the fission fragments (by measuring the energy distribution without coincidence), the most probable energy is 15 MeV and the half-maximum value at 21.5 MeV. These values are in essential agreement with previous measurements of the alpha-particle angular and energy distributions although our value for the most probable alpha-particle energy is somewhat lower than the values obtained by previous authors.[2,3]

Table I compares the light- and heavy-fragment peak positions ($\bar{E}_L$ and $\bar{E}_H$) and widths (σ_L and σ_H) of the single-fragment energy distribution in fission accompanied by the emission of high-energy alpha particles (alpha fission for short) and binary fission as obtained in our experiment. For comparison we also show the results of Fraser et al.[1] for binary fission. (The peak positions for binary fission in our measurement are, of course, identical with those of Fraser et al. since these were our calibration points.) The values of $\bar{E}_L$, $\bar{E}_H$, σ_L, and σ_H shown in Table I (including those of Fraser et al.) were obtained by fitting the experimental distribution to two Gaussian distributions. Also shown in Table I are the average value and width (standard deviation) of the combined energy E_F of the two fission fragments. The average total kinetic energy in alpha fission (including the energy of the alpha particle) in our experiment was 185.2 ± 0.1 MeV and the width (standard deviation) of the distribution was 12.7 ± 0.1 MeV. However, since our measurement included only alpha particles above 10 MeV the actual total kinetic energy in alpha fission may be lower by as much as one MeV. The errors stated are statistical errors only. The average kinetic energy ratio, R, of the two fission fragments is 1.323 ± 0.002 and the width of the distribution is 0.142 ± 0.001 as compared to 1.330 ± 0.001 and 0.150 ± 0.001 for binary fission (statistical errors only). All the above values for alpha fission-fission were obtained for an alpha particle angle of 90° with respect to the two fission-fragment detectors.

Table I. Mean values and standard deviations of the kinetic energy of the light and heavy fragments ($\bar{E}_H$, σ_H, $\bar{E}_L$, σ_L) fitted to two Gaussian distributions, and the kinetic energy of the two fission fragments for alpha fission ($\theta_L = 90°$) and binary fission. Also shown are the values obtained by Fraser et al.[a] for binary fission. All values are given in MeV. The errors stated are statistical errors only.

	Alpha	Binary	Fraser et al.[a]
$\bar{E}_H$	74.3 ±0.1	78.8 ±0.2	78.8
σ_H	7.16 ±0.06	8.89 ±0.12	9.10 ±0.01
$\bar{E}_L$	97.3 ±0.1	104.1 ±0.1	104.1
σ_L	5.75 ±0.05	6.22 ±0.09	6.14 ±0.01
$\bar{E}_F$	169.0 ±0.1	181.1 ±0.1	182.1
σ_F	12.57 ±0.10	13.51 ±0.06	15.2

[a]See reference 1.

In the rest of this Letter we wish to discuss the results of the analysis of the angular distribution of the alpha particles as a function of the energy ratio R of the two fission fragments. This ratio corresponds to the mass ratio of the fragments at scission (primary mass ratio) except for corrections due to neutron emission. In Fig. 1 we show the angular distribution of the alpha particles for seven energy-ratio intervals of the fission fragments. The angular distributions have been corrected for finite detector size[4] and finite extension of the source.[5] Due to uncertainties in these corrections the wings of the distributions cannot be trusted and the actual distributions are probably somewhat narrower than those shown in Fig. 1. Because of the essentially symmetric shape of the distributions, the position of the peaks is almost unaffected by the corrections.

The most striking feature of Fig. 1 is the shift of the most probable direction of the alpha particle towards the direction of the heavy fragment as the energy ratio R increases. Thus the most probable value of θ_L (the angle between the direction of the alpha particle and the direction of the light fragment) for almost symmetric fission ($1.0 \leq R < 1.1$) is 72° whereas for very asymmetric fission ($2.0 \leq R$) the peak of the angular distribution is shifted towards the heavy fragment [θ_L(peak) = 99°].

The systematic shift of the most probable angle with mass ratio may be explained in the following way: The angular distribution of the alpha particles is predominantly due to the Coulomb force between the two fission fragments and the alpha particle which is emitted in the "neck" region connecting the two fission fragments before scission. If the alpha particles are emitted from a point very much closer to fragment a than to fragment b, the Coulomb force of fragment a will predominate and the angular distribution of the alpha particles will be shifted towards the direction of fragment b. The gradual shift of the most probable angle in Fig. 1 towards the heavy fragment as the mass ratio increases indicates that the most probable point of emission of the alpha particle is strongly dependent on the mass ratio: This point is close to the heavy fragment for almost symmetric fission and close to the light fragment for large mass ratios R. The shift of the most probable angle with R would also be expected if in almost symmetric fission the heavy fragment is nearly spherical whereas the light fragment is highly deformed, and the deformation of the heavy fragment increases and that of the light fragment decreases with increasing R until at very high mass ratios the light fragment is almost spherical and the heavy fragment is highly deformed. (If the point of emission were independent of R, the shift of the most probable angle would be opposite to that shown in Fig. 1 due to the larger Coulomb force of the heavier fragment.)

Assuming the alpha particle to be emitted at the scission point[6] (i.e., the point at which the "neck" between the two fragments ruptures), we arrive at the following conclusion: The scission point is close to the heavy fragment for almost symmetric fission and it shifts towards the light fragment as the mass ratio increases. For a mass ratio $R=2$ the scission point is already close enough to the light fragment to cause most of the alpha particles to be emitted towards the direction of the heavy fragment.

The results shown in Fig. 1 imply a discontinuity in the variation of the most probable angle $\theta_\alpha(A)$ with respect to the direction of a given fragment of mass A at a fragment mass corresponding to symmetric fission. The function $\theta_\alpha(A)$ is shown in Fig. 2. It can be obtained

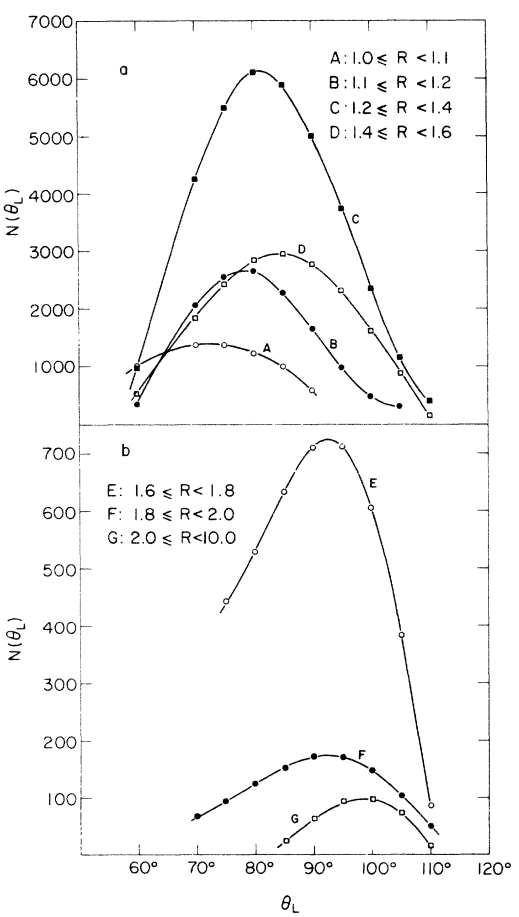

FIG. 1. Angular distribution of the alpha particles for seven intervals of the fission-fragment mass ratio R. θ_L is the angle with respect to the direction of the light fragment.

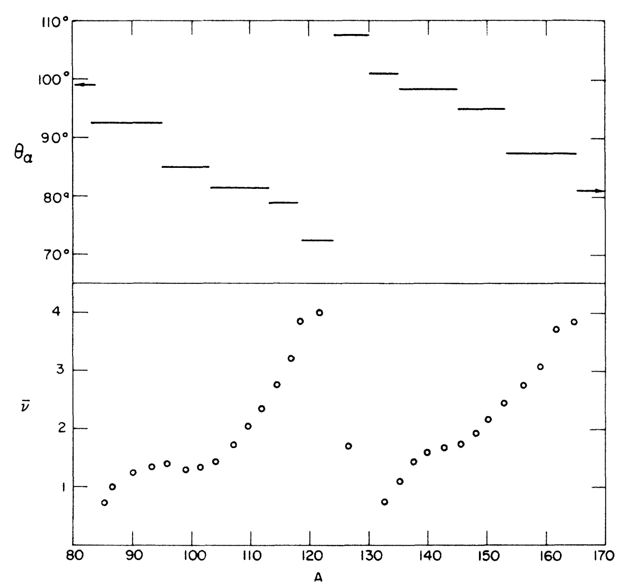

FIG. 2. Most probable angle θ_α of the alpha particles with respect to the direction of the fission fragment in alpha fission and average number of neutrons in binary fission as a function of fragment mass. $\bar{\nu}(A)$ was taken from H. R. Bowman, J. C. D. Milton, S. G. Thompson, and W. J. Swiatecki, Phys. Rev. 129, 2133 (1963).

from Fig. 1 by neglecting the effect of neutron emission (i.e., assuming $E_1/E_2 = A_2/A_1$ for the relation between the initial fragment masses A_1 and A_2 and the measured fragment energies E_1 and E_2). Since our results (Fig. 1) were obtained for comparatively large R intervals, the error due to this approximation is small. The discontinuity of $\theta_\alpha(A)$ at $A \approx 124$ is similar to the "discontinuity" in the average number of neutrons as a function of fragment mass $\bar{\nu}(A)$ in binary fission. Figure 2 shows the function $\bar{\nu}(A)$ for binary fission of Cf^{252} as obtained by Bowman et al.[7] Similar curves were published by Whetstone[8] and Terrell.[9] [It should be noted that a given value of θ_α for a fragment of mass A also determines the complementary angle $(180°-\theta_\alpha)$ as the most probable angle of the complementary fragment of mass 248-A. Hence only one half of the function $\theta_\alpha(A)$ as plotted in Fig. 2 conveys new information. The other half is redundant and was plotted here only for sake of convenience. This is not true for the function $\bar{\nu}(A)$.]

The similarity between the two functions plotted in Fig. 2 is not fortuitous. The experimentally observed variation of $\bar{\nu}(A)$ with fragment mass as seen in Fig. 2 has been taken as evidence that a shift in the position of the scission point does also occur in binary fission.[8,10] The arguments are well known and will be given here only very briefly: A small value of $\bar{\nu}(A)$ for a given fragment indicates that the average excitation energy of this fragment is small and hence the deformation energy of the fragment at the moment of scission must also have been small (since the deformation energy at the moment of scission is later transformed into excitation energy). A small deformation energy implies that the fission fragment was almost spherical at the moment of scission, i.e., the scission point was close to the center of the fragment.

We may therefore conclude that if the scission point is close to a given fragment the value of $\bar{\nu}$ for this fragment in binary fission will be small and the angle of the alpha particle with respect to the direction of this fragment in alpha fission will be large. This anticorrelation between $\bar{\nu}(A)$ in binary fission and $\theta_\alpha(A)$ in alpha fission is evident in Fig. 2. It indicates that a similar shift occurs in the position of the scission point as a function of R in binary and alpha fission. It also lends further support to the supposition that the configuration of the nucleus at (and before) scission in alpha fission closely resembles the configuration in binary fission.

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