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Scission point configuration of ^{252}Cf fission

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The Fossati-Pinelli study of the scission point configuration of ^{252}Cf based on the calculations of trajectories of long-range α particles emitted in fission provides previously unavailable experimental evidence supporting the basic assumption of the statistical theory of nuclear fission. However, their stated conclusion and that of a similar analysis by Krishnarajulu and Mehta need modification. It is found that the broad and fluctuating distributions of initial energies of the α particle and the fission fragments obtained by these two groups might not be real even though they are mathematically valid. Nevertheless, together with other information available to us, the unreal part may be eliminated and both works then yield results that are wholly consistent with the statistical theory of fission. The validity of the dynamical theories will be discussed.

[NUCLEAR REACTIONS, FISSION LRA-fission, statistical theory.]

The kinetic energy and angular distribution of the long-range α-particles in ternary fission (spontaneous fission of ^{252}Cf) have been used to reconstruct the scission point configuration which is crucial to the fission theory. It is hoped that this information will decide whether fission should be treated by the statistical theory or by the dynamical theory. Earlier works[1-4] based on best-fit trajectory calculations generally concluded with a scission-point configuration characterized with large values of the interfragment distance D_0, initial kinetic energy of the α-particle $E_{\alpha 0}$, and initial kinetic energy of the main fission fragments E_{F0}. This result has often been cited to favor the dynamical theory of fission. On the other hand, the scission-point configuration predicted by the statistical theory, characterized by small values of D_0, $E_{\alpha 0}$,E_{F0} has been used in trajectory calculations to derive angular and energy distributions of the α-particles. The results are in good agreement with experimental values and thus the α-particle data are consistent with the statistical theory.[5] The discrepancy between the two kinds of calculations has been discussed and the validity of the large values of $E_{\alpha 0}$, E_{F0}, and D_0 questioned.[5]

Recently two additional best-fit trajectory calculations have been published by Fossati and Pinelli[6] and by Krishnarajulu and Mehta.[7] Both yield wide distributions of $E_{\alpha 0}$ and E_{F0} covering both the small and the large values of earlier calculations. These results are difficult to understand from the point of view of the fission theory - the fission process cannot be both statistical and dynamical. The wide distributions also involve erratic fluctuations which are disturbing. On the other hand, in both these calculations an enormously large number (10^5) of trajectories are calculated with an exhaustive coverage of possible initial parameter values, which is a decided improvement over the earlier best-fit calculations.[1-4]

The wide distributions of Fossati and Pinelli's results show that the initial kinetic energy of the α-particle $E_{\alpha 0}$ ranges from 0 to 4 MeV; that of the main fragments E_{F0} ranges from 0 to 60 MeV and the interfragment distances D_0 ranges from 19 to 31 fm. The small values of these quantities correspond to those given by the statistical theory. For the first time these values were brought out by the best-fit trajectory calculations This demonstrates the shortcomings of the earlier best-fit trajectory calculations[1-4] which did not accept these values because their coverage of the possible initial parameter values is not extensive enough. Important regions were overlooked[5] and therefore their conclusions are not valid. On the other hand, both Fossati-Pinelli's and Krishnarajulu-Mehta's results also include large values of $E_{\alpha 0}$, E_{F0} and D_0 given by the earlier calculations.[1-4]

Fossati and Pinelli interpreted their results by asserting that the distribution may be regarded as being composed of two groups of α-particles: Group (a) is characterized by small values of $E_{\alpha 0}$ and E_{F0} very close to those given by the statistical theory and is considered by the authors as strong evidence supporting the statistical theory. These α-particles are considered to be emitted in scission configurations close to those of binary fission. Group (b) corresponds to those configurations with large values of $E_{\alpha 0}$ and E_{F0}. These α-particles are considered to be emitted by fragments in flight about 10^{-21} sec after binary scission. Let us disregard for the moment the difficulties involved in the emission of this group of α-particles which will be discussed later. If we accept this interpretation, then the ternary scission point of group (b) α-particles is completely unrelated to the binary scission point, and this group of α-particles is completely irrelevant to the issue of statistical theory versus dynamical theory. Only group (a) is relevant to this issue and the evidence from group (a) strongly supports the statistical theory. Therefore, if their interpretation is correct, their work already provides unambiguous, conclusive support to the statistical theory and clearly settles the issue. On the other hand, Krishnarajulu and Mehta considered the issue still unsettled.

The contention of this paper is that the conclusions of Fossati and Pinelli, and Krishnarajulu and Mehta are somewhat in error in that those configurations with large values of $E_{\alpha o}$, E_{Fo} and D_o are not real - they are merely mathematical artifacts of the method of analysis. This does not alter the above conclusion on the statistical theory based on Fossati and Pinelli's work. This also makes it possible to draw definite conclusions from Krishnarajulu and Mehta's work.

The essential point is this: If the experimentally observed kinetic energies and directions of the three particles determine a set of three trajectories, they still leave the starting point of the trajectories undetermined. Any time point t_1, t_2, ..., along the trajectories could be taken as the starting point to determine the scission point configuration and the final kinetic energies and directions would be exactly the same. An early point t_e would lead to a scission point configuration of small values of $E_{\alpha o}$, E_{Fo} and D_o; a later point t_ℓ would lead to large values of the same. Using final kinetic energies and directions to determine the initial conditions of the three body problem by best-fit trajectory calculation will necessarily lead to a wide range of distributions of $E_{\alpha o}$, E_{Fo} and D_o corresponding to all times t_1, t_2, ..., along the trajectories. (See the appendix.) This by itself does not mean that the physical starting point is early or late or even a distribution. The best-fit trajectory calculation cannot determine the real physical values of $E_{\alpha o}$, E_{Fo} and D_o. (The earlier best-fit trajectory calculations[1-4] did not lead to a wide distribution of these quantities as the later ones[6,7] do because they invoked arbitrary restrictions such as limiting the initial value of $E_{\alpha o}$ or limiting the initial position of the α-particle to be on the line joining the centers of the main fragments.)

Additional conditions must be invoked to determine the starting point of the trajectory and to determine the scission point configuration. For a late starting point t_ℓ the initial interfragment distance D_o is large. This could be so only under either one of the following conditions:

(a) The fragments (or at least one of the two) are elongated to a very large extent at the point of scission (defined as the starting point of the purely coulomb interactions among the three particles) to keep physical contact with the α-particle.

(b) The α-particle is emitted at the starting point by tunneling out of one fragment (thus no physical contact of the α-particle with the fragments at the starting point) sometime after binary scission as Fossati and Pinelli suggested.

We want to show that both possibilities can be excluded by evidence already known to us. In case (a) the fragments (or at least one of the two), elongated to a large extent, would be associated with a large amount of deformation energy. Thus the number of prompt neutrons ν would be much greater than the experimental value ($\nu = 3.8$). This value allows only very small deformations of the fragments and thus allows only small values of D_o (in the neighborhood of 19fm, certainly not 30fm) as shown by the earlier work on prompt neutron distribution[8] and a recent work on the scission-point configuration of ^{235}U.[9] Thus the initial configurations with large values of D_o (and thus large values of $E_{\alpha o}$ and E_{Fo}) cannot be real.

In case (b) the α-particle appears by barrier tunneling out of one fragment sometime after binary scission of the main fragments. For those initial configurations with large values of D_o this means that the α-particle is emitted at a low energy state so that it will appear at the end of the tunnel at a distance considerably larger than the nuclear radius. This corresponds to a very large α-emission lifetime (many years), which is contradictory to the very short lifetime (10^{-21}sec) required here.

Therefore, in both cases (a) and (b), those initial configurations with large values of D_o are not real. Their appearance is thus merely a mathematical artifact permitted by the best-fit calculation. As a result only small values

Table 1. Comparison of three Fossati-Pinelli trajectories with the time evolution of a reference trajectory.

Fossati-Pinelli Trajectories					
No.	D_o(fm)	E_{Fo}(MeV)	x_o(fm)	y_o(fm)	$E_{\alpha o}$(MeV)
22	20.84	10	10.86	2	0.501
21	23.59	30	11.37	3	1.751
23	27.32	50	15.91	4	4.001
Reference Trajectory					
T*	D_o(fm)	E_{Fo}(MeV)	x_o(fm)	y_o(fm)	$E_{\alpha o}$(MeV)
5.1	22.12	12.17	11.89	3.03	1.64
8.5	24.67	29.01	13.73	6.45	3.78
11.9	28.14	46.08	16.02	11.40	6.66

T* = Time (10^{-22}sec)

of D_O are real. The small values of D_O are consistent with the statistical theory. Dynamical theories with large values of D_O are eliminated. This discussion applies equally well to the results of Krishnarajulu and Mehta.

Actually all trajectory calculations to data, despite previous disagreements, are mathematically consistent with one another. They all generally lead to the same trajectory but differ in the starting point which is left undetermined by the best-fit method anyway. With the help of the additional information they can all be interpreted to support the same physical conclusion just stated.

The statistical theory, of course, may not be the only one that is consistent with the small values of D_O. Starting from the scission point 0 of the statistical theory, we may trace down the trajectories for a short time to find another point 0' which may be considered as the scission point without violating experimental data of α-particles, kinetic energy and prompt neutrons provided that the increased deformation is obtained at the expense of the internal excitation energy. The latter energy is only of the order of 10 MeV and therefore 0' cannot be far from 0. With the fragments cold, the theory leading to such a scission point 0' will have to be a nondissipative dynamical theory. Such a theory is likely to predict undamped asymmetric oscillation and therefore likely to contradict the experimental mass distribution - the mass-yield curve would have four peaks instead of two as discussed in an earlier paper.[10]

Appendix

To demonstrate the point that those trajectories with large values of D_O and E_{FO} may be considered as the time evolution of those with small values of the same rather than as independent trajectories, we compare in Table 1 three of Fossati-Pinelli's trajectories (Nos. 21, 22, 23 in their Table 2) with the time evolution of a reference trajectory, which is one of the trajectories we calculated[5] that closely matches the D_O and E_{FO} values of one of the three (No. 22). We find that the D_O and E_{FO} values of the other two (Nos. 21, 23) are indeed matching closely the time evolution values of the reference trajectory. The initial coordinates of the α-particle are x_O and y_O. The values of y_O (and thus $E_{\alpha O}$) do not match closely because in Fossati-Pinelli's work no trajectories with y_O>4fm are included. Nevertheless the trend of variation is consistent with that in the reference trajectory. Considering the ranges of "errors" of the Fossati-Pinelli values (10 MeV for F_{FO}, 0.25 MeV for $E_{\alpha O}$, 1 fm for y_O and 0.5fm for x_O) the three trajectories may be considered as nearly the same trajectory differing only in starting time. (These "errors," some of them are quite large, also make it less meaningful in trying to compare the three trajectories by extrapolating one ahead or behind of time.)

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