PHYSICAL REVIEW C VOLUME 16, NUMBER 1 JULY 1977

Scission point configuration of thermal-neutron induced fission of ^{235}U

Charles S. Brown and Peter Fong
Physics Department, Emory University, Atlanta, Georgia 30322
(Received 9 September 1976)

Trajectory calculations of the long-range α particles emitted in thermal-neutron induced fission of ^{235}U have been carried out based on the initial conditions determined by the statistical theory of fission. The results agree very well with the experimental results of angular and energy distributions of the α particle and thus lend strong support to the statistical theory. The discrepancy of this calculation with the best-fit trajectory calculations is resolved by showing that the latter are mathematically correct but physically wrong because they contradict with the experimental results of the number of prompt neutrons emitted per fission.

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

1. Introduction

Fission theories can generally be developed in two alternative approaches: statistical[1] and dynamical.[2] It is desirable to secure direct experimental evidence that will decide which approach is physically correct. The study of the long-range α particles (LRA particles) emitted in fission fulfills this need. The LRA particle, after its emission at the scission point, is accelerated by the electrostatic field of the two moving fission fragments. The final angular and energy distributions of the α particles are determined by the initial conditions of the classical three-body electrostatic-force problem. This initial condition is actually the condition of the scission point of the fission process. Any complete theory of fission should give a definite prediction of this configuration. The statistical theory predicts that the LRA particle and the fission fragments should assume small kinetic energy values, of the order of 0.5 MeV, at the scission point[1] whereas one nondissipative dynamical theory predicts that the fission fragments should have a large kinetic energy of the order of 20 MeV.[2] The controversy between the two theories can be settled by studying the scission point configuration based on the experimental angular and energy distributions of the LRA particle.

Unfortunately the experimental information does not give us the values of a complete set of canonical variables at the final time which would have enabled us to integrate the equations of motion backward in time to reconstruct the initial conditions at the scission point. Previous mathematical analysis of the problem, referred to as the best-fit trajectory calculations,[3-5] thus starts by assuming a variety of initial conditions, then proceeds to carry out the trajectory calculations of each assumed condition, and finally concludes by letting experimental results decide which assumed initial condition is the correct one. Results obtained by different groups are not exactly in agreement but most of them show the fission fragments to have a substantial amount of kinetic energy at the scission point, of the order of 30 MeV. The results have been cited to support the dynamical theory.

Since the statistical theory has already made a definite prediction of the scission point configuration, geometric[6] as well as dynamic,[1] it is natural to use this initial condition to carry out the trajectory calculation of the three-body problem. This has been done for the case of spontaneous fission of ^{252}Cf.[7] The predicted results agree quite well with the experimental ones, supporting the statistical theory.

Recently experimental work on the LRA particle distributions for the case of thermal-neutron induced fission of ^{235}U has been carried out by Carles et al.[8] and by Gazit et al.[9] A similar trajectory calculation based on the statistical-theory-predicted initial condition of ^{235}U is now carried out and reported in this paper. The discrepancy with the best-fit calculations of ^{252}Cf[3-5] and ^{235}U[9] will be discussed at the end.

2. Trajectory Calculation

The formulation of the equations of motion of the classical three-body electrostatic-force problem, the determination of the initial values of the canonical variables from the statistical-theory-determined scission-point configuration[6,1] and the procedure of numerical integration by computer are exactly the same as in the ^{252}Cf calculation.[7] Only the computer programming is different. The computer used is Univac 70/7. The total computing time is 740 seconds.

Trajectories of the three particles are calculated for the following mass ratios of fission fragments: 116/116 (Fig. 1), 121/111 (Fig. 2), 126/106 (Fig. 3),

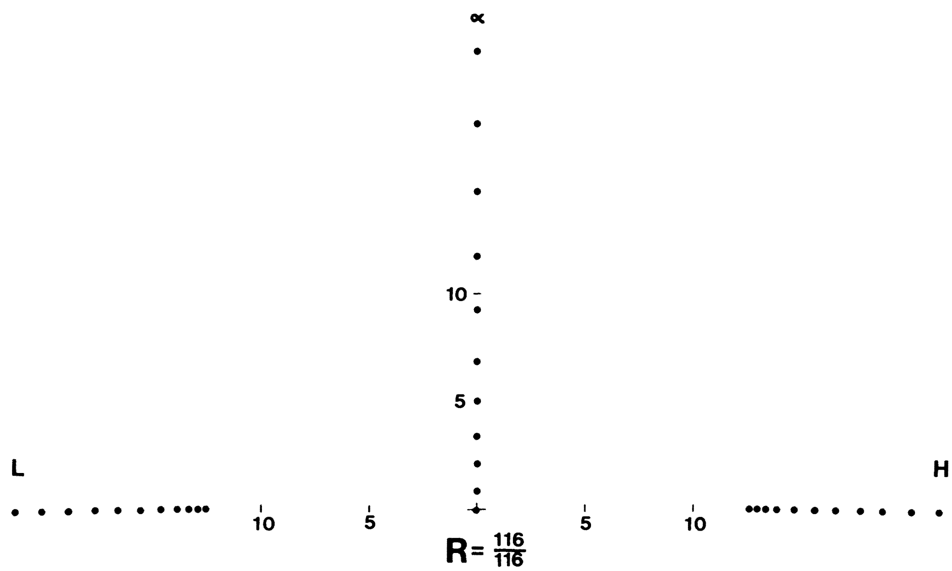

Figure 1. Trajectories of the α-particle and the fission fragments (H and L) for the mass ratio 116:116.

131/101 (Fig. 4), 141/91 (Fig. 5), 151/81 (Fig. 6), 161/71 (Fig. 7). The portion of the trajectories depicted in the figures corresponds to a time of 2×10^{-21}sec. The time between two consecutive dots is 2×10^{-22}sec whereas the time increment Δt in the computer iteration is 10^{-23}sec. The complete trajectories have been computed to a total time of 10^{-13}sec.

Figures 2-4 show the dominant influence of the heavy fragment on the LRA particle. Its greater electric charge and its shorter distance to the α particle--because of the closing of the 82 neutron shell, and thus the less deformation, of the heavy particle--make the α particle move veering toward the light fragment. On the other hand, Figures 6-7 show the unusual "reflection" of the α particle which is also observed in the previous calculation of ^{252}Cf.[7] The light fragment is now in the 50-proton shell region and is thus closer to the α particle. It initially pushes the latter toward the heavy fragment. Once the α particle has moved closer to the heavy fragment, the influence of the

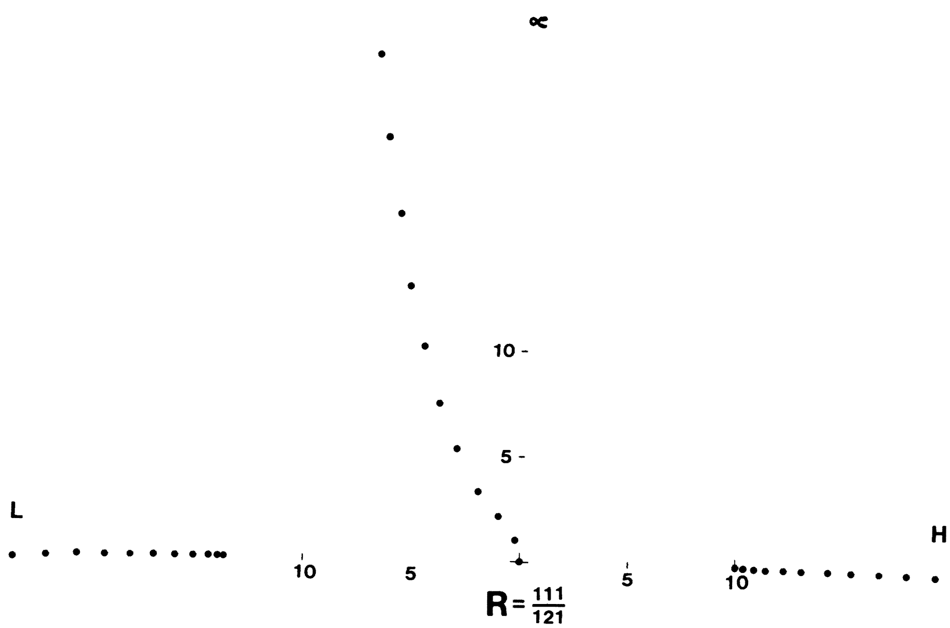

Figure 2. Trajectories of the α-particle and the fission fragments (H and L) for the mass ratio 121:111.

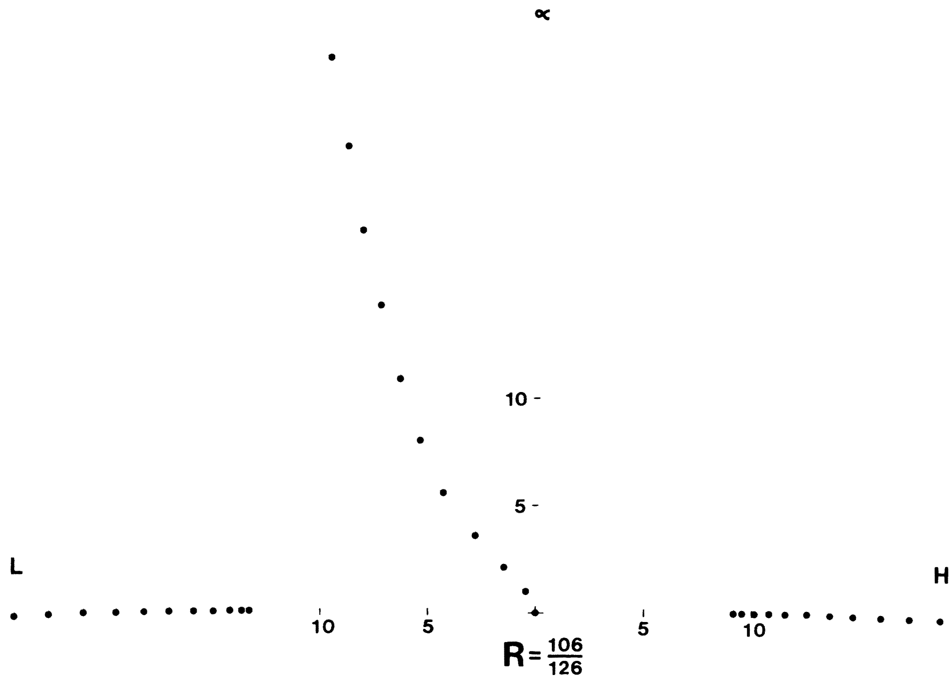

Figure 3. Trajectories of the α-particle and the fission fragments (H and L) for the mass ratio 126:106.

latter becomes predominant and the α particle is reflected and moves toward the light fragment. Thus in all mass ratios the α particle is always emitted veering toward the light fragment.

The angular correlation results thus obtained are summarized in Fig. 8 in which the angle between the LRA particle and one fission fragment is plotted as a function of the mass number of that fragment. The experimental re-

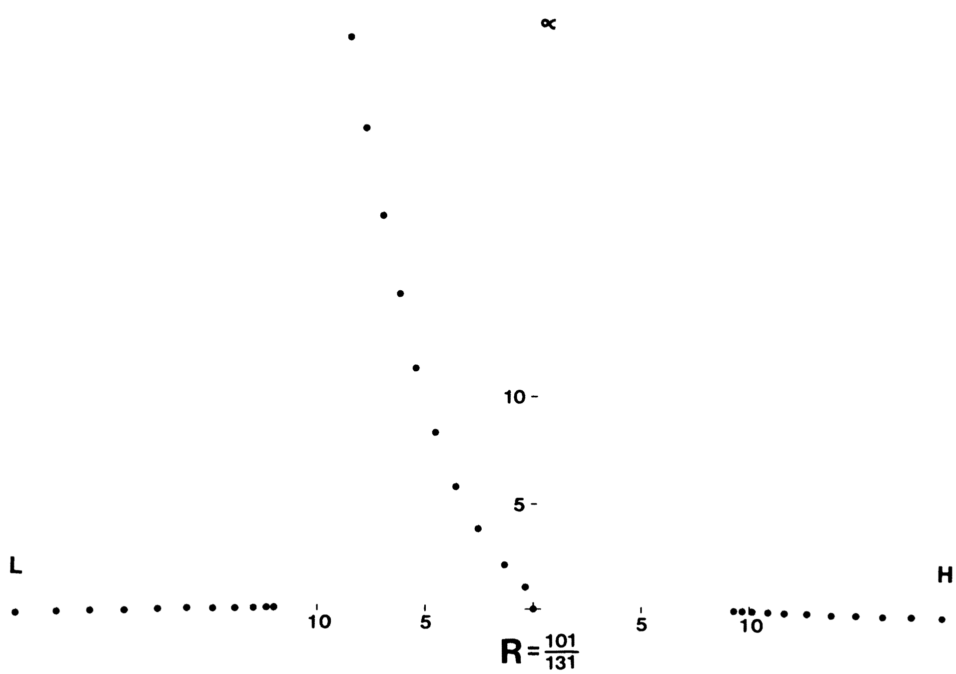

Figure 4. Trajectories of the α-particle and the fission fragments (H and L) for the mass ratio 131:101.

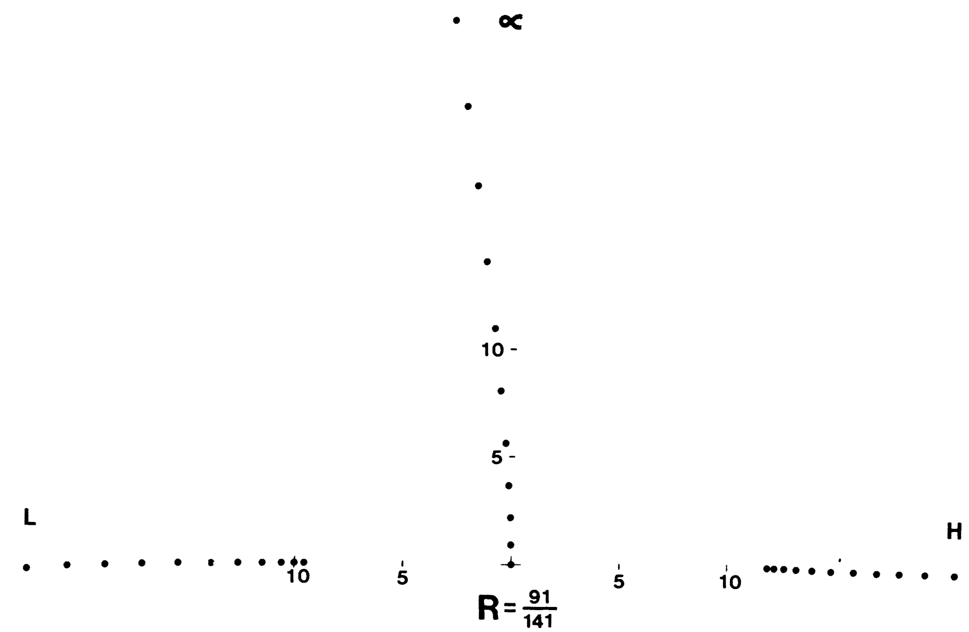

Figure 5. Trajectories of the α-particle and the fission fragments (H and L) for the mass ratio 141:91.

sults of Carles et al. and Gazit et al. are also plotted for comparison. The agreement is excellent.

It has been stated in the previous work[7] that the reflection of the LRA particle is very sensitively dependent on the initial kinetic energy of the α particle. The experimental comparison of the angular correlation thus provides a very sensitive test for the initial kinetic energy value. The reflection in Figs. 6-7 can happen only for small values of this energy, in the neighborhood of 0.5 MeV. The agreement shown in Fig. 8 thus verifies the statistical-theory prediction of this energy in a very sensitive way.

The final kinetic energy of the LRA particle obtained in this calculation is shown in Fig. 9 as a function of

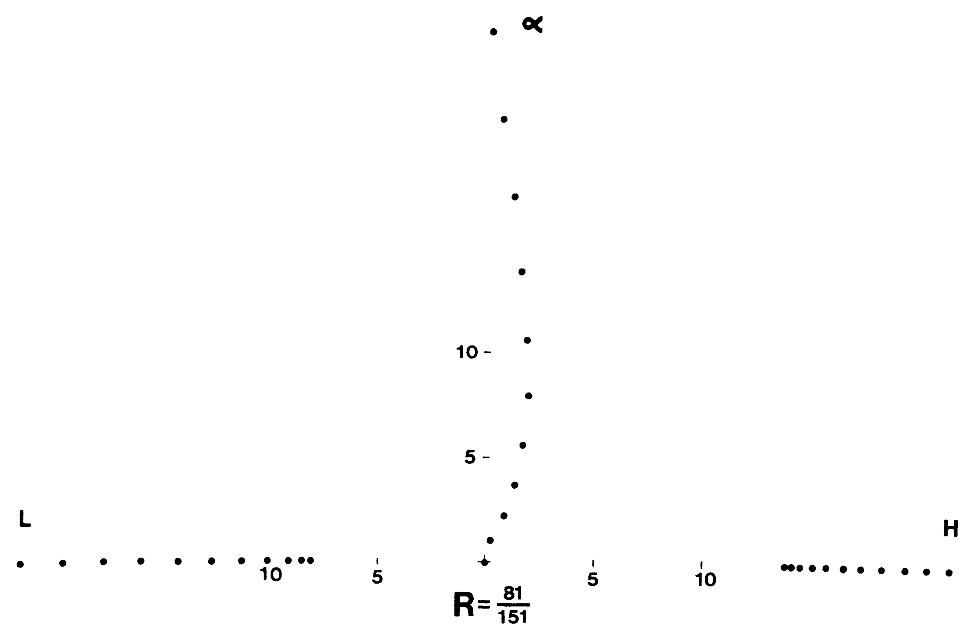

Figure 6. Trajectories of the α-particle and the fission fragments (H and L) for the mass ratio 151:81.

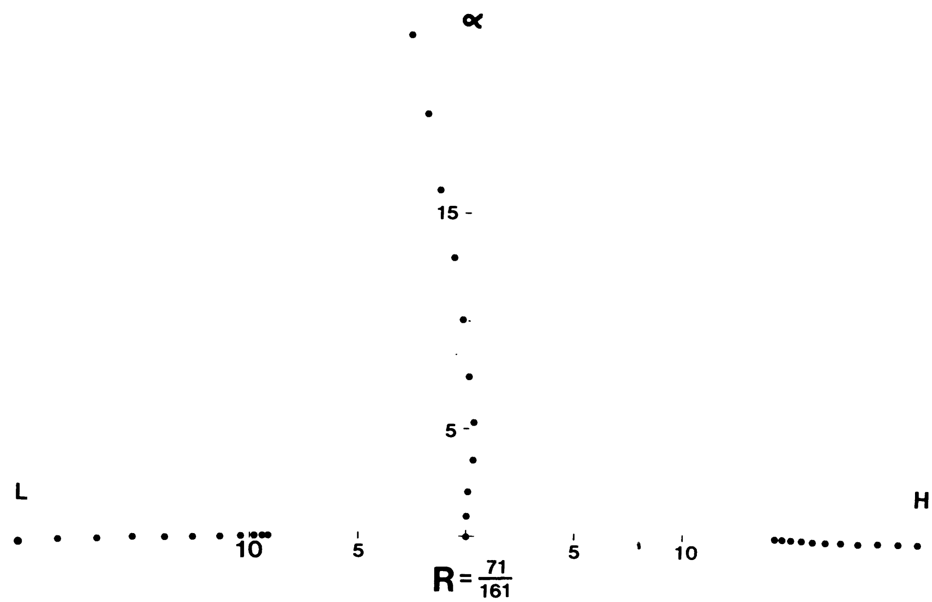

Figure 7. Trajectories of the α-particle and the fission fragments (H and L) for the mass ratio 161:71.

the mass ratio of fission. The corresponding experimental values of Carles et al. are also shown, which can be represented by a horizontal straight line. The agreement is good.

Thus the scission point configuration, geometric as well as dynamic, as determined by the statistical theory, does lead to angular and energy distributions of the LRA particle in good agreement with the experiment results. The LRA particle being a sensitive probe of the scission point configuration, the experimental results may thus be considered as evidence consistent with the statistical theory.

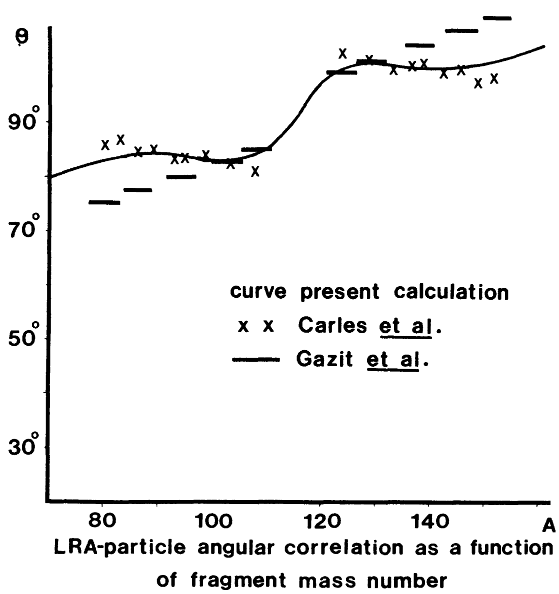

Figure 8. Calculated angle between the long-range α-particle and one fission fragment as a function of the mass number of that fragment compared with the experimental results of Carles et al. and Gazit et al.

3. Discussions

The discrepancy of the present calculation with the best-fit calculations (summarized in Table IV of reference 9) must now be resolved.

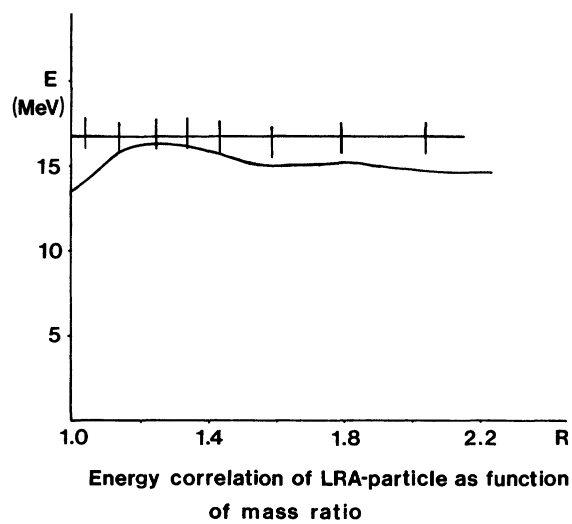

Figure 9. Calculated kinetic energy of the long-range α-particle as a function of the mass ratio of fission (curve) compared with experimental values of Carles et al. (vertical bars).

The latter claim that, contrary to the statistical-theory prediction, the fission fragments as well as the LRA particle have already gained a substantial fraction, about 20% of their final kinetic energy at the scission point. Also that the centers of the two fission fragments at the scission point are separated by a much larger distance D than that given by the statistical theory. How can both agree with the same experimental results of LRA fission?

We want to show that the best-fit calculations are mathematically correct but physically wrong because they contradict with the experimental value of ν, the number of prompt neutrons per fission. That these physically contradictory results could all be mathematically correct is due to the fact that the experimental values of angle and energy of the three particles, once associated with a set of trajectories of the three particles, still cannot determine the starting point on the trajectories. In fact, any point in time may be taken as the starting point and the final energy and angle values of the three particles would remain exactly the same. It seems that all trajectory calculations, the best-fit ones and the statistical-theory based one, agree on the trajectories in general--after all, they all account for the experimental angular and energy distributions. They differ only in the starting point of the trajectories. The statistical theory takes a very early starting point. All the others take a much later starting point; that is why they give a much larger value of D and much larger initial values of kinetic energies of the three particles because of the acceleration of the three particles by the Coulomb forces during the time elapsed. This mathematical relation has been pointed out in the earlier paper.[7] Since the empirical energy and angular distributions leave the starting point undetermined, all starting points are equally valid mathematically. Therefore, the different scission-point configurations arrived at in the two kinds of calculations are not contradictory to each other mathematically as far as LRA-particle distributions are concerned. However, physically they cannot be both correct. Their differences cannot be settled by LRA particle distributions; they will have to be settled by another piece of experimental information. The prompt neutron information fulfills this purpose.

As already mentioned, the scission point configurations obtained by the best-fit calculations have in common a large inter-fragment distance D. In addition, the two main fragments have already developed a substantial amount of kinetic energy, of the order of 30 MeV. This means that a sizable fraction of the mutual Coulomb energy of the two fission fragments has been converted to kinetic energy while the fragments are still joined together. The large interfragment distance D means that the two fragments must have been stretched out along the axis to a large extent. Thus the fission fragment deformation energy and the number of prompt neutrons ν must be very large. The ν value may be compared with the experimental value. However, these artificially devised configurations do not contain sufficient physical information to allow a calculation of the deformation energy. Fortunately significant information may be derived by comparing them with one particular scission point configuration that has all the physical information we need, i.e., the scission point configuration Hasse obtained in his dynamical theory of fission.[2]

In the Hasse scission-point configuration the fragments have already developed an amount of kinetic energy equal to about 14% of the mutual Coulomb energy. This configuration being specified dynamically in every detail in terms of a liquid drop model, we can calculate the ν value exactly. The calculation shows that the fragments, after separation, would have a total amount of excitation energy of about 44 MeV and therefore the ν value would be about 5.4. The scission point configurations obtained by the best-fit trajectory calculations are such that 20% of the mutual Coulomb energy has already been converted into kinetic energy at the scission point. Therefore the corresponding fission fragments would be stretched out even more than those in the Hasse configuration. The deformation energy and thus the ν value would be even greater than those of the Hasse configuration, i.e., $\nu > 5.4$. The experimental value of ν is only 2.4 for thermal-neutron induced fission of ^{235}U and 3.8 for spontaneous fission of ^{252}Cf. Therefore these proposed scission-point configurations cannot be real. They are too elongated. The starting point on the trajectories is chosen at too late a time.

The same point also can be argued in the following way. Let us compare a number of real scission-point configurations of different degrees of elongation along the fission axis corresponding to the kinetic energy distribution. According to a previous calculation,[6] those with a decrease of the mutual Coulomb energy (compared with the most probable configuration) are accompanied with an increase of the deformation energy of a comparable amount. In the scission configurations of the best-fit-calculations, 30 MeV of the mutual Coulomb energy has already been converted into kinetic energy by an increase of the elongation. The deformation energy of these configurations would be increased by a comparable amount and the number of prompt neutrons would be increased by about 4, which would make the ν value much larger than the experimental value.

As the trajectories obtained in the best-fit calculations (not the starting point) are likely to be correct, the only conclusion that can be drawn is that the real scission point is at a point on the trajectory at an earlier time than those specified in the best-fit calculations--it must be early enough so that the fragments will not be stretched out too much and the ν value can be made as small as 2.4 for ^{235}U. At an earlier time the kinetic energies of all three particles are much smaller. In particular, the α-particle kinetic energy will be reduced greatly because the α particle gains energy rapidly in the beginning of the trajectory. The initial kinetic energy of the α particle of the scission point configurations given by the best-fit calculations is in the neighborhood of 3 MeV. A rough calculation shows that, to reduce the ν value to 2.4, the time must be so early that this energy is to be reduced by 75%. Such a reduction would bring the energy value to 0.7 MeV, which is very close to the value specified by the statistical theory, 0.5 MeV. This agreement is significant because this energy is a sensitive test of the fission theory--a small value favors the statistical theory and a large value favors a dynamical model with low or zero dissipation.[7] Therefore, far from contradicting the statistical theory, all the best-fit calculations actually support the statistical theory and oppose the nondissipative dynamical theory when we invoke the experimental value of ν to determine the otherwise indeterminate starting point of the trajectory. The discrepancy between the two kinds of trajectory calculations is thus resolved.

The fact that the initial conditions of the statistical theory explain correctly the experimental results of LRA fission does not by itself exclude the possibility of the dynamical theory's being able to explain the same results. However, with the constraint of the number of prompt neutrons, the only alternative available is a configuration in which the inter-fragment distance D is not much different from that of the statistical theory. In a nondissipative dynamical theory the fission fragments before scission are "cold" and the internal excitation energy of the statistical model, of the order of 10 MeV, will have to be shifted to the deformation energy to maintain the same ν value. This makes the configuration a little more elongated (D increased by about 1.5 fm), which in turn necessitates a shift of about 10 MeV from the Coulomb energy to the kinetic energy of the fragments at the scission point. Such a shift can be accomplished by allowing a short time of acceleration of the fragments before scission (the α particle will be accelerated at the same time to about 2 MeV). If such a shifted state is taken as the scission-point configuration, the trajectories would remain the same and the agreement with experimental results of the α particles can be maintained. However, in such a nondissipative dynamical theory with zero viscosity, the system is likely to develop undamped oscillation. The resulting mass distribution is unlikely to agree with the experimental results as discussed in an earlier paper,[10]--the mass-yield curve would have four peaks instead of two.

In a dissipative dynamical theory based on two-body viscosity developed by Davies, Sierk and Nix[11] the agreement with experimental fragment kinetic energy values is achieved by assuming a small viscosity which is far from sufficient to damp critically the quadrupole oscillation. Such a theory is likely to encounter the same difficulty of violating the experimental mass distribution as just discussed. On the other hand, in a dissipative dynamical theory based on one-body dissipation (collision of individual nucleons with the moving potential wall), the same agreement is achieved with a large dissipation.[12] While a large dissipation is required in a statistical theory, the scission point of a highly dissipative dynamical theory in general is different from that of the statistical theory. However, the two would be geometrically indistinguishable if the former should predict the kinetic energy and prompt neutron distributions K(A) and ν(A) as well as the latter does. Even that is no guarantee that the dissipative dynamical theory would correctly predict the mass distribution. On the other hand, if it should predict in addition the single-pair fragment kinetic energy distribution as well as the statistical theory does, then the two scission points would be dynamically indistinguishable. Then the two theories would be indistinguishable.

In comparing the dynamical theory with the statistical theory, notice must be taken to the fact that the statistical theory has not only explained the kinetic energy and prompt neutron distributions,[6] but also has explained the mass distribution (asymmetric fission[13]), charge distribution,[14] ternary fission,[15] and spontaneous fission distributions.[1] Past discrepancies of the statistical theory have been resolved,[16] and the Maruhn-Greiner theory[17] has been shown to be equivalent to the statistical theory.[18] Concerning the crucial, central issue of the fission problem, no dynamical theory has satisfactorily explained asymmetric fission and no dynamical theory is likely to be able to explain asymmetric fission.[11]

1. P. Fong, Phys. Rev. 102, 434 (1956); also Statistical Theory of Nuclear Fission, Gordon and Breach, New York (1969).
2. A typical example is R. W. Hasse, Nucl. Phys. A128, 609 (1969).
3. Y. Boneh, Z. Fraenkel and I. Nebenzahl, Phys. Rev. 156, 1305 (1967).
4. G. M. Raisbeck and T. D. Thomas, Phys. Rev. 172, 1272 (1968).
5. A. Katase, J. Phys. Soc. Japan 25, 933 (1968).
6. P. Fong, Phys. Rev. Lett. 11, 375 (1963).
7. P. Fong, Phys. Rev. C 2, 735 (1970).
8. C. Carles, M. Asghar, T. P. Doan, R. Chastel and C. Signarbieux, Physics and Chemistry of Fission, Proceedings of the Second Symposium, IAEA, Vienna, (1969), p. 119.
9. Y. Gazit, A. Katase, G. Ben-David, R. Moreh, Phys. Rev. C 4, 223 (1971).
10. P. Fong, Phys. Rev. C 13, 1259 (1976).
11. K. T. R. Davies, A. J. Sierk and J. R. Nix, Phys. Rev. C 13, 2385 (1976).
12. J. Blocki et al., Lawrence Berkeley Laboratory Report (unpublished).
13. P. Fong, Phys. Rev. C 10, 1122 (1974).
14. J. Wing and P. Fong, Phys. Rev. 157, 1038 (1967).
15. P. Fong, Phys. Rev. C 3, 2025 (1971).
16. P. Fong, Bull. Am. Phys. Soc. 19, 1112 (1974).
17. J. Maruhn and W. Greiner, Phys. Rev. Lett. 32, 548 (1974).
18. P. Fong, Phys. Rev. Lett. 34, 699 (1975).