Statistical Theory of Nuclear Fission and Prompt Neutron Distribution*

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It is shown that the statistical theory of nuclear fission is consistent with the recent experimental results of prompt neutron distribution in fission if we assume the existence of some constraint in the process of approaching equilibrium which controls the partition of excitation energy between the two fragments.

THE statistical theory of nuclear fission[1] has met one serious difficulty in explaining the recent experimental results of prompt neutron distribution.[2,3] The theory predicts that the most probable modes of fission (asymmetric fission) are associated with the emission of a large number of prompt neutrons. Furthermore, it predicts that the heavy fragment emits more neutrons than the light. However, the experimental results are that the average number of prompt neutrons is nearly the same for various modes of mass division. Furthermore, the average number of neutrons emitted by the light fragment $\bar{\nu}_L$ is nearly the same as that from the heavy fragment $\bar{\nu}_H$. The most startling discovery is that symmetric fission is actually asymmetric in a dynamical sense in view of the fact that one fragment emits many more neutrons than the other.

The purpose of this article is to show that the statistical theory is still consistent with these experimental results, if it is assumed that some constraint exists in the process of approaching equilibrium. The previous statistical theory was worked out without any constraint. The assumption of a slowly deforming liquid drop is actually a simplifying approximation. The experimental fact that symmetric fission is dynamically asymetric may be taken as evidence for the existence of a dynamical mechanism which may act as a constraint when the system approaches equilibrium. Without working out the details of this mechanism, we may take the experimental distribution of the number of prompt neutrons with respect to the fragment mass as the one required by the constraint, and thence proceed to deduce equilibrium condition under such a constraint. From the experimental values of ν_L and ν_H, we may deduce the excitation energies of the light and the heavy fragments, E_L and E_H. Use the level density formula,

$$W(E)=c\exp[2(aE)^{\frac{1}{2}}], \tag{1}$$

discussed in the previous work[1]; the relative probability for a mode of fission, according to the statistical principle, is given by

$$P\sim c_L\exp[2(a_LE_L)^{\frac{1}{2}}]c_H\exp[2(a_HE_H)^{\frac{1}{2}}]. \tag{2}$$

Equation (2) enables us to calculate the mass distribution curve which may be compared with experimental results.

For thermal neutron fission of U^{235}, we use the experimental values of ν_L and ν_H by Dozremin *et al.*[3] The ratio of ν_L and ν_H is assumed to be the ratio of E_L and E_H. As the experimental results are that $\nu_L+\nu_H$ is nearly constant with respect to the mass ratio, we assume that the total excitation energy E_L+E_H is a constant, the value of which is taken to be 27 Mev. E_L and E_H may now be calculated. The relative probabilities for various mass divisions are then calculated according to Eq. (2) and are plotted in Fig. 1 (a), where the radiochemical mass distribution curve is also given for comparison. For spontaneous fission of Cf^{252}, Whetstone's[2] experimental values of ν_L and ν_H are used. For simplicity, E_L and E_H are assumed to be the values of ν_L and ν_H multiplied by 8.5 Mev. The relative probabilities of various mass divisions are calculated and plotted in Fig. 1 (b), where the radiochemical mass distribution curve by Nervik[4] is also given for com-

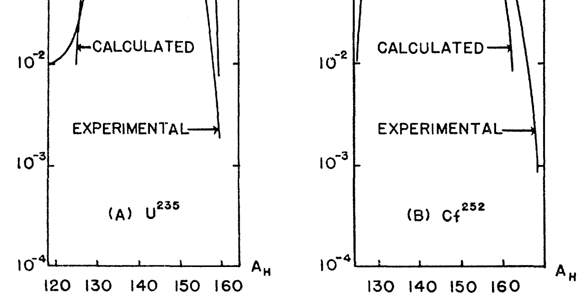

FIG. 1. Mass-distribution curves of thermal-neutron fission of U^{235} and spontaneous fission of Cf^{252}. The yields of the heavy fragments are plotted as a function of the mass number.

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[4] W. E. Nervik, University of California Radiation Laboratory Report UCRL-5584, February, 1960 (unpublished).

parison. Detailed agreement is not expected, considering the approximations involved in the calculation and the difference between the fission counting mass distribution curve and the radiochemical mass distribution curve. Nevertheless the pronounced asymmetric fission peak is unmistakable.

The experimental error of the neutron data used for calculation may change the shape of the calculated curve somewhat. However, the values of ν_L and ν_H of U^{235} are accurate to about $\pm 8\%$; the resulting change of the calculated probability is about a factor of 4 higher or lower. The difference of the calculated probability, by a factor of about 10^3 between symmetric and asymmetric fission, is thus beyond the experimental error of the data used. The values of ν_L and ν_H of Cf^{252} are accurate to about $\pm 5\%$; the range of variation of the calculated probability is even smaller. The accuracy of the values of a_L and a_H, which are based on fast neutron-capture cross sections of 42 nuclides, is already discussed at length in the previous paper.[1] It thus seems that the prompt neutron data do not contradict the statistical theory, although some mechanism will have to be assumed to play the part of providing the necessary constraint.

A comment is in order concerning the nature of the mechanism responsible for this peculiar distribution of prompt neutrons. The Whetstone neck[2] is a naive rendering of this mechanism in terms of the liquid-drop model. The appearance of such a neck is not called for by the simple liquid-drop model, and the energy of the neck seems to be too high in view of the usually small value of ν. It seems that the explanation of this distribution is not likely to be found in any simple model. Incidentally, it must not be forgotten that the interpretation of the experimental results is based on the isotropic emission of prompt neutrons in the fragment frame of reference, which may not be the case in view of the large deformation of the fission fragments.

Another comment may be made here concerning the variation of the total excitation energy with respect to the mass ratio of splitting. In the previous work,[1] the total excitation energy is found to be a maximum for the most probable mode of fission (asymmetric fission). It was calculated from the total energy release in fission (which is obtained by taking the mass difference) subtracted of the total kinetic energy of the fragments (which is assumed to be equal to the Coulomb energy of the two charged drops in contact). Later work,[5] with improved mass data, established that the total energy release has a maximum in the asymmetric fission region. On the other hand, recent experimental data[6] show that the kinetic energy of fragments is not exactly the same as the Coulomb energy of two charged drops. Therefore, it is not impossible that the excitation energy turns out to be nearly a constant, independent of the mass ratio of splitting as indicated by the experimental data of prompt-neutron distribution.

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[6] For example, W. E. Stein and S. L. Whetstone, Jr., Phys. Rev. **110**, 476 (1958).