Fission of cold and heated californium nuclei

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A comparison of the data on the fission probability in the reactions (n, f) and (I, xn) for the californium isotopes has established that strongly heated nuclei correspond to a liquid-drop-model fission barrier with approximate height 2 MeV, a height lower by a factor of more than 2.5 than the fission barrier for cold californium nuclei. This conclusion is supported by an analysis of a large aggregate of data on the Γ_f/Γ_n ratio.

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A study of the energy dependence of the fission probability of heavy nuclei entails considerable difficulties connected with the exclusion of the contribution of processes with prior emission of neutrons. The study is therefore limited to a comparison of the fission probability of cold nuclei—from data on the fissility at low excitations, $\sigma_f/\sigma_c \approx \Gamma_f/\Gamma_T$—and of sufficiently strongly heated nuclei—from the cross sections of the reaction of multiple emission of neutrons

$$\gamma_x^A = \left(\frac{\sigma_{xn}}{\sigma_c\, p_x}\right)_A = \prod_{i=0}^{x}\left(\frac{\Gamma_n}{\Gamma_T}\right)_{A-i} \approx \left\langle \frac{\Gamma_n}{\Gamma_T} \right\rangle_{\overline{A}_f}^{x} \tag{1}$$

where $\Gamma_f, \Gamma_n, \Gamma_T = \Gamma_f + \Gamma_n$ are the average fission, neutron, and total widths and cross sections for production of the compound nucleus, p_x is the probability of emission of x-neutrons, and A_f is the average mass number of the fissioning nuclei within the chain of the neutron decays.

However, it is precisely within this approach that one can solve one of the recently raised theoretical quaestions: what is the fission barrier of strongly heated nuclei[1]? It is expected that at sufficiently high excitation energies $E \gtrsim 50$ MeV the realignment of the shell structure of the nucleus is practically complete and its fission should follow the liquid-drop model. In other words, the fission probabilities of the cold and heated nuclei should correspond to different barrier heights:

$$E_f^{\text{cold}} = E_f^{\text{dm}} + \delta W_f - \delta W_g \quad \text{and} \quad E_f^{\text{hot}} \approx E_f^{\text{dm}}, \tag{2}$$

where E_f^{dm} is the fission barrier in the drop model, and δW_f and δW_g are the shell corrections in the transition and ground states of the fissioning nuclei ($\delta W_g < 0$ for most nuclei). The analysis of Γ_f/Γ_n of the pre-actinides in the vicinity of the doubly magic nucleus ^{208}Pb agrees with this prediction.[2] It is of interest to verify this prediction for heavy nuclei and to consider the entire aggregate of data.

In the transuranium region we have $E_f^{\text{cold}}(Z,A) \approx \text{const}(5.5\text{–}6\text{ MeV})$, whereas

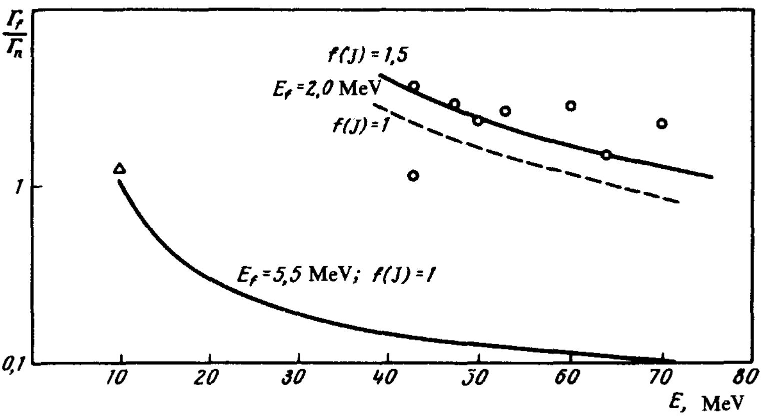

FIG. 1. Comparison of the experimental data on Γ_f/Γ_n for ^{250}Cf with the results of calculation from the Fermi-gas model: triangles—(n,f) reaction[3], circles—(I,xn) reaction.[4,5]

E_f^{dm} decreases rapidly with increasing Z, so that the most suitable for the investigation are the heaviest nuclei, in which the shell term $\delta W_g - \delta W_f$ constitutes an appreciable fraction of E_f^{cold}. In Fig. 1 are compared the ratios Γ_f/Γ_n for the cold ^{250}Cf nucleus, as obtained from the cross section for the fission of ^{249}Cf by neutrons of energy 2–4 MeV,[3] and for the neighboring isotopes $^{248-251}$Cf in a strongly heated state, obtained from the cross sections σ_{xn} $(x\geqslant 4)$ for the reactions $(^{12}\mathrm{C}, xn)$ with the nuclei $^{235-238}$U [4] and the reactions ^{238}U $(^{13}\mathrm{C}, xn)$.[5]

In the analysis of the probability of the (I, xn) processes we dispensed with the "geometric-mean method," which is widely used to determine Γ_f/Γ_n from $\langle\Gamma_f/\Gamma_n\rangle = (\gamma_x^A)^{1/x}$, since the data extracted in this manner correspond to two low values of $A_f = A-(x-1)/2$ and $E \approx (x+1)/2\times 8$ MeV at an appreciable scatter of these quantities, particularly the excitation energy E. More definite information on the energy dependence of Γ_f/Γ_n can be obtained by the "pair method" used by us, which consists of comparing the cross sections σ_{xn}^A and $\sigma_{(x-1)n}^{A-1}$. Since the residual nucleus after emission of one neutron in the first reaction and the nucleus produced in the second reaction coincide both in nucleon composition and in energy, the ratio $\gamma_x^A/\gamma_{x-1}^{A-1}$ according to (1) is equal to $(\Gamma_n/\Gamma_T)_A$ for the compound nucleus A with initial excitation E.

The curves of Fig. 2 were calculated from the Fermi-gas model[2]

$$\frac{\Gamma_f}{\Gamma_n} = f(J)\,\frac{\kappa a_n^{1/2}}{2A^{2/3}}\,\frac{E-B_n'}{(E-E_f')^{3/2}}\exp\left[2\sqrt{a_f(E-E_f')} - 2\sqrt{a_n(E-B_n')}\right] \quad (3)$$

with level-density parameters $a_f = a_n = A/10$ MeV^{-1} and $\kappa = 10$ MeV; E'_f and B'_n are the barrier height and the neutron binding energy, respectively, corrected for pairing. The discrepancy between the lower curve $E_f = E_f^{\mathrm{cold}} = 5.5$ MeV at high energies cannot be attributed to the influence of the angular momentum; the corresponding factor

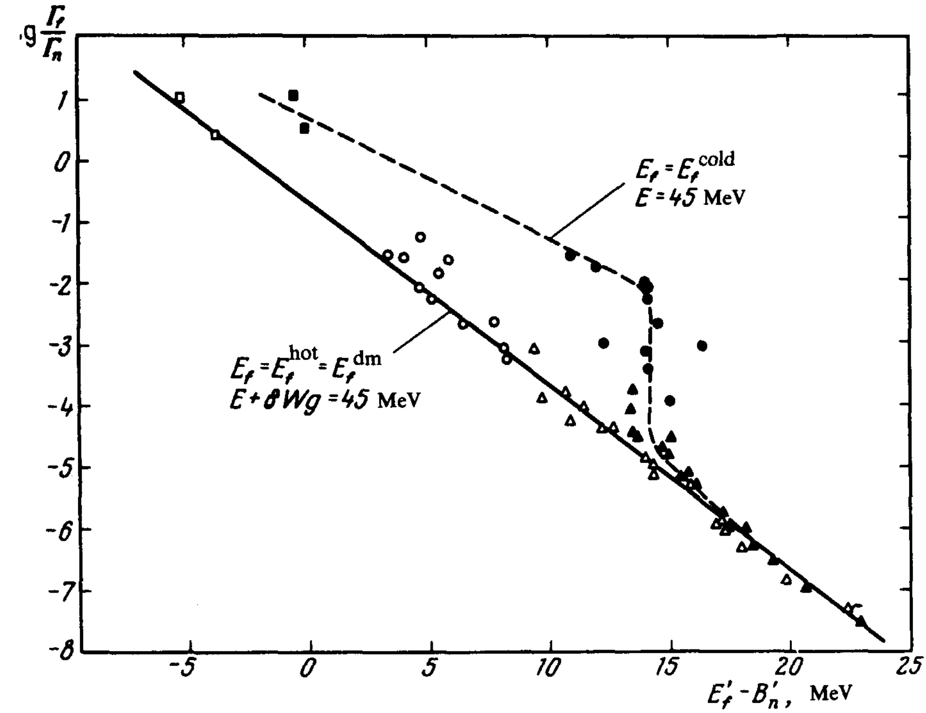

FIG. 2. Plot of $\log(\Gamma_f/\Gamma_n)$ against the difference $E'_f - B'_n$ under various assumptio concerning the value of E_f: dark symbols—$E_f = E_f^{\rm cold}$; light symbols—$E_f = E_f^{\rm hot} - E_f^{\rm dm}$. The different symbols distinguish between the values of Γ_f/Γ_n for t following characteristic nuclear regions: $Z = 98$–102—□, ■; $Z = 80$–85—○, $Z < 80$—△, ▲.

$f(J)$ is estimated on the average to be 1.5 for the reaction (^{12,13}C, xn). It was al established that it is impossible to satisfy the data on Γ_f/Γ_n simultaneously in the co and hot state if the parameters of the level density or of the barrier height are remain constant. Yet agreement with experiment on the high-energy section can l easily reached by choosing the value $E_f = E_f^{\rm dm} = 2$ MeV calculated from the liqui drop model with the Pauli-Ledergerber parameters.[6] To describe Γ_f/Γ_n at low ene gies it is necessary to use a more exact model for the density level, in which account taken of shell effects and of the residual interaction between the nucleons.

Figure 2 shows the data on Γ_f/Γ_n ($E = 45$ MeV) for a wide range of nucl $Z = 71$–102 [2,7] as functions of the difference $E'_f - B'_n$. From relation (3) we obta for these quantities at high excitations $E \gg E'_f - B'_n$ the simple connection[2]:

$$\lg \frac{\Gamma_f}{\Gamma_{n\,\rm cold}} \approx C_1 - C_2(E_f - B_n). \qquad (\cdot$$

The use of $E_f = E_f^{\rm cold}$ for the calculation of the abscissa on Fig. 2 leads to considerat deviations from (4), which are proportional to the contribution of the shell comp nent $\delta W_f - \delta W_g$ to E_f^{cold}. Replacement of E_f^{cold} by $E_f^{\text{hot}} = E_f^{\text{dm}}$ and a redefinition of the fixed excitation energy in accordance with the liquid-drop model[1,2] $E + \delta W_g = 45$ MeV eliminates these deviations to a considerable degree.

We have thus shown that the asymptotic value of the fission barrier, as predicted by the theory,[1] agrees with the liquid drop model.

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