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ON THE ROLE OF THE SECOND WELL OF THE DEFORMATION POTENTIAL ENERGY IN NUCLEAR FISSION IN THE LEAD REGION

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Introduction

The role of the second minimum of the deformation energy $V(\varepsilon)$ in heavy nuclei is known rather well - it is considered to be responsible for delayed fission, i. e. the spontaneously fissioning isomers /1,2/. Earlier /3/ it was shown that the minimum in $V(\varepsilon)$ does not disappear in the lighter nuclei (up to Pt) though in those nuclei it is displaced in deformation from $\varepsilon \cong 0.6$ to $\varepsilon \cong 0.4$ and the height of the outward potential barrier rapidly increases with decreasing Z-value. This circumstance sets the lower limit for the region where spontaneously fissioning isomers (U-Cm) are observed. Observation of transitions from the second well to the first one is also very difficult. So, it would be of interest to search for other manifestations of spontaneously fissioning isomers in preactinides, which may not be associated with decay from the second well.

In this context our attention has been attracted to the island of spherical nuclei lying in the vicinity of the doubly magic nucleus ^{208}Pb whose statistical properties look rather peculiar against the background of deformed nuclei because , in particular, of a considerable difference between the coefficients of the level density rotational enhancement /4,5/, i.e.

$$K_{rot} = \begin{cases} \sigma_{\perp}^2 \text{ for deformed nuclei} \\ 1 \text{ for spherical nuclei,} \end{cases} \qquad (1)$$

where $\sigma_{\perp}^2 = F_{\perp} \times T$ is the spin cut-off factor, which is larger than 10^2 for T=1 MeV; $F_{\perp}$ is the perpendicular moment of inertia and T is nuclear temperature. The "jump" of K_{rot} in eq.(1) in passing from one nucleus to another considerably affects the energy dependence of nuclear fissility, $P_f(E)$ (i.e. the ratio between the fission cross section and that for compound nucleus formation) in the preactinide region /5,6/.

The present paper deals with a study of the influence of the second well in $V(\xi)$ on $P_f(E)$. The effect is expected to be the most pronounced in spherical nuclei and manifests itself as follows. With increasing compound-nucleus excitation energy E , the level density in the second well , as a result of the difference between $\varepsilon_2 \cong 0.4$ and $\varepsilon_1 \cong 0$ leading to $K_{rot}^2 \gg K_{rot}^1$, can become equal to or even greater than that of the first well,despite the lower excitation energy $E - E_2$. Here subscripts 1 and 2 refer to the first and the second well, respectively. This fact should lead to an increase in the probability of neutron emission and to a decrease in nuclear fissility. The smaller the energy difference between the two minima , $E_2 = V(\varepsilon_2) - V(\varepsilon_1)$, the earlier the excitation energy effect manifests itself. The expected influence of the second well will be sharply decreased in the case of the nuclei deformed in the ground state because of a smaller difference between K_{rot}^1 and K_{rot}^2.

2. Attenuation of $K_{rot}(T,\varepsilon)$ and nuclear fissility

Our analysis of experimental information is based on the description of nuclear fissility /5,6/ :

$$P_f(E) = \frac{\hbar^2}{4\mu r_0^2 A^{2/3}} \times \gamma(\bar{J}) \times \frac{\int_0^{E-E_f} \rho_f(U,0)\, dU}{\int_0^{E-B_n} \rho_n(U,0)\,(E-B_n-U)\, dU}, \quad (2)$$

where $\rho_f(U,J)$ and $\rho_n(U,J)$ are ,respectively, the level densities of the fissioning nucleus at the saddle point and of the residual nucleus A-1 after emission of a neutron, as function of the excitation energy U and the angular momentum J; $\gamma(\bar{J})$ is the factor which takes into account the J dependence of $\rho_i(U,J)$ (i=f,n) , E_f is the barrier height and B_n is the neutron binding energy. In calculating $\rho_i(U,J)$ use was made of the superfluid model of the nucleus with the phenomenological inclusion of shell and collective effects. The model parameters were in agreement with the observed density of neutron resonances $\rho_{exp}(B_n,J)$ /5,7/. In what follows we will turn to the only but very essential specification which we are introducing in the conventional description of $\rho_i(U,J)$ and $P_f(E)$ /5-7/.

The adiabatic estimate $K_{rot}^{ad} = \sigma_{\perp}^2$ for deformed nuclei made in eq.(1) is valid when the single-particle modes of motion are assumed to be independent of rotation of the nucleus as a whole. This assumption is valid if the compound nucleus temperature T is below than

$$T_0 = \hbar\omega_0\varepsilon \cong 41A^{-1/3}\varepsilon \quad (3)$$

according to ref. /4/, where ε is quadrupole deformation, as before and $\omega_0 \cong 41A^{-1/3}\hbar^{-1}$ MeV is the average frequency of the anisotropic oscillator potential. The results of level density calculations /8/,in which the interactions between the rotational and internal degrees of freedom were taken into account, have confirmed the qualitative estimate (3) . In particular, they have shown that the attenuation factor which, as the nucleus gets heated, leads to a decrease in K_{rot} as compared to K_{rot}^{ad}, can be approximately described using the critical value T_0 of eq.(3).

The factor $K_{rot}(T,\varepsilon)$ can be presented in the following form

$$K_{rot} = (K_{rot}^{ad} - 1)q(\varkappa) + 1; \quad \varkappa = T/T_0 \cong 0.025A^{1/3}T/\varepsilon , \qquad (4)$$

where $q(\varkappa) \to 1$ for small $\varkappa$ values ($K_{rot} \to K_{rot}^{ad}$) and $q(\varkappa) \to 0$ for large $\varkappa$ ($K_{rot} \to 1$). A number of modifications of the analytical description of $q(\varkappa)$ is offered /8-10/. We have chosen the simplest one

$$q(\varkappa) = \exp(-\beta\varkappa^2) \quad , \qquad (5)$$

which coincides with $q(\varkappa)$ in ref. /9/ at $\beta = 1$. In what follows we employ the value $\beta = 1.37$ obtained by fitting the level density to $\rho_{exp}(B_n,J)$.

Thus, the attenuation of K_{rot} with energy depends substantially on nuclear deformation. This dependence is of major importance for nuclear fissility since for $E < 100$ MeV in question the deviation of K_{rot} from K_{rot}^{ad} in the neutron emission channel is considerable whereas it is negligibly small in the fission channel. These results contradict the previous assumptions /5,6/ concerning K_{rot}^{f} and K_{rot}^{n}.

3. Neutron emission by the nucleus in the second well

The top part of the figure shows the potential energies $V(\varepsilon)$ calculated using the shell correction method as in ref./3/. In the lower part of the figure the results of calculating the fissility parameter using the present model of $\rho(U,J)$ (the left hand scale) are compared with experimental data for the three typical preactinide nuclei - the spherical ^{212}Po, the

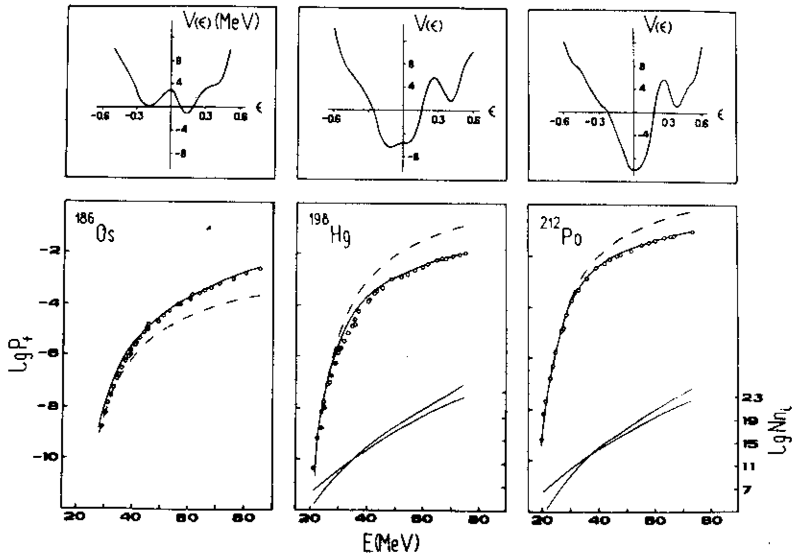

Figure. Top: the potential deformation energies $V(\varepsilon)$ of the ^{186}Os, ^{198}Hg and ^{212}Po nuclei. Bottom : the energy dependences of fissility $P_f(E)$ for the same nuclei (the upper curves) and the numbers of the residual nucleus final states accessible to neutron emission N_{n_i} for Hg and Po (the lower curves). The experimental data (open points) are taken from /5/, the calculations of $P_f(E)$ are carried out: (i) without taking into account the attenuation factor K_{rot} (dashed curve) ; (ii) taking into account the attenuation factor K_{rot} and neutron emission in the second well (full curve).

deformed ^{186}Os, and the ^{198}Hg nucleus considered to be an intermediate case in refs./5,6/. The $P_f(E)$ calculation was carried out using the barrier parameters from the phenomenological model /11/ and with equal asymptotic level density parameters in the fission and neutron emission channels, $\tilde{a}_f/\tilde{a}_n = 1$, in contrast to the conventional usage /5,6/, when E_f and $\tilde{a}_f/\tilde{a}_n$ values were considered to be free parameters in fitting the calculated results to the experimental data. Those parameters not specified are taken from refs. /5-7/. It should be noted that in the figure all the curves were calculated taking into account also fission processes preceded by the emission of several neutrons.

The dashed curves shown in the figure were calculated using eq.(1) and K_{rot}^{ad} based on the traditional classification of nuclei according to the nature of the spectra of low - lying levels (^{212}Po and ^{198}Hg are spherical nuclei, and ^{186}Os is a deformed one).The inclusion of the K_{rot} attenuation according to eqs.(4) - (5) eliminates the disagreement with the experimental data in the case of ^{186}Os, but does not change the situation for the other two nuclei since $K_{rot} = 1$ for spherical nuclei. The latter are characterized by a growing deviation of the dashed curves from the experimental points with increasing E, this deviation occurring somewhat earlier in ^{198}Hg than in ^{212}Po. In previous studies /5,6/ the discrepancies of results for ^{212}Po and adjacent nuclei were considered being due to the deviations of K_{rot} in the fission channel from the adiabatic estimate.These deviations define the attenuation factor as $q(E-E_f) = P_f^{exp}(E)/P_f(E)$, which was supposed to be valid also for describing the neutron emission channel.

The results of the calculations of fission probabilities for ^{212}Po and ^{198}Hg taking into account neutron emission by the nucleus in the second well ,which are shown by the full curves, to a considerable extent remove the disagreement. In these calculations the denominator of exp.(2),that is the number of the residual nucleus final states accessible to neutron emission for J = 0, which has the form

$$N_{n_i} = \frac{4\mu r_0^2 A^{2/3}}{\hbar^2} \times \int_0^{U^i_{max}} \rho_{n_i}(U,0)\ (U^i_{max}-U)\ dU \quad , \qquad (6)$$

is replaced by the sum $\sum_{i=1,2} N_{n_i}$,where i = 1 or 2 refers to the first or second well , $U^1_{max} = E - B_n$ and $U^2_{max} = E - B_n - E_2$.This generalization of exp.(2) is a direct consequence of the statistical description of the decay probability for excited nuclei in terms of the two-humped barrier /2/.The nuclear deformation ε_i was fixed in our calculation of N_{n_i} . It would be more logical to consider the effective deformation $\varepsilon_{eff}(T)$ which corresponds to the free energy minimum or to the entropy maximum. However, as refs. /9,10,13/ and our estimates show, this would not qualitatively change the results obtained.

The energy dependence of N_{n_i} (i=1,2) for spherical nuclei is given below the fissility parameter curves in the figure, the curve for N_{n_2} growing more rapidly. One can see that at some excitation energy there exists the intersection point,where $N_{n_1} = N_{n_2}$; as a result the nuclei in question happen to fission like spherical ones at low energies and like very deformed ones at high energies because of the predominance over fission of neutron emission by the nucleus in the second well. For the deformed ^{186}Os nucleus this is not important because it has no second well and, moreover, even if it had existed, its role would have been strongly suppressed since the difference between K^1_{rot} and K^2_{rot} is much smaller in the deformed nuclei in the ground state than in the spherical ones.

Conclusion

The inclusion of the dependence of K_{rot} on nuclear deformation and of neutron emission by the nucleus in the second well removes the difficulties and disadvantages of the previous analysis of the fissility of the preactinide nuclei /5,6/. We did not try to vary the parameters in order to better describe the experimental data. It may be worth doing so after including the dynamical effects /12/.

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