TEMPERATURE DEPENDENCE OF THE MASS PARAMETERS IN NUCLEAR FISSION

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The different mass parameters are studied in the frame of nuclear fission theory. The mass asymmetry and the separation between the two fragments are used as two collective coordinates in the asymmetric two-center shell model. The different mass parameters in the case of fission of the ^{238}U nucleus are calculated with a temperature dependence. The mass parameters are also studied in terms of the mass number changes for different nuclei. Analytical expression of the mass parameter are obtained using the cranking model. Numerical calculations are carried out for the mass parameters with different temperatures and for different nuclei. The obtained results show the importance of including the temperature and the effect of the mass numbers on the different mass parameters.

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1. Introduction

The development of the nuclear shell model, helps [1] much to understand different phenomena which are dominated by the single-particle degrees of freedom. The nuclear fission process is a continuous change of the nuclear shape from the original nucleus, *via* strongly deformed shapes, to the final state of the separated fragments. For each set of parameters, an associated single-particle Hamiltonian is deduced [1], [2] from the asymmetric two center shell model (ATCSM) which consists of two deformed harmonic-oscillator potentials joined smoothly at the neck together with some corrections. Renormalization is obtained by using the liquid drop formula and introducing [3] the modification of the surface asymmetry constant. The behaviour of the potential energy as a function of two parameters has been found [4] very interesting especially in mass asymmetry calculations. Calculations have been carried out for a full three-dimensional minimalization in the neck ε and the deformations β_1 and β_2 at each pair of the separation ΔZ between the two centers of the two fragments and the mass asymmetry η. The coordinate-dependent mass parameters of the kinetic energy operator in the fission processes and heavy ion collisions have been calculated [5] using the cranking formula in the two-center oscillator model. The mass parameters are found to change very rapidly, particularly when the two fragments have a large overlap. The mass asymmetry vibrations in the final stages of the fission process have been developed [6] by introducing a parametrized friction term and its effects in the calculations. In these calculations, the relative motion of the nascent fragments and its interactions with the mass asymmetry vibrations are taken into account. The mass transfer in heavy ion reactions have been studied [7] quantum mechanically within the fragmentation theory. The finite temperature is included in the cranking model to calculate [8] the exact mass parameter from the cranking formula. Calculations of the fission mass yields show that the investigation of the adiabatic cranking formula of the mass parameters introduces new features and requires a realistic two center potential to describe the fission process. So, the inclusion of a finite decay width is a first step to get reliable values for the finite temperatures or microscopic corrections.

In the present work, study of the different mass parameters $B_{\eta\eta}$, $B_{\varepsilon\varepsilon}$ and $B_{\eta\varepsilon}$ is introduced as a function of two collective coordinates being a mass asymmetry η and the separation ΔZ between the centers of the two fragments. Effects of including the temperature and the change of the mass number of the fissioning nucleus are considered. The cranking formula mass parameter is used in which the effect of the temperature and the finite decay width are included. The asymmetric two center shell model is introduced to deduce the theoretical expressions for the single particle wave function to be used in the mass parameters calculations. Numerical calculations are carried out to show the dependence of the different mass parameters $B_{\eta\eta}$, $B_{\varepsilon\varepsilon}$ and $B_{\eta\varepsilon}$ on the temperature and on different fissioning nuclei.

In Section 2, the cranking formula of the temperature dependent mass parameters is introduced. Numerical calculations and results are described in Section 3. Discussion and conclusions are given in Section 4.

2. The cranking model mass parameter

The cranking model mass parameters including the finite temperatures are given [9–12] by an expression

$$B_{ij} = 2h^2 \sum_{\mu>\nu} \frac{\langle\mu\left|\frac{\partial H}{\partial q_i}\right|\nu\rangle\langle\left|\frac{\partial H}{\partial q_j}\right|\mu\rangle}{(E_\mu - E_\nu)^3 + (E_\mu - E_\nu)\Gamma^2},$$

$$\left[\tanh\left(\frac{E_\mu - \lambda}{2KT}\right) - \tanh\left(\frac{E_\nu - \lambda}{2KT}\right)\right], \tag{1}$$

where Γ is the mean decay width and λ is the Fermi energy.

In the theory of fission the process is described by different five collective coordinates. These coordinates are the mass asymmetry η given by $\eta = (A_1 - A_2)/(A_1 + A_2)$, the separation ΔZ between the centers of the two fragments, the deformations of the two fragments β_1 and β_2, and finally the neck parameter ε. Also, in Eq. (1), the kets $|\mu\rangle$ and $|\nu\rangle$ are the single particle wave functions calculated [1] from the asymmetric two center shell model (ATCSM).

3. Numerical calculations and results

The cranking formula given by equation (1) is used to calculate the mass asymmetry parameter $B_{\eta\eta}$ as a function of all of the different collective coordinates. Numerical calculations are carried out for mass parameter $B_{\eta\eta}$ at different values of the temperature T to show the dependence of $B_{\eta\eta}$ on the temperature T. The results of the calculations of the mass asymmetry parameter $B_{\eta\eta}$ for the ^{238}U nucleus as a function of the mass asymmetry η for different values of the temperatures T are shown in Fig. 1.

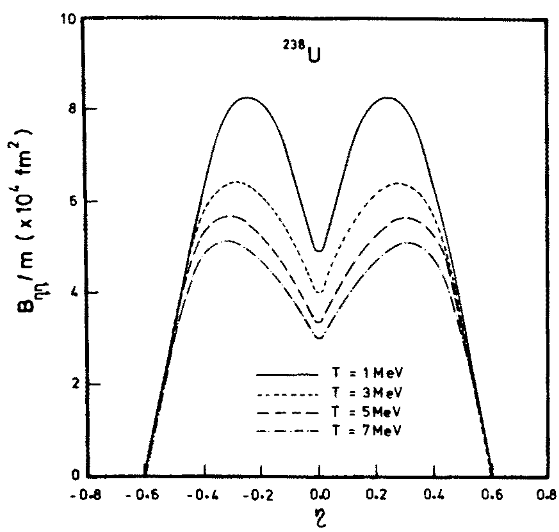

Fig. 1. The mass asymmetry parameter $B_{\eta\eta}$ as a function of the mass asymmetry η for different values of temperatures for the fission of the ^{238}U nucleus.

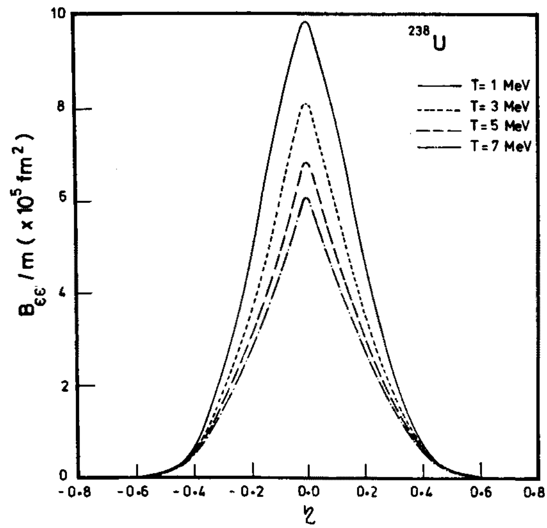

Fig. 2. The neck mass parameter $B_{\epsilon\epsilon}$ as a function of the mass asymmetry η for different values of temperatures for the fission of the ^{238}U nucleus.

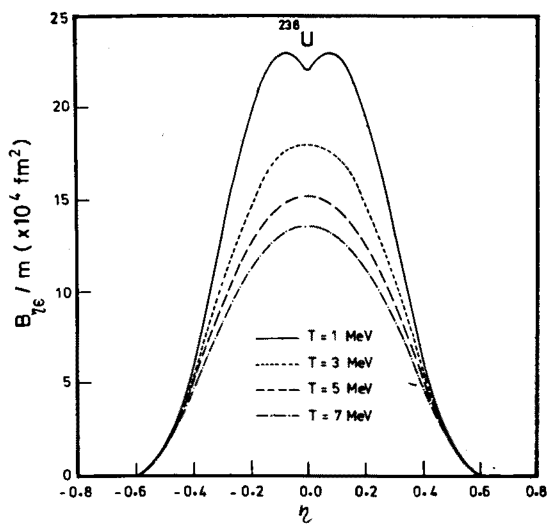

Fig. 3. The coupling mass parameter $B_{\eta\epsilon}$ as a function of the mass asymmetry η for different values of temperatures for the fission of the ^{238}U nucleus.

Figs 2 and 3 show similar calculations for the neck mass parameter $B_{\varepsilon\varepsilon}$ and for the mass asymmetry neck mixing mass parameter $B_{\eta\varepsilon}$, respectively. The changes of the mass asymmetry parameter on the separation ΔZ between the center of the two fragments are shown in Fig. 4 for different values of the temperature T.

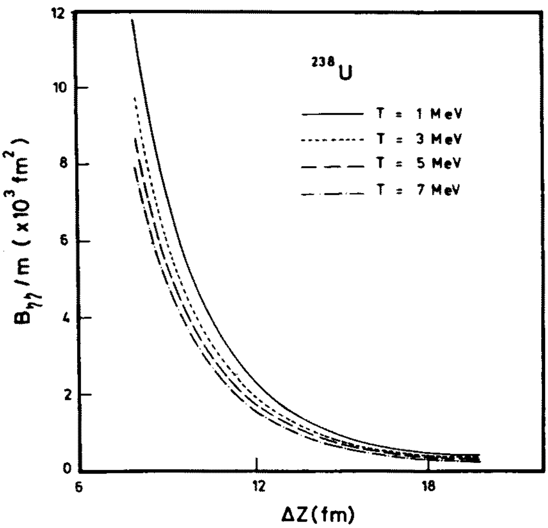

Fig. 4. The mass asymmetry parameter $B_{\eta\eta}$ as a function of the separation ΔZ for different values of temperatures for the fission of the ^{238}U nucleus.

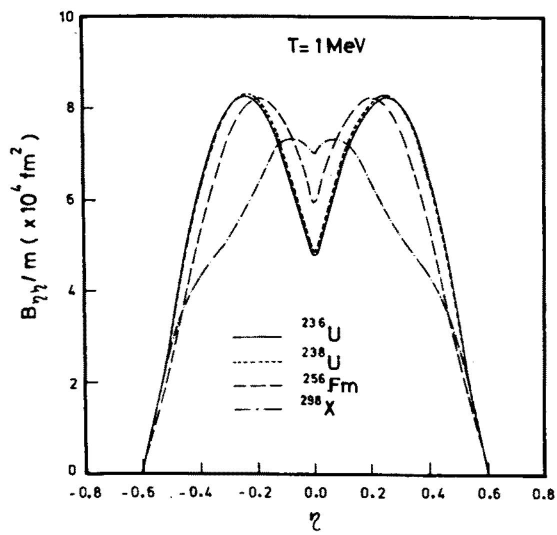

Fig. 5. The mass asymmetry parameter $B_{\eta\eta}$ as a function of the mass asymmetry η for different nuclei at the temperature of 1 MeV.

On the other hand, numerical calculations are performed to show the effect of changing the mass number of the fissioning nuclei in the fission process. Fig. 5 shows the dependence of $B_{\eta\eta}$ on η for the different fissioning nuclei ^{236}U, ^{238}U, ^{256}Fm and ^{298}X. Similar calculations are introduced in Fig. 6 for $B_{\epsilon\epsilon}$, while that for the mass asymmetry-neck mixing mass parameter as a function of the mass asymmetry η are shown in Fig. 7.

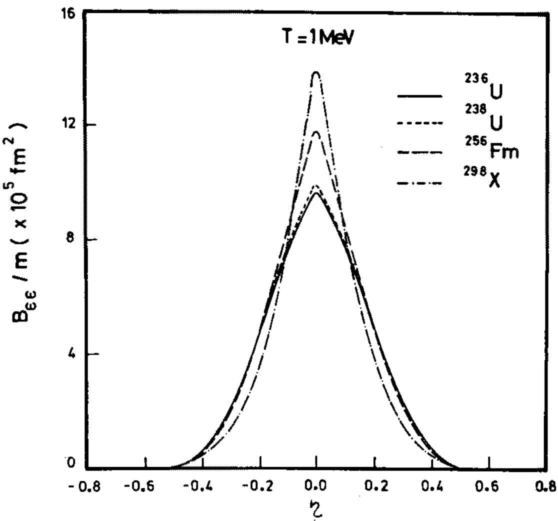

Fig. 6. The neck mass parameter $B_{\epsilon\epsilon}$ as a function of the mass asymmetry η for different nuclei at the temperature of 1 MeV.

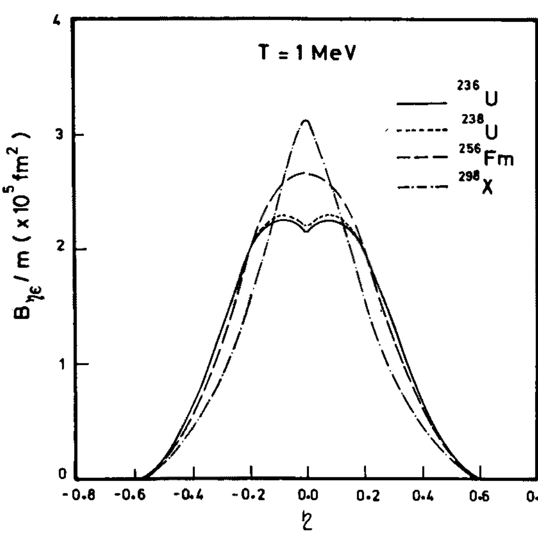

Fig. 7. The coupling mass parameter $B_{\eta\epsilon}$ as a function of the mass asymmetry η for different nuclei at the temperature of 1 MeV.

4. Discussion and conclusions

In the present work, the theory of nuclear fission is applied with calculations of the different mass parameters as a function of the two collective coordinates, the mass asymmetry η and the separation ΔZ between the centers of the two fragments. The curves presented in Fig. 1 give the mass asymmetry parameter $B_{\eta\eta}$ for ^{238}U nucleus as a function of the mass asymmetry for the value of $\Delta Z = 5$ fm which is corresponding to the minimized values of β_1, β_2 and ε with values equal to 0.75, 1.55 and 1.15, respectively. These calculations are carried out for different values of the temperature T. Each curve in Fig. 1 which corresponds to each value of the temperature is found to have two peaks which by increasing the value of the temperature, it is found that the values of the mass asymmetry parameter $B_{\eta\eta}$ decrease and the two peaks are flattened and shifted to the outside. Similarly, the same effect is found for the case of the neck mass parameter $B_{\eta\eta}$ as a function of the mass asymmetry η, where the values of $B_{\varepsilon\varepsilon}$ decrease by increasing temperature, but moreover as seen from Fig. 2 the relations are symmetric between $B_{\varepsilon\varepsilon}$ and η. Fig. 3 shows the calculations of the coupling mass parameter $B_{\eta\varepsilon}$ for different temperatures with two maxima asymmetric fission for a value of T=1 MeV but with increasing the temperature of values T=3, 5 and 7 MeV, the values of the coupling mass parameter decreases gradually and tend to the symmetric case. Then the mass asymmetry mass parameter is studied as a function of the separation ΔZ for different values of the temperature. Fig. 4 shows that for small separation values, the mass asymmetry mass parameter is very large and a clear decreasing occurs when the temperature rises from 1 MeV to 7 MeV. Also, at large values of the separations, the values of $B_{\eta\eta}$ decrease rapidly and become as temperature independent.

The different mass parameters $B_{\eta\eta}$, $B_{\varepsilon\varepsilon}$ and $B_{\eta\varepsilon}$ are calculated as a function of η for different nuclei with different mass numbers as ^{236}U, ^{238}U, ^{256}Fm and ^{298}X. The calculations of the mass asymmetry mass parameter $B_{\eta\eta}$ as shown in Fig. 5 have two maxima for the ^{236}U nucleus which, by increasing the mass number, are lowered and shifted towards the inside region and becomes approximately as one peak representing a symmetric case for the mass numbers greater than 298. Fig. 6 shows that the value of the neck mass parameter $B_{\varepsilon\varepsilon}$ increases by increasing the mass numbers of the fissioning nuclei. Calculations of the coupling mass parameter $B_{\eta\varepsilon}$ as a function of η show that the values of the two peaks increase by increasing the mass numbers and tend to the symmetric case for ^{298}X as indicated in Fig. 7.

Therefore, from the present study we can conclude that all of the mass parameters depend on the value of the temperature and all of them decrease by increasing temperatures. This effect is expected because the nucleons have more energy due to the raising of temperature which resist the translation between the two fragments due to the collision between the nucleons. Also, we see that, symmetric fission can be obtained from the heavy nuclei which have mass numbers greater than 298.

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