INFLUENCE OF NUCLEAR CURVATURE ON FISSION DYNAMICS* **

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(Received December 3, 2001)

The dynamical evolution of an excited, rotating and deformed nucleus is described by solving the Langevin equation in a one or multi-dimensional deformation space investigating in particular the fission channel in coincidence with the emission of light particles. The influence of curvature terms in the used mass formula on fission dynamics and multiplicities of emitted light particles is studied over a large range of nuclear masses.

PACS numbers: 24.60.Dr, 24.60.–k, 24.10.Lx, 24.75.+i

1. Introduction

The model which we developed deals with light particle evaporation (n, p, α) in conjunction with the fission process. In a first step [1,2] we restricted the description to highly excited nuclei where symmetric fission dominates. The dynamical evolution of the compound nucleus from its rather compact initial state to its elongated scission configuration is then described by a single collective coordinate q related to nuclear elongation and which is assumed to follow a stochastic equation of motion of the Langevin type:

* Presented at the XXVII Mazurian Lakes School of Physics, Krzyże, Poland, September 2–9, 2001.

** This work has been partly supported by the Polish State Committee for Scientific Research (KBN) under contract no. 2P03B 11519, by the Program of Scientific Exchange between the IN2P3, France and the Polish State Committee for Scientific Research (KBN) — no. 99-95, and by the POLONIUM agreement no. 01704UG

$$\begin{cases} \frac{dq}{dt} = \frac{p}{M(q)}\,, \\ \frac{dp}{dt} = \frac{1}{2}\left(\frac{p}{M(q)}\right)^2 \frac{dM(q)}{dq} - \frac{dV(q)}{dq} - \frac{\gamma(q)}{M(q)}p + F_{\mathrm{L}}(t)\,. \end{cases}$$

Taking at the same time particle evaporation into account, this dynamical equation is coupled to the equation governing particle emission in the framework of the Weisskopf evaporation theory [3]. Finally, our results are obtained by a weighting procedure with the fusion–fission cross section of the reaction. A detailed description of the model is given in Refs. [1,2].

Until now, we used a collective potential $V(q)$ obtained in the Myers–Świątecki Liquid Drop model (MS-LD) [4], which contains volume, surface and Coulomb terms. The Liquid Drop (LD) parameters of the MS-LD were determined by a fit to nuclear masses. But, as is well known, this parametrisation overestimates the fission barrier heights of light nuclei. The agreement between theory and experiment for prefission particle multiplicity was, however, rather satisfactory over a wide range of nuclear masses [2].

In the case of light nuclei, one can, however, expect a non negligible influence of nuclear curvature along the fission process. In order to investigate this effect, K. Pomorski and J. Dudek included first and second order curvature terms in the LD formula and, taking into account the most recent experimental data, proposed a new set of the LD parameters. This more elaborated version of the MS-LD model, which we will refer to the Lublin–Strasbourg Drop model (LSD), gives rise to a better reproduction of masses and barrier heights [5], which make us interested to investigate the influence on fission dynamics of the new curvature terms in the potential energy surface calculations.

2. Influence of nuclear curvature on emission probabilities

Let us consider the probability of emitting a given particle (n, p or α) from an excited and rotating nucleus, and discuss emission widths as a function of nuclear deformation with and without curvature terms in the LD parametrisation. In Fig. 1 we consider the nucleus ^{188}Pt at two different excitation energies. Obviously, the emission probability increases with elongation, which is quite logical since a larger deformation corresponds to a larger surface through which transmission can occur. More interesting is the fact that emission rates present a strong dependence on the new curvature terms in the framework of the Weisskopf evaporation theory. Actually, taking into account nuclear curvature leads to a slightly different level density parameter a which can be written in the following form:

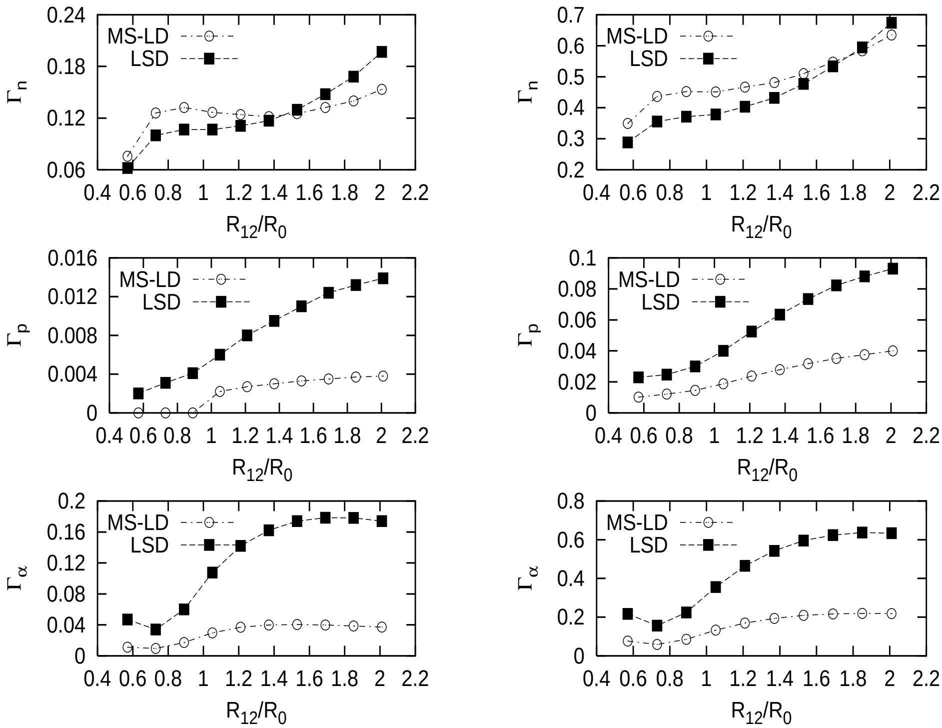

Fig. 1. Neutron, proton and α particle emission widths Γ_n, Γ_p, Γ_α as a function of nuclear elongation $q=R_{12}/R_0$ for the compound nucleus ^{188}Pt at an angular momentum $L=60\hbar$ and an excitation energy $E^*=60$ MeV (left side) and $E^*=100$ MeV (right side).

$$\begin{aligned} a(Z,N,q) \;=\; & a_v\left(1+\kappa_v I^2\right)A + a_s\left(1+\kappa_s I^2\right)A^{2/3}B_s(q) \\ & + a_{\rm cur}\left(1+\kappa_{\rm cur}I^2\right)A^{1/3}B_{\rm cur}(q) + a_{\rm curG}\left(1+\kappa_{\rm curG}I^2\right)A^0 \\ & + a_{\rm coul}Z^2A^{-1/3}B_{\rm coul}(q)\,. \end{aligned}$$

The values of the parameters defining a are summarised in Table I. Due to the exponential dependence of the total level density on the level density parameter a, even a small change on a caused by the inclusion of curvature terms can give rise to non negligible changes in the emission rates the Weisskopf evaporation model. So, including curvature terms leads to a higher width for charged particles, whereas, for neutrons, the details of this behaviour depend on the excitation energy and the considered nucleus.

TABLE I

Constants defining the level density parameter a for the new LSD model using the temperature dependence of LD parameters obtained by of Guet *et al.*, [6].

$10^3 a_v$	$10^3 a_s$	$10^3 a_{\rm cur}$	$10^3 a_{\rm curG}$	$10^3 a_{\rm coul}$	κ_v	κ_s	$\kappa_{\rm cur}$	$\kappa_{\rm curG}$
52.3	106.08	−44.63	−249.08	0.5468	0.6224	7.891	0.0	0.0

3. Influence of curvature on the fission barrier heights

The inclusion of curvature terms in the LD formula leads to a decrease of the fission barrier height, what implies a decrease of the critical angular momentum of the system for which the barrier disappears. In Fig. 2 we present the deformation energy up to the scission configuration for the nucleus ^{188}Pt at an excitation energy $E^* = 100$ MeV. A barrier height of the order of 0.4 MeV is obtained for an angular momentum $L = 68\hbar$ in the MS-LD model, whereas the same barrier height is obtained already at $L = 58\hbar$ in the LSD parametrisation. Nevertheless, one notices that taking nuclear curvature into account practically does not change the slope of the fission barrier.

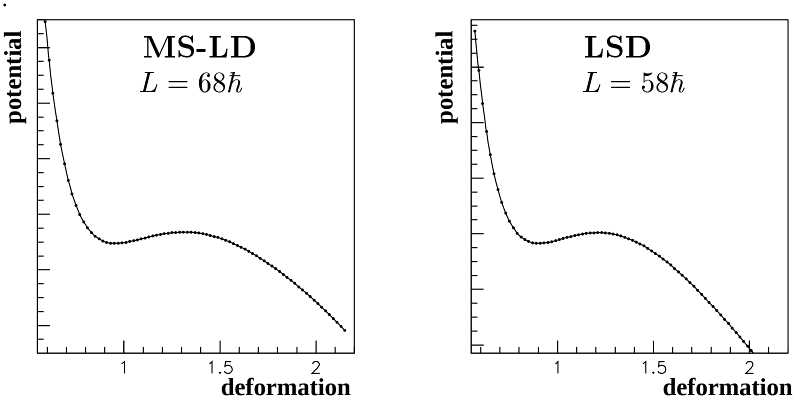

Fig. 2. Mean symmetric fission path for the compound nucleus ^{188}Pt at an excitation energy $E^* = 100$ MeV and a fission barrier height $U_{\rm B} \approx 0.4$ MeV.

4. Influence of curvature on prefission particle multiplicities

Let us first consider different entrance channels producing the compound nucleus ^{188}Pt. In Table II we summarise the neutron, proton and α particle prefission multiplicities obtained using the two LD parametrisations in comparison with the available experimental data.

TABLE II

Light particle prefission multiplicities for different reactions leading to the compound nucleus ^{188}Pt.

	MS-LD	LSD	exp.
$^{34}\mathrm{S} + ^{154}\mathrm{Sm} \longrightarrow ^{188}\mathrm{Pt}$ $E^* = 66.5$ MeV			
M_n	1.75	2.29	2.50 ± 0.7
M_p	0.00	0.00	–
M_α	0.00	0.07	–
$^{16}\mathrm{O} + ^{172}\mathrm{Yb} \longrightarrow ^{188}\mathrm{Pt}$ $E^* = 99.7$ MeV			
M_n	4.65	4.52	5.4 ± 0.7
M_p	0.01	0.05	–
M_α	0.03	0.32	–
$^{34}\mathrm{S} + ^{154}\mathrm{Sm} \longrightarrow ^{188}\mathrm{Pt}$ $E^* = 100.0$ MeV			
M_n	4.48	4.44	4.5 ± 0.7
M_p	0.01	0.05	–
M_α	0.05	0.34	–

Because of larger charged particle emission widths in the model containing curvature terms, the corresponding prefission multiplicities are also larger for the LSD parametrisation. Moreover, the decrease of the angular momenta under consideration using the LSD model leads to different centrifugal forces what can also have a substantial effect on particle emission. In the case of neutrons, one notices a smaller effect of curvature terms at higher than at lower energy. As seen in Fig. 1, neutron emission rates are smaller at $E^* = 100$ MeV with curvature terms than without and this almost whatever the deformation. On the other hand, considering the mean fission path shown in Fig. 2, we can see that its length Δq from ground state to the scission point is a little longer ($\Delta q = 1.24$) in the LSD than in the MS-LD ($\Delta q = 1.20$) model which implies a larger fission time and, consequently, more time for emitting particles. The larger emission probability in the MS-LD picture but the shorter fission time seem to compensate, so that one finally obtains about the same number of emitted neutrons. At lower excitation energy, it looks like if curvature terms favour neutron emission. In fact, comparing neutron emission widths around this energy (Fig. 1), we notice that they are larger in the MS-LD model for smaller deformations and larger in the LSD one for more deformed shapes. Consequently, due to this emission at large elongation, one expects a larger neutron prefission multiplicity in the LSD parametrisation. In any case, the theoretical results for neutrons are in quite reasonable agreement with the experimental data:

the influence of curvature terms seems to be small. The same investigation was done for the compound nucleus ^{160}Yb and similar conclusions can be drawn.

Let us now consider the lighter compound nucleus ^{126}Ba: theoretical and experimental neutron results are summarised in Table III for different entrance channels. One observes a larger difference in the predictions of the two models (as compared with heavier nuclei) and a better agreement with experiment with the LSD parametrisation. As lighter nuclei can exhibit along their path to fission more elongated and neck-in shapes, such a behaviour is not really astonishing.

TABLE III

Neutron prefission multiplicities for different reactions leading to the compound nucleus ^{126}Ba.

	E^* (MeV)	MS-LD	LSD	exp.
$^{28}\mathrm{Si} + ^{98}\mathrm{Mo} \longrightarrow ^{126}\mathrm{Ba}$	131.7	1.50	2.48	2.52 ± 0.12
$^{28}\mathrm{Si} + ^{98}\mathrm{Mo} \longrightarrow ^{126}\mathrm{Ba}$	118.5	1.32	2.02	2.01 ± 0.13
$^{28}\mathrm{Si} + ^{98}\mathrm{Mo} \longrightarrow ^{126}\mathrm{Ba}$	101.4	0.38	1.36	1.32 ± 0.09
$^{19}\mathrm{F} + ^{107}\mathrm{Ag} \longrightarrow ^{126}\mathrm{Ba}$	118.5	1.32	2.08	1.85 ± 0.11
$^{19}\mathrm{F} + ^{107}\mathrm{Ag} \longrightarrow ^{126}\mathrm{Ba}$	101.5	1.00	1.23	1.31 ± 0.17

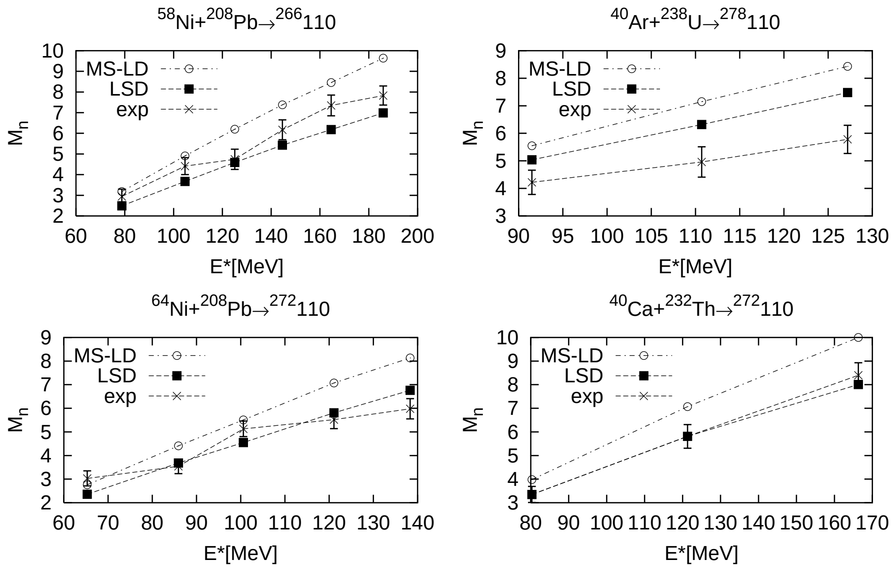

Fig. 3. Neutron prefission multiplicity as a function of excitation energy of the system for several isotopes of the element $Z = 110$.

Finally, we studied the case of some super heavy elements. In Fig. 3 we present experimental and theoretical neutron prefission multiplicities for different isotopes of the element $Z=110$. One can conclude for these nuclei on the rather small influence of nuclear curvature, which could have been expected keeping in mind that heavy nuclei fission at rather compact deformations.

5. Conclusion

Including curvature in the LD model leads to a better reproduction of nuclear masses and fission barrier heights. Our study showed the rather small influence of curvature terms on fission barrier slopes and neutron prefission multiplicities in the case of heavy and super heavy nuclei, justifying, *a posteriori*, our predictions on prefission multiplicities evaluated using the MS-LD model. We, however, also showed that nuclear curvature can play an important role in lighter nuclei which improves our theoretical description of fission dynamics including light particle emission. One important result of our study consists in the strong dependence on curvature terms of emission widths for charged particles. Unfortunatly, very few experimental data are presently available for charged particle multiplicities. As these measurements seem to constitute a very severe test of our structure-dynamics-evaporation model, we would like to strongly encourage our friends experimentalists to investigate the emission of charged particles in coincidence with the fission process.

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