MULTIDIMENSIONAL SKYRME-DENSITY-FUNCTIONAL STUDY OF THE SPONTANEOUS FISSION OF ^{238}U*

J. Sadhukhan[a,b,c], K. Mazurek[a,b,d], J. Dobaczewski[a,e,f]
W. Nazarewicz[b,e,g], J.A. Sheikh[a,b], A. Baran[h]

[a]Department of Physics and Astronomy, University of Tennessee
Knoxville, Tennessee 37996, USA
[b]Physics Division, Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, Tennessee 37831, USA
[c]Physics Group, Variable Energy Cyclotron Centre
1/AF Bidhan Nagar, Kolkata 700064, India
[d]The Henryk Niewodniczański Institute of Nuclear Physics, PAN
Radzikowskiego 152, 31-342 Kraków, Poland
[e]Institute of Theoretical Physics, Faculty of Physics, University of Warsaw
Pasteura 5, 02-093 Warszawa, Poland
[f]Department of Physics, University of Jyväskylä
P.O. Box 35 (YFL), 40014 University of Jyväskylä, Finland
[g]Department of Physics and Astronomy and NSCL/FRIB Laboratory
Michigan State University, East Lansing, Michigan 48824, USA
[h]Institute of Physics, University of M. Curie-Skłodowska
Radziszewskiego 10, 20-031 Lublin, Poland

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We determined the spontaneous fission lifetime of ^{238}U by a minimization of the action integral in a three-dimensional space of collective variables. Apart from the mass-distribution multipole moments Q_{20} (elongation) and Q_{30} (left–right asymmetry), we also considered the pairing-fluctuation parameter λ_2 as a collective coordinate. The collective potential was obtained self-consistently using the Skyrme energy density functional SkM*. The inertia tensor was obtained within the nonperturbative cranking approximation to the adiabatic time-dependent Hartree–Fock–Bogoliubov approach. The pairing-fluctuation parameter λ_2 allowed us to control the pairing gap along the fission path, which significantly changed the spontaneous fission lifetime.

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This study of spontaneous-fission lifetimes is based on the energy-density-functional (EDF) theory and relies on the collective potential and inertia determined within the adiabatic time-dependent Hartree–Fock–Bogoliubov (ATDHFB) approach. In practical calculations, we use the Skyrme EDF parametrization SkM* [1] and density-dependent pairing. The methodology adopted in this work strictly follows Refs. [2–4].

The ATDHFB inertia is calculated as

$$\mathcal{M}_{ij}^{C} = \frac{1}{2\dot{q}_i\dot{q}_j}\sum_{\alpha\beta}\frac{\left(F_{\alpha\beta}^{i*}F_{\alpha\beta}^{j} + F_{\alpha\beta}^{i}F_{\alpha\beta}^{j*}\right)}{E_\alpha + E_\beta}\,, \tag{1}$$

where $\dot{q}_i$ and $\dot{q}_j$ represent time derivatives of the collective coordinates. The sum is evaluated over all quasiparticle states and E_α denotes the quasiparticle energy. Matrices F^i are obtained from

$$-F^{i*} = \left(B^T\frac{\partial\rho}{\partial q_i}A + B^T\frac{\partial\kappa}{\partial q_i}B - A^T\frac{\partial\kappa^*}{\partial q_i}A - A^T\frac{\partial\rho^*}{\partial q_i}B\right)\dot{q}_i\,, \tag{2}$$

where A and B are the Hartree–Fock–Bogoliubov (HFB) matrices, obtained self-consistently from the constrained HFB equations. The particle and pairing densities, ρ and κ respectively, are determined uniquely from A and B.

The total Routhian is

$$H'_{\rm HFB} = \hat{H}_{\rm HFB} - \sum_{l=2,3} q_l\hat{Q}_{l0} - \sum_{\tau=p,n}\left(\lambda_\tau\hat{N}_\tau - \lambda_{2\tau}\left(\hat{N}_\tau^2 - \langle N_\tau^2\rangle\right)\right)\,, \tag{3}$$

where $\hat{H}_{\rm HFB}$ is the HFB Hamiltonian, $\hat{Q}_{20}$ and $\hat{Q}_{30}$ are quadrupole and octupole moments, respectively, and $\hat{N}_\tau$ is particle-number operator. The terms associated with $\lambda_{2\tau}$ modify the pairing correlations of the system [2, 5] that can be assessed through the average pairing gaps

$$\varDelta_\tau = \frac{{\rm Tr}'\,\hat{\varDelta}^\tau\rho_\tau}{{\rm Tr}\,\rho_\tau}\,, \tag{4}$$

where $\hat{\varDelta}^\tau$ is the pairing field and ${\rm Tr}'\,A = \sum_n A_{n\bar{n}}$, with bar over n indicating the time-reversed state.

Calculations presented in this work were performed in a three-dimensional (3D) collective space, where moments Q_{20} and Q_{30} control axial nuclear shapes and $\lambda_2 = \lambda_{2p} = \lambda_{2n}$ allows for simultaneously changing proton and neutron pairing correlations. An early discussion of the effect of pairing fluctuations on fission dynamics was presented, for example, in Refs. [6, 7]

(see Ref. [2] for a comprehensive list of references). Although the potential energy V increases as the pairing gap deviates from the HFB value, the collective inertia behaves as $\sim 1/\Delta^2$ and, therefore, the minimum-action path favors stronger pairing correlations [2].

In this contribution, we carry out a comparative study of ^{238}U, assuming axial geometry. The role and importance of other degrees of freedom, such as triaxiality [2], will be discussed elsewhere.

Potential energy surfaces shown in Fig. 1 allow us to study competition between the deformation and pairing effects. It turns out that the pairing

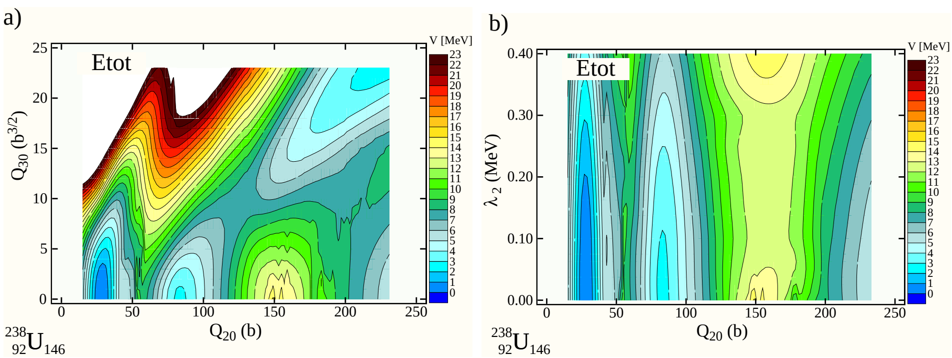

Fig. 1. Potential energy surfaces of ^{238}U in the (Q_{20}–Q_{30}) plane for $\lambda_2 = 0.0$ (left) and in the (Q_{20}–λ_2) plane for $Q_{30} = 0.0$ (right).

fluctuations are more important around the first saddle than in the ground-state energy minimum. As it is shown in Fig. 2, with increasing pairing, the potential energy increases, whereas the mass tensor, in general, decreases. Such a competition significantly affects the fission lifetimes. For example, our 2D calculations (along the $\lambda_2 = 0$ path) yield $T_{\rm SF} = 2.34 \times 10^{21}$ y, while the 3D calculations including pairing predict $T_{\rm SF} = 3.63 \times 10^{17}$ y, which is closer to the experimental value of 8.2×10^{15} y. This is consistent with findings of recent Refs. [8, 9] based on Gogny–EDF framework.

In summary, we performed a preliminary axial-symmetry study of spontaneous fission of ^{238}U, in which pairing fluctuations were treated dynamically by minimizing the collective action. Using the microscopic input based on the ATDHFB approach, we obtained a fair agreement with experiment.

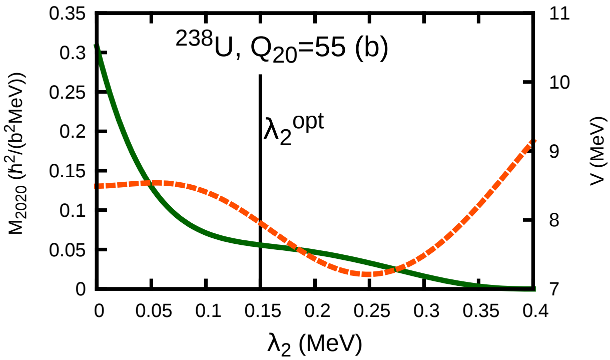

Fig. 2. The quadrupole diagonal inertia (solid line) and potential energy (dashed line) as functions of the pairing-fluctuation parameter λ_2. The multipole moments ($Q_{20} = 55$ b and $Q_{30} = 0$) correspond to the fission barrier. The vertical line marks the value of $\lambda_2^{\rm opt}$ that corresponds to the calculated dynamical fission path.

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