

Microscopic description of the competition between spontaneous fission and α -decay in neutron-rich Ra, U and Pu nuclei

R Rodríguez-Guzmán¹ and L M Robledo²

¹ Physics Department, Kuwait University, Kuwait 13060, Kuwait

² Departamento de Física Teórica, Universidad Autónoma de Madrid, 28049-Madrid, Spain

E-mail: raynerrobertorodriguez@gmail.com

Abstract. Constrained mean-field calculations, based on the Gogny-D1M energy density functional, have been carried out to describe fission in Ra, U and Pu nuclei with neutron number $144 \leq N \leq 176$. Fission paths, collective masses and zero-point quantum vibrational and rotational corrections are used to compute the spontaneous fission half-lives. We also pay attention to isomeric states along the considered fission paths. Alpha decay half-lives have also been computed using a parametrization of the Viola-Seaborg formula. Though there exists a strong variance of the predicted fission rates with respect to the details involved in their computation a robust trend is obtained indicating, that with increasing neutron number fission dominates over α -decay. Our results also suggest that a dynamical treatment of pairing correlations is required within the microscopic studies of the fission process in heavy nuclear systems.

1. Introduction

Fission is a large amplitude collective motion the theoretical description of which, still remains a challenge in modern nuclear structure physics with a major impact on several basic research and technological areas [1,2]. A detailed knowledge of fission in heavy and superheavy nuclei is required, to better understand the very limits of the nuclear stability. The fission properties of neutron-rich nuclei are relevant in the nucleosynthesis and abundances of elements with mass number $A > 120$ due to the fission recycling in the r-process [3]. Furthermore, microscopic studies of the fission paths and related properties are very useful to deepen our knowledge of the different decay channels (fission, α -decay, ...) in heavy nuclear systems. In this contribution, we report on our results regarding the competition between spontaneous fission and α -decay in neutron-rich Ra, U and Pu nuclei [4–6].

In this section, we briefly outline the theoretical framework used in our calculations [4–6]. We have resorted to the Hartree-Fock-Bogoliubov (HFB) approximation [7] based on the parametrization D1M [8] of the Gogny [9] energy density functional (EDF). We have used as constraining operators the axially symmetric quadrupole $\hat{Q}_{20}$ and octupole $\hat{Q}_{30}$ operators as well as the necking $\hat{Q}_{Neck}(z_0, C_0)$ operator to reach two-fragment (2F) solutions starting from the one-fragment (1F) ones. Aside from the constraints already mentioned, as well as the usual HFB ones on both the proton and neutron numbers, a constraint on the operator $\hat{Q}_{10}$ is used to prevent spurious center of mass effects. The HFB quasiparticle operators [7] have been



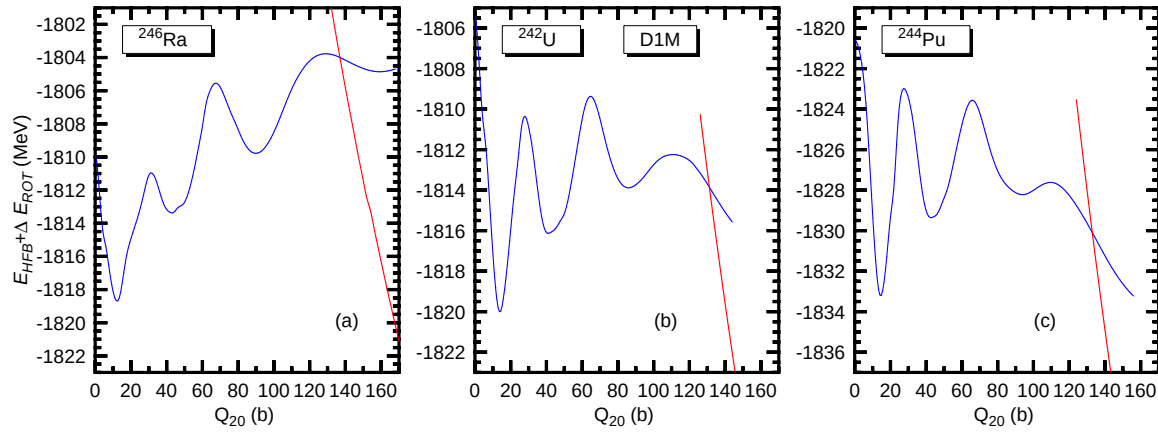


Figure 1. (Color online) The HFB plus the zero point rotational energies obtained with the Gogny-D1M EDF are plotted in panels (a), (b) and (c) as functions of the quadrupole moment Q_{20} for the nuclei ^{246}Ra , ^{242}U and ^{244}Pu . Both the 1F (blue) and 2F (red) solutions are included in the plot. For more details, see the main text.

expanded in an axially symmetric (deformed) harmonic oscillator (HO) basis containing states with J_z quantum numbers up to 31/2 and up to 26 quanta in the z direction. The lengths of the HO basis have been optimized so as to minimize the total HFB energy. For the solution of the HFB equations, an approximate second order gradient method [10] has been used.

We have computed the spontaneous fission half-life t_{SF} within the WKB formalism

$$t_{SF} = 2.86 \times 10^{-21} \times (1 + e^{2S}) \quad (1)$$

where the action S along the (one-dimensional projected) quadrupole constrained fission path reads

$$S = \int_a^b dQ_{20} \sqrt{2B(Q_{20}) (V(Q_{20}) - (E_{GS} + E_0))} \quad (2)$$

with integration limits a and b corresponding to the classical turning points for the energy $E_{GS} + E_0$. The potential $V(Q_{20})$ is given by the HFB energy corrected by the rotational $\Delta E_{ROT}(Q_{20})$ and vibrational $\Delta E_{vib}(Q_{20})$ energies. The collective masses $B(Q_{20})$ have been computed using both the Generator Coordinate Method (GCM) and the Adiabatic Time-Dependent HFB (ATDHFB) schemes. For the parameter E_0 we have assumed a typical value of 1.0 MeV. In our calculations, we take the 2F curves as intersecting the 1F ones [4–6]. We have computed the α -decay half-lives using a recent parametrization

$$\log_{10} t_{\alpha} = \frac{AZ + B}{\sqrt{Q_{\alpha}}} + CZ + D \quad (3)$$

of the Viola-Seaborg formula [4, 11].

2. Results

We have computed the fission paths (i.e., the 1F and 2F curves) for Ra, U and Pu nuclei with the neutron numbers $144 \leq N \leq 176$. A typical outcome of our calculations is shown in figure 1

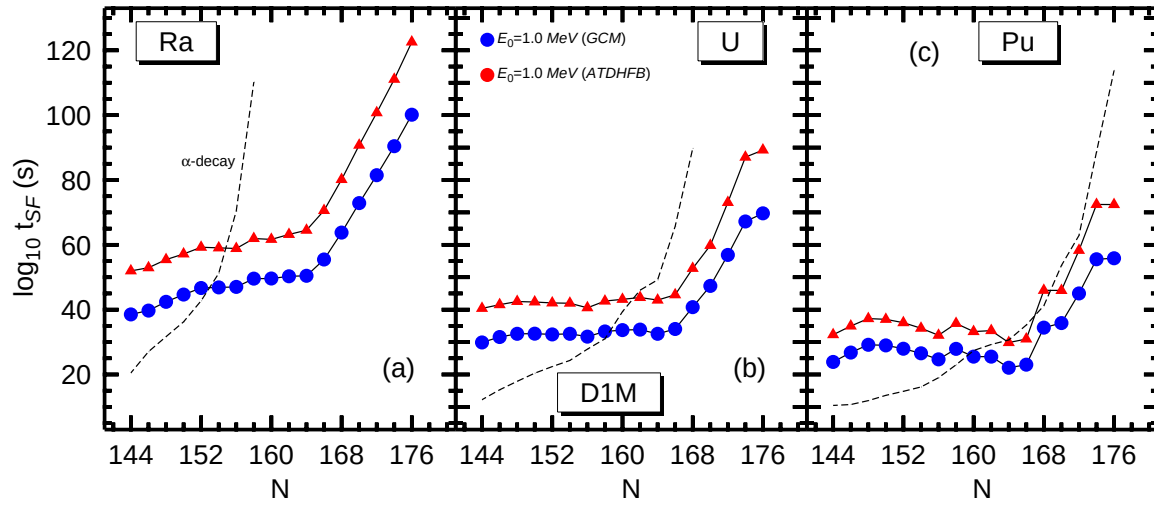


Figure 2. (Color online) The spontaneous fission half-lives t_{SF} , predicted within the GCM and ATDHFB schemes, for the considered Ra, U and Pu nuclei, are depicted as functions of the neutron number in panels (a), (b) and (c). Results have The α -decay half-lives are plotted with dashed lines. For more details, see the main text.

where the HFB plus the zero point rotational energies are plotted, as functions of the quadrupole moment, for ^{246}Ra , ^{242}U and ^{244}Pu , taken as illustrative examples. A similar analysis has been carried out for all the other studied nuclei. The zero-point vibrational energies $\Delta E_{vib}(Q_{20})$ are not included in figure 1, as they are rather constant as functions of Q_{20} . As can be seen, the ground state is located around $Q_{20} = 12b$ while the first fission isomer appears around $Q_{20} = 42b$ with an excitation energy of 2.33, 3.91 and 3.83 MeV in ^{246}Ra , ^{242}U and ^{244}Pu . This first fission isomer, is separated from the ground state by an inner barrier, the top of which is located around $Q_{20} = 30b$. The height of the inner barrier amounts to 7.70, 9.66 and 10.16 MeV, respectively. Note, that a reduction of the inner barrier heights, typically by a few MeV, takes place once triaxial degrees of freedom are taken into account. However, such a reduction comes together with an increase of the collective inertia and, as a result, its influence on the predicted t_{SF} values equation (1) is quite limited (see, [4] and references therein). From figure 1, we observe the second and third fission barriers as well as a (parity-breaking) second fission isomer ($Q_{20} \approx 90 - 94b$) in between them with excitation energy of 8.92, 6.13 and 4.95 MeV for ^{246}Ra , ^{242}U and ^{244}Pu . Octupole correlations (i.e. $Q_{30} \neq 0$ values) start to play a role for $Q_{20} \geq 60b$ leading to a reduction of the outer barriers as compared with a reflection-symmetric situation. For the three isotopic chains, well defined second fission isomers appear along the 1F paths for the mass numbers $240 \leq A \leq 254$ showing that the shell effects leading to such isomers are systematically present in our calculations. Some additional shallow minima are also found along the 1F paths for heavier nuclei [4–6]. A change in tendency is observed in the 1F fission paths of the studied Ra, U and Pu nuclei around the neutron number $N=164$ followed, by a steady increase in the height of the inner and second barriers as well as in the excitation energies of the second fission isomers. From the increase in the height of the inner barriers and the widening of the 1F curves one could expect, as it is shown to be the case below, larger spontaneous fission half-lives as we move towards more neutron-rich regions.

The spontaneous fission half-lives are plotted in figure 2 as functions of the neutron number for the studied Ra, U and Pu nuclei. As can be seen, the ATDHFB t_{SF} values are always larger than the GCM ones [4–6]. For example, for ^{242}U they are $\log_{10} t_{SF} = 42.36$ s and 32.58 s, respectively. Increasing the parameter E_0 [see, equation (2)] leads to a reduction of t_{SF} however, the

trend observed in the figure remains the same. This is also true if, instead of the parametrization D1M, we resort to any other of the most recent parametrizations (i.e., D1S and/or D1N) of the Gogny-EDF [4]. For the Ra, U and Pu isotopes with $N \geq 166$ one observes a steady increase in the spontaneous fission half-lives. This behavior agrees well with the change in tendency observed in the corresponding 1F paths and makes the heavier neutron-rich isotopes stable against fission, diminishing the importance of fission recycling in the r-process. In figure 2, we have also depicted the α -decay half-lives equation (3). Here, one should keep in mind that the parameter set D1M is well suited for such calculations as it has been tailored to provide a better description of the nuclear masses [8]. As observed in the figure, the α -decay lifetime, which is initially shorter than the fission one, becomes longer for large enough neutron numbers. In the case of Ra isotopes our calculations predict the crossing point to be $N \approx 152$ -154 while for Pu isotopes it is found to be $N \approx 160$ -164, i.e., around two mass units later than for U nuclei. Finally, let us also mention that pairing correlations have a strong impact on the predicted spontaneous fission half-lives due to the inverse dependence of the collective masses with the square of the pairing gap [12]. We have repeated the calculations changing the strength of the pairing fields by 5 and 10 % [4] and found that the predicted spontaneous fission half-lives change by several orders of magnitude. However, even in such a case, the main conclusions stated before (i.e., there is a steady increase of t_{SF} in the heavier neutron-rich nuclei and fission becomes dominant over α -decay with increasing neutron number) still hold indicating that the trend predicted by our calculations is a robust one. Our results also suggest the need for a dynamical treatment of pairing correlations within microscopic fission studies. The first steps in this direction have already been undertaken in Ref. [13].

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