Fission half-life calculation using simple effective interaction

L. M. Robledo[1], T.R. Routray[2]*, X. Vi˜nas[3], S. P. Pattnaik[2,4], M. Centelles[3] and B. Behera[2]
[1]*Departamento de F´ısica Te´orica (M´odulo15), Universidad Aut´onoma de Madrid,* E-28049, SPAIN
[2]School of Physics, Sambalpur University, Jyotivihar-768 019, INDIA
[3]*Departament de F´ısica Qu`antica i Astrof´ısica and Institut de Ci`encies del Cosmos(ICCUB), Facultat de F´ısica, Universitat de Barcelona, Diagonal 645, E-08028* Barcelona, SPAIN
[4]*Department of Physics, Govt. Junior College, Sundargarh , Odisha, 770001, INDIA*
* *email: trr1@rediffmail.com*

Introduction

The simple effective interaction (SEI) with Gaussian form has been quite successful in studying the bulk properties of nuclei, both spherical and deformed, over the nuclear chart [1 and references therein]. In the recent work [2] the study of the potential energy surface (PES), defined as the Hartree-Fock-Bogoulibov (HFB) energy computed with HFB wave functions constrained to definite values of the axial quadrupole moment, for nuclei ranging from light to very heavy ones have been performed and compared with the predictions of Gogny D1S predictions. The calculation of fission dynamics is necessary in order to ascertain the ability of the interaction for its use starting from static properties to dynamical processes in nuclei.

Formalism

The SEI energy density functional is constructed from, as given in Ref [2], the finite range interaction and Coulomb and spin orbit terms are included together with a zero-range density dependent pairing interaction fitted to produce nuclear matter gaps obtained with Gogny force. To describe the path to fission, the amplitudes of the Bogoliubov transformation defining those HFB wave functions are computed as the solution of the HFB equation. The axial symmetry configurations are only considered. The quasiparticle operators are expanded in an axially symmetric harmonic oscillator basis. The spontaneous fission half-life is computed with the standard WKB formalism where T_{sf} is given (in seconds) by [3]

$$T_{sf} = 2.86\ 10^{-21}\ (1 + \exp(2S))\ . \quad (1)$$

The action along the Q2 constrained path is

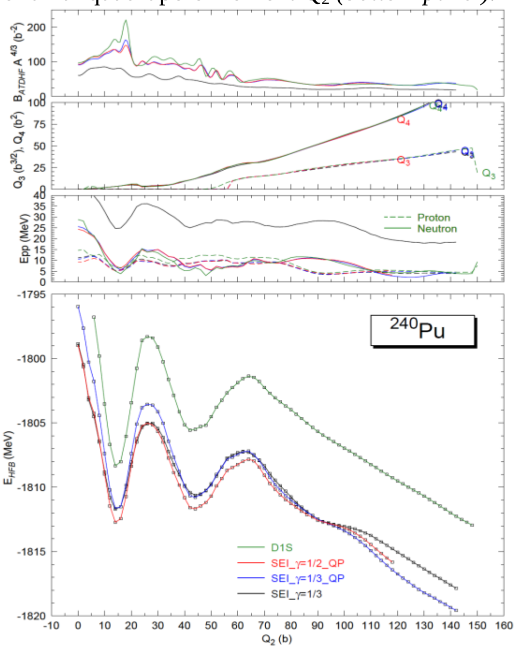
$$S = \int_a^b dQ_2 \sqrt{2B(Q_2)(V(Q_2) - E_0)}\ . \quad (2)$$

For the collective quadrupole inertia $B(Q_2)$ we have used the Adiabatic Time Dependent HFB (ATDHFB) expression computed in the "cranking" approximation. The quantity $V(Q_2)$ entering the action is the HFB energy minus the zero point energy (ZPE) correction $\varepsilon_0(Q_2)$ associated with the quadrupole motion and minus the rotational energy correction given by the rotational approximation with the Yoccoz moment of inertia. Finally, an additional parameter E_0 is introduced in the action. It is meant to represent the quantal ground state energy obtained after considering quantal fluctuations in the quadrupole degree of freedom.

Results and Discussion

Fission barrier is calculated for ^{240}Pu and the two barriers are shown as a function of axial quadrupole moment Q_2 in the bottom panel of the Figure 1 for the EOSs of SEI corresponding to γ=1/3 and 1/2 and Gogny D1S. It may be mentioned here that the particle-particle correlation energy E_{pp} in the neutron channel is found to be overestimated in case of SEI as can be seen from the dark black curve in the second panel from bottom in the figure. A large E_{pp} shall result into a small collective moment of inertia $B(Q_2)$ (black curve in the top panel) that will result into a low fission life time. In fact the calculation with this particle-particle correlation predicts $T_{sf}=5.3\times10^{-2}$ s for the EOS γ=1/3 in place of the experimental value 3.6×10^{18} s. In an attempt to modify the pairing contributions, the pairing correlations in neutron-neutron (nn) and proton-proton (pp) channels have been quenched. This quenching by factors f_p=1 and f_n=0.85 leads to a nice reproduction of Gogny's results in the two channels and over a large range of quadrupole moments as can be seen from the second panel from bottom in the figure where the dark black curve is for the original set (without

Figure 1. B_{ATDHF} A 4/3 (b^{-2}), Q_3 ($b^{3/2}$), Q_4 (b_2) and Epp (MeV) as a function of axial quadrupole moment Q_2 *(top panel)*. The E_{HFB} as a function of axial quadrupole moment Q_2 *(bottom panel)*.



quenching consideration). This modification, of course, disturbs the earlier prediction of the root mean square deviation (rms) values of the energies and radii over the nuclear chart that has been readjusted by refitting the parameter t_0 . The rms deviation of energy that now have values 1.82 and 1.85 for γ=1/3 and1/2 respectively (instead of 1.79 and 1.84 for the unquenched cases). With this quenched pairing correlation, the fission half-life of ^{240}Pu is now obtained to be T_{sf}=2.8x10^5 s for γ=1/3. Although there is some improvement achieved, but it is still far away from experimental value 3.6x10^{18} s . The prediction of Gogny D1S is 5x10^{31} s. The discrepancy between theory-experiment looks terrible but one has to take into account the strong sensitivity of the lifetimes to tiny details in the action, it enters exponentially in the penetrability factor, and therefore in the lifetime.

Calculations have been carried out to analyze the inner and outer barrier heights and the excitation energy of the fission isomer where experimental data is available [4]. The results obtained with the quenched pairing SEI with γ = 1/3 are summarized in the table 1.

Table1. E_A , E_B and E_{II} are the empirical heights of the inner, outer fission barrier and the fission isomer excitation energies respectively.

Symbol	Z	A	E_A (MeV)	E_{II} (MeV)	E_B (MeV)
Th	90	230	5.5	1.6	5.1
		232	5.9	0.9	5.1
U	92	232	5.5	1.9	4.6
		234	6.3	1.2	4.7
		236	7.1	1.0	5.0
		238	7.6	0.8	5.2
Pu	94	238	7.6	1.0	4.2
		240	8.1	0.9	4.5
		242	8.5	0.8	4.7
		244	8.9	0.9	5.1
Cm	96	242	8.5	0.6	3.5
		244	9.2	0.6	4.2
		246	9.6	0.8	4.4
		248	9.2	0.6	4.2

The general conclusion is that the new SEI_{QP} with quenched pairing produces collective inertias which are in much better concordance with those obtained with Gogny D1S. However, the behaviour of the potential energy for large quadrupole moment values is different what leads to an underestimation of the outer barrier heights and the fission isomer excitation energies of the order of 1 or 2 MeV. This underestimation is not that big, but obviously matters if SEI_{QP} has to be used to predict fission data. Finally, the calculated spontaneous fission half-lives turn out to be too small. If this is the case, a fine tune refitting of the SEI would be required.

References

[1] Behera B, Viñas X, Routray T R and Centelles M 2015 J. Phys G: Nucl. Part. Phys. 42 045103

[2] Behera B, Viñas X, Routray T R, Robledo L M, Centelles M and Pattnaik S P 2015 J. Phys G: Nucl. Part. Phys. 43 (2016) 045115

[3] Robledo L M, Baldo M, Schuck P and Viñas X Journal of Physics: Conference Series **321** (2011) 012015

[4] G F Bertsch G F, Loveland W, Nazarewicz W and Talou P J. Phys. G: Nucl. Part. Phys. 42 (2015) 077001