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Spontaneous Fission of Double-odd Nuclei in Ω-nonconserving Model

Spontaniczne rozszczepienie jąder podwójnie nieparzystych w modelu niezachowującym

Спонтанное деление дважды нечетных ядер в Ω-несохраняющей модели

Dedicated to Professor
Stanisław Szpikowski on occasion
of his 60th birthday

1. INTRODUCTION

Calculating fission half life times one accepts the conservation of both the energy and the angular momentum of the nucleus. The third component of the angular momentum is also assumed to be constant during the barrier penetration process and it determines the third angular momentum component of the whole system. In our previous paper [1] we assumed the same. However, it seems that there is no reason to keep the angular momentum projection Ω of the odd particle constant.

As it was shown earlier, the inclusion of axial and asymmetric distrotions leads to a mixing of Ω quantum numbers as well as parities π in odd particle state [2]. This in consequence decrease the specialization energy.

Such a treatment of fission process leads also to modifications in the mass tensor. Consequently the mass tensor and the fission barrier modifications lead to new estimations of fission half lifes and hindrance factors which were studied extensively in our previous paper [1] where the comparison to existing experimental data was given.

The aim of presented paper is to show the effect of 'Ω nonconserving' on the hindrance factors and to compare them to previously calculated ones.

2. METHOD OF CALCULATION OF T_{sf}

To generate the single particle orbits we use the Nilsson potential [3] with deformation parameters ε_2, ε_4. The pairing correlations were included in the BCS model. The deformation energy was calculated according to the Strutinsky prescription [4]. The smooth part of the energy was the same as in ref. [5].

The mass parameters entering the probability of barrier penetration is given in the adiabatic approximation by the formula [6]

$$B_{\varepsilon_i \varepsilon_j} = 2\hbar^2 \left\{ \sum_{\nu\omega} \frac{\langle \nu | \frac{\partial \hat{H}}{\partial \varepsilon_i} | \omega \rangle \langle \omega | \frac{\partial \hat{H}}{\partial \varepsilon_j} | \nu \rangle}{\left[E_\nu + (1 - 2\delta_{\omega\nu}) E_\omega\right]^3} \right.$$

$$\left[(u_\nu v_\omega + u_\omega v_\nu)^2 (1 - \delta_{\omega\mu}) + \delta_{\omega\mu} (u_\nu u_\omega - v_\nu v_\omega)^2 \right]$$

$$\left. + \frac{1}{\hbar} \sum_\nu \frac{1}{E_\nu^5} \left[\Lambda_i^\nu \Lambda_j^\nu - \Delta \left(\Lambda_i^\nu \langle \nu | \frac{\partial \hat{H}}{\partial \varepsilon_j} | \nu \rangle + \Lambda_j^\nu \langle \nu | \frac{\partial \hat{H}}{\partial \varepsilon_i} | \nu \rangle \right) \right] \right\} \tag{1}$$

where

$$\Lambda^{\nu}_{i} = \frac{\partial \lambda}{\partial \varepsilon_i} \Delta + \frac{e_\nu - \lambda}{2\Delta} \frac{\partial \Delta^2}{\partial \varepsilon_i} . \qquad (2)$$

The superscript μ at $B^{\mu}_{\varepsilon_i \varepsilon_j}$ is the designation of the odd single particle state for which the mass parameter is calculated. The states $|\nu\rangle$, $|\omega\rangle$ are Nilsson single particle states. The parameter λ is the Fermi energy of the system, and Δ is the BCS gap parameter.

The fission process is treated as a penetration through a one-dimensional barrier taken along an effective statical path $\varepsilon_4 = \varepsilon_4(\varepsilon_2)$ determined from the condition

$$V(\varepsilon_2, \varepsilon_4)\Big|_{\varepsilon_2=\text{const}} = \text{min.} \qquad (3)$$

The penetration probability P in a WKB approximation reads

$$P = (1 + \exp\{S\})^{-1} , \qquad (4)$$

where S is an action integral

$$S = \frac{2}{\hbar^2} \int_{s_1}^{s_2} \sqrt{2\, V(s) - E\, B(s)}\, ds , \qquad (5)$$

calculated along the trajectory specified above. The mass B(s) is called an effective static mass parameter and has the following form

$$B(s) = \sum_{i,j} B_{\varepsilon_i \varepsilon_j} \frac{d\varepsilon_i}{ds} \frac{d\varepsilon_j}{ds} \qquad (6)$$

Here s is the length of the trajectory and s_1 and s_3 are entrance and exit points respectively and are determined from the equation E = V(s), where E = 0.5 MeV [3, 7].

The half life time is given now by the relation

$$T = \frac{\ln 2}{n} \frac{1}{P} \qquad (7)$$

where n is a number of assaults of the nucleus on the fission barrier in a time unit. The value 0.5 MeV for E makes n equal to $10^{20.38}$/s.

The change in the action integral Δ s calculated as a difference between the action S for odd-even/odd system and the neighbouring even-even one is simply connected to the hindrance factor h defined by

$$h \equiv \frac{T_{sf}^{o-e/o}}{T_{sf}^{e-e}} = e^{\Delta S} . \qquad (8)$$

Here $T_{sf}^{o-e/o}$ and T_{sf}^{e-e} are spontaneous fission half life times of odd-even/odd and even-even systems, respectively.

Since in our model we use only ε_2 and ε_4 degrees of freedom the absolute values of T_{sf} are certainly not good enough to reproduce the experimental data.

In order to have better agreement one has to include other deformations such as ε_{35}, ε_6 and γ. On the other hand if one calculates the value of Δ S in a way described above, one can believe that the effect of other degrees of freedom does not enter the result very much.

The action $S^{o-e/o}$ for the odd-even/odd system being the sum of properly calculated S_p^{e-e} of even-even system [7] and approximate value of Δ S is used then to calculate spontaneous fission half life time $T_{sf}^{o-e/o}$. In the action S_p^{e-e} all effects connected to ε_{35}, ε_6 and deformations are fully included. Spontaneous fission half life time of odd-even and/or odd-odd nucleus is given by the expression

$$T_{sf}^{o-e/o} = h \, T_{sf}^{e-e} (S_p^{e-e}) .$$

Such a procedure makes it possible to compare $T_{sf}^{o-e/o}$ with experimental data.

The problem of nonconserving the total projection Ω of angular momentum was discussed in ref. [2] and is connected to the γ degree of freedom. The inclusion of γ into the calculations makes the Nilsson state to be a mixture of components with different Ω values. It was shown that Nilsson single particle states of this kind lower the potential barrier of the nucleus on an amount of 1-2 MeV [8].

Table 1. Hindrance factors for odd-even and odd-odd nuclei.
Upper number corresponds to 'nonconserving' model.
The lower numbers are those presented early [1].

N \ Z	97	99	101	103	105	107	109
146	0.1 1.5	0.1 0.3	1.5 4.8	0.3 0.6	0.1 2.5	0.2 0.2	0.1 2.8
147	4.2 8.0	3.8 7.0	4.3 11.0	1.1 3.3	1.0 2.4	0.5 0.7	0.9 3.1
148	0.1 1.6	0.4 0.4	1.5 3.6	0.4 0.6	0.2 2.4	0.2 0.3	0.0 2.7
149	2.6 6.1	2.9 5.0	3.4 7.8	2.2 2.5	1.8 2.9	0.9 1.0	1.7 3.3
150	0.0 1.7	0.6 0.6	0.7 3.3	0.5 0.6	0.3 1.9	0.2 0.4	0.1 2.7
151	3.4 5.8	4.0 4.5	3.4 7.2	1.5 1.9	1.2 2.1	0.2 0.3	0.8 3.0
152	0.1 1.7	0.3 0.3	0.8 3.3	0.4 0.5	0.4 1.8	0.3 0.2	0.1 2.8
153	1.3 5.7	1.0 1.8	2.2 5.4	1.4 1.8	1.2 2.5	0.2 1.3	0.9 2.9
154	0.2 1.9	0.1 0.2	1.2 3.4	0.4 0.6	0.4 1.6	0.1 0.2	0.1 2.8
155	1.8 5.7	2.2 2.3	2.6 5.0	0.9 1.8	1.6 1.8	0.9 0.9	1.4 3.0
156	0.3 2.1	0.2 0.5	1.0 3.6	0.4 0.4	0.5 1.5	0.1 0.2	0.1 2.8
157	2.4 6.0	3.2 3.4	2.0 6.4	1.1 1.2	0.9 1.9	0.4 1.4	0.9 3.1
158	0.4 2.2	0.2 0.5	1.0 4.3	0.1 0.4	0.5 1.5	0.0 0.2	0.0 3.0
159	3.5 5.1	2.8 3.0	1.5 6.6	1.0 1.3	1.1 1.8	0.1 0.8	0.2 2.6

In order to reproduce the nonaxiality of single particle states we postulate the nonconservation of Ω during the barrier penetration process. The odd particle is placed on the lowest empty axially symmetric single particle Nilsson orbit and the specialization energy (a difference between the energy of an odd system and the corresponding energy of even-even one) is calculated for the whole fission barrier. During the fission process the particle changes the orbits and correspondingly its value but having the lowest possible energy.

In the minimum of the potential energy and behind the potential barrier the odd nuclear system has a well defined 3-rd angular momentum component Ω which reproduces the ground state value of Ω. The last property depends on the choice of $\varkappa$, μ parameters of the Nilsson model and was discussed in our previous paper [1].

3. RESULTS

Fig. 1 presents the barriers of ^{256}Md as calculated before [1] and in the presented paper. For odd-even nuclei the high of the barrier is about 0.5÷0.8 MeV smaller as compared to the barriers calculated with conserved Ω . For odd-odd nuclei the corresponding numbers lie in the interval 1.0÷1.5 MeV. The Ω nonconserving model leads also to changes in mass parameters B. This may be seen in Fig. 2 where mass parameters of ^{256}Md are presented. Both effects lead to decreasing spontaneous fission half lives and corresponding hindrance factors. The latter are summarized in Table 1. One sees that the new hindrance factors in Ω "nonconserving model" (the upper numbers) are smaller from the old ones Ω conserving model (lower numbers) by about 3 units.

In the case of odd-odd nuclei we observe decreasing of hindrance factors with increasing atomic number Z for a given isotope (N = const). It is caused by the fact that the fission barriers for a larger Z are shortened. For even-odd nuclei the hindrance factors are relatively small.

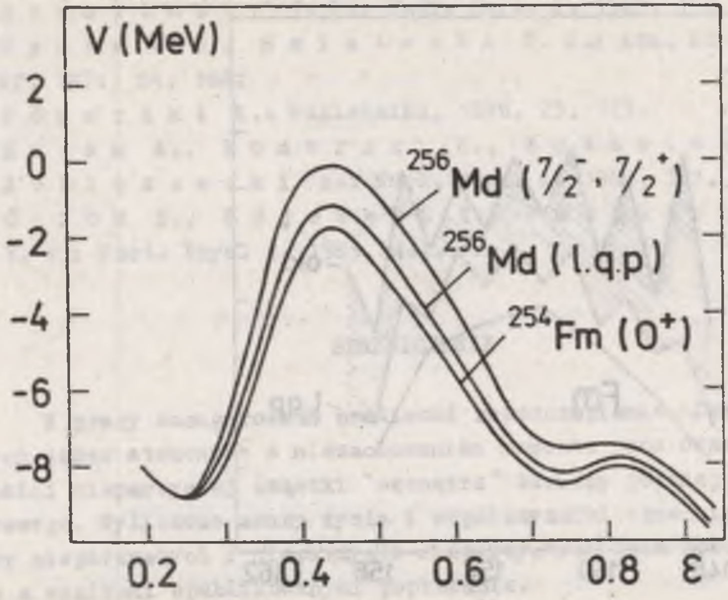

Fig. 1. Fission barriers for ^{256}Md. (lqp) denotes the barrier obtained for the case of two particle occupied the lowest Nilsson orbits.

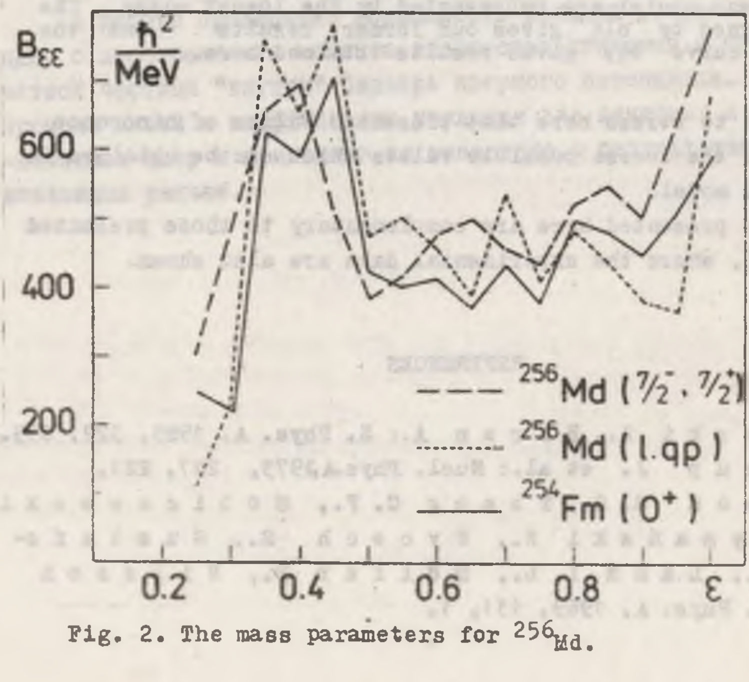

Fig. 2. The mass parameters for ^{256}Md.

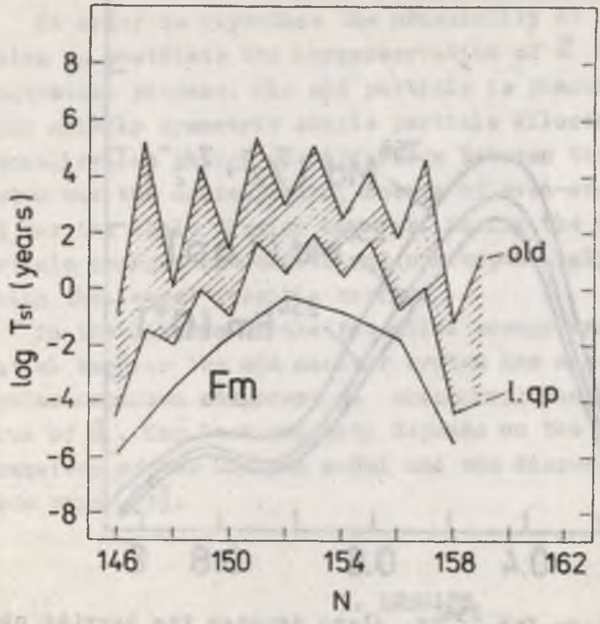

Fig. 3. Spontaneous fission half life times for Md isotopes. The even-even nuclei are represented by the lowest curve. The curve designed by 'old' gives our former results and the curve 'lqp' gives results obtained here.

We want to stress here that presented values of hindrance factors have the lowest possible values which can be obtained in the accepted model.

Results presented here are complementary to those presented in paper [1], where the experimental data are also shown.

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STRESZCZENIE

W pracy zasugerowano możliwość rozszczepienia nieparzystych jąder atomowych z niezachowaniem momentu pędu oraz parzystości nieparzystej cząstki `wewnątrz´ bariery potencjału jądrowego. Wyliczono czasy życia i współczynniki wzmocnienia jąder nieparzystych i nieparzysto-nieparzystych oraz porównano je z wynikami opublikowanymi poprzednio.

Р Е З Ю М Е

В работе предложена возможность деления нечетных атомных ядер с несохранением момента количества движения и четности нечетной частицы "внутри" барьера ядерного потенциала. Вычислены времена жизни и коэффициенты усиления для нечетных и нечетно-нечетных ядер и приведено их сравнение с результатами опубликованными раньше.