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ANALYSIS OF EXPERIMENTAL DATA FROM FUSION-FISSION REACTIONS WITHIN FOUR-DIMENSIONAL LANGEVIN DYNAMICS*

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A four-dimensional stochastic approach to dynamics of nuclear fission induced by heavy ions was applied to analyze the key observables from fusion-fission reactions resulted in the highly excited compound nuclei. We took into account not only three shape collective coordinates introduced on the basis of the c, h, α-parametrization but also orientation degree of freedom (K-state) — spin about the symmetry axis. We systematically investigated the possible deformation dependence of the viscosity coefficient k_{s} predicted by chaos theory and deformation dependence of the γ_K coefficient deduced by Lestone *et al.* In the framework of 4D dynamical model, we examined the correlation between dissipation strength and mass, energy and angular distributions of fission fragments. Our calculations demonstrate that the deformation dependent coefficient k_{s} and γ_K value obtained by Lestone is suitable for simultaneous description of experimental mass-energy and angular distributions of fission fragments in 4D model for heavy nuclei, in contrast with the 3D model. The influence of k_{s} and γ_K parameters on the calculated results could be separated.

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1. Introduction

Fission is one of the most complex nuclear reaction mechanisms. Depending on the composition and excitation energy of the fissioning nucleus, various aspects affect the process. For more than 20 years, statistical modeling of the fission still have not been able to provide theoretical results consistent with the experimental data, especially for the heavy nuclei. Thus, the dynamical consideration [1] of the entire fission process is crucial [2] and the nuclear viscosity is one of the key points in dynamical consideration.

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All dynamical models should be formulated with the collective dynamical variables and nuclear shape parametrization. The significance of orientation degree of freedom of the nucleus, K-coordinate, was recently elucidated [3]. Thus the question of dissipation strength came up once again. Moreover, there is even more complicated question — the correlation between dissipation for the shape collective coordinates and dissipation for the K-coordinate.

2. The model

All ingredients constituting our model and incorporation of the tilting mode dynamic to make the 4D Langevin dynamic can be found in [4, 5] and references therein. Here, we depict some details of nuclear dissipation magnitudes used in our investigations.

The dissipation is one the most affecting factors in the nuclear dynamics, so many works were dedicated to the precise investigations of various mechanisms and values. Hydrodynamical two-body mechanism is suppressed due to the Pauli blocking principle, and one-body dissipation is expected to dominate. Many calculations proved this consideration. The key value for the one-body nuclear viscosity is the k_{s} scaling factor, which sets up the magnitude of the dissipation. Many previous works to fit the experimental data treated k_{s} as a free parameter and scaled it in the wide range and even composed the empirical deformation dependence. More reasonable and well-founded option is to use the scaling factor found on the basis of the "chaos-weighted wall formula" [6].

The question of the K-mode dissipation value is more ambiguous. According to Lestone [3], we employed a base constant value as the initial first option. This value was extracted by Lestone from the heavy nuclei fission fragment angular distribution fits and may vary by 2 or 3 times of magnitude. In figure 1, various K-mode dissipation options and values used in our calculations are presented. The deformation-dependent γ_K value is formulated for the case of a dinucleus [3]

$$\gamma_K = \frac{1}{R_{\mathrm{N}} R_{\mathrm{cm}} \sqrt{2\pi^3 n_0}} \sqrt{\frac{J_{\parallel} |J_{\mathrm{eff}}| J_{\mathrm{R}}}{J_{\perp}^3}} \,, \tag{1}$$

where R_{N} is the neck radius, R_{cm} is the distance between the centers of mass of the nascent fragments, n_0 is the bulk flux in standard nuclear matter ($0.0263\ \mathrm{MeV\,zs\,fm^{-4}}$), and $J_{\mathrm{R}} = M_0 R_{\mathrm{cm}}^2/4$ for a reflection-symmetric shape.

In figure 1 the dinucleus deformations correspond to the range of deformations, where $q_1 > 1.6$. So, for the shapes without the neck, one should use some approximation. The constant values for the shapes without the neck

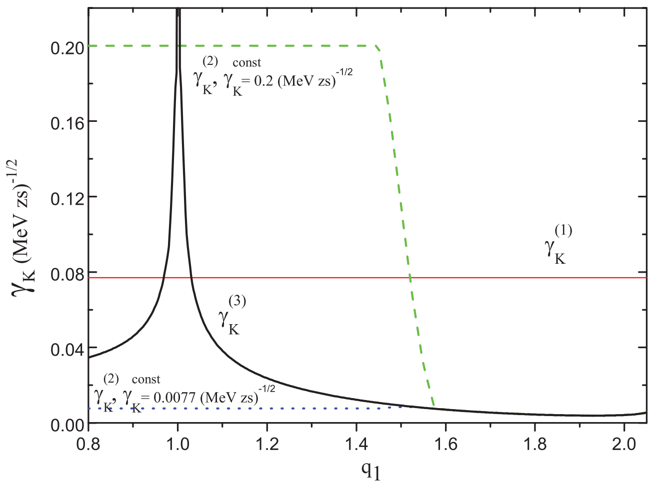

Fig. 1. (Color online) Various dependencies of the γ_K parameter on elongation q_1. The thin solid line corresponds to $\gamma_K^{(1)} = 0.077$ (MeV zs)$^{-1/2}$; the dashed and dotted curves correspond to the $\gamma_K^{(2)}$, obtained with $\gamma_K^{\text{const}} = 0.2$ (MeV zs)$^{-1/2}$ and $\gamma_K^{\text{const}} = 0.0077$ (MeV zs)$^{-1/2}$; the thick solid curve corresponds to the deformation-dependent $\gamma_K^{(3)}$ parameter given by (1).

combined with the formula for the dinucleus deformations provide us with the second option. As an example, it is presented by the dashed (green) and dotted (blue) lines. We used three constant values for the compact shapes within the second option. Lestone formula (1) extended to the compact shapes is the third $\gamma_K^{(3)}$ option [7].

3. Results and discussions

The influence of the orientation degree of freedom on fission barriers is well pronounced. Fission barriers increase, especially those of non-rotating nucleus and it could be more than 10 MeV in comparison with non-rotating nucleus [4]. Saddle point configurations shift to the more elongated forms in the case of the non-zero K-value. K-mode influence over the nuclear stiffness results in the Businaro–Gallone point shift towards large Z^2/A and considerable differences for the saddle and scission deformation stiffness in comparison with the zero K-value treatment. The latter leads us to the expectations of much wider mass distributions for fission fragments. Our previous investigations and comparisons [4, 5] of the 3D and 4D results with various k_s magnitudes confirmed our expectations. The prescission neutron multiplicity and the variance of the mass distribution of the fission fragments increased. In general, 4D model is in better agreement with the experimental data, especially for the heavy nuclei.

The mean kinetic energies of the fission fragments within 4D calculations are insensible regardless of the dissipation options for all collective coordinates and are in good agreement with the Viola systematic as can be clearly seen from figure 2. Some important technical details for calculating the fission fragment total kinetic energies and corresponding mean values can be found in [2, 9].

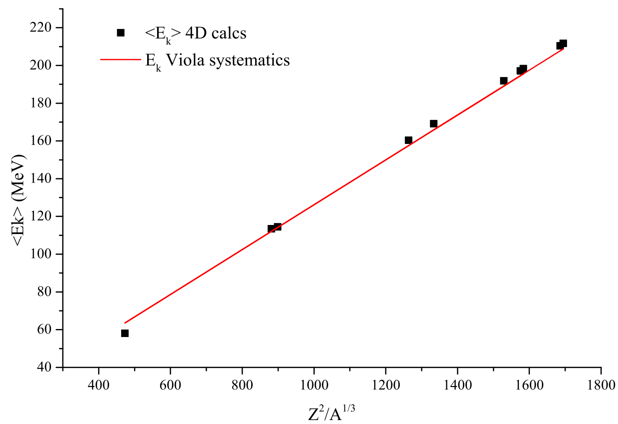

Fig. 2. (Color online) The calculated mean kinetic energy $\langle E_{\mathrm{K}} \rangle$ for various nuclei as the function of $Z^2/A^{(1/3)}$ (filled squares). Our recent 4D results for the ^{224}Th ^{248}Cf and ^{252}Fm are supplemented with our previous 4D results [4, 5]. The solid/red line represents the Viola systematic values $\langle E_{\mathrm{K}} \rangle = 0.1189\ Z^2/A^{1/3} + 7.3$ (MeV) [8].

The 4D thorium and californium calculations results for some of the key observables are presented in figure 3. In order to distinguish the influence of the dissipation options, we have employed three k_{s} options and three γ_K options for each of the k_{s} value. We obtained that the prescission neutron multiplicity and MED fission fragment variances are insensible to the γ_K option variation. On the contrary, anisotropy of the fission fragment angular distribution is more expressed if influenced by the γ_K option and magnitude.

The more detailed investigations of the dynamically derived angular distributions were done for two ^{252}Fm reactions [7] with the detailed experimental data on anisotropy available. The main trend is still the same — γ_K option influence is much more expressed and anisotropy increases along with the growth of the γ_K value. The experimentally obtained nearly independent anisotropy as the function of fission fragment mass is well reproduced by our calculations.

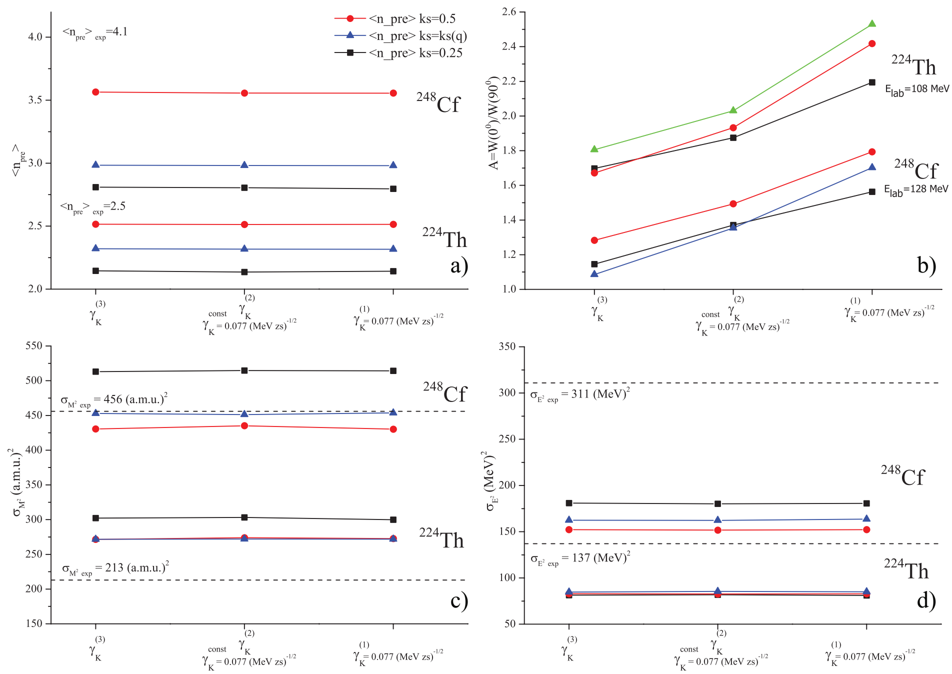

Fig. 3. (Color online) ^{224}Th ($E_{\mathrm{lab}} = 108$ MeV) and ^{248}Cf ($E_{\mathrm{lab}} = 128$ MeV) 4D dynamic results for some of the key observables with various k_{s} and γ_K nuclear dissipation options. Panel (a) presents the experimental and calculated prescission neutron multiplicity for both nucleus as the function of the γ_K options. The line with the circles (red) was calculated with $k_{\mathrm{s}} = 0.5$, the line with triangles (blue) — with $k_{\mathrm{s}} = k_{\mathrm{s}}(q)$, and the line with the boxes (black) is for the $k_{\mathrm{s}} = 0.25$ dissipation coefficient. Designations for results with different k_{s} options are the same for all four panels on the graph. Panel (b) presents the results for the fission fragment angular distribution anisotropy as the function of the dissipation options. Panels (c) and (d) present the results for the fission fragment MED characteristics — the fission fragment mass variance and fission fragment mean fragment total kinetic energy variance respectively.

4. Conclusions

The 4D calculations for heavy nuclei allow consistent description of MED parameters and prescission neutron multiplicity. The influence of k_{s} and γ_K parameters on the results could be separated. It is possible to use the deformation dependent γ_K coefficient, calculated according to Lestone. However, in order to reproduce experimental data on the anisotropy, it is necessary to increase the γ_K coefficient up to 0.2 (MeV zs)$^{-1/2}$ for compact shapes. This result confirms our previous observations [10]. The 4D dynamical calculations predict independence of the anisotropy of the fission fragment angular distribution on the fission fragment mass, and it is in agreement with the experimental data.

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