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Warszawa, April 8^{th}, 2024

Opinion on the doctoral thesis of MSc. Pavel Vladimirovich Kostryukov
"Dynamic description of low and middle energy nuclear fission"

The doctoral dissertation of MSc. Pavel V. Kostryukov, titled "Dynamic description of low and middle energy nuclear fission" presents a thorough theoretical study of the dynamics of fission in heavy or super-heavy nuclei. A model is developed in the doctoral project to describe both spontaneous- and (neutron- or photon-) induced fission. The model proposed provides a description of the surface evolution in the fissioning system to predict properties like mass and charge distributions for the fragments or their kinetic energy following the separation of the two fission products. Its predictive capabilities are then probed by comparing the results with experimental data for heavy nuclei, before applying the model to super-heavy nuclei. Predictions of fission properties for super-heavy nuclei are of crucial importance in the context of the production of new isotopes of elements from Rf to Og as well as in the predictions for the production of new elements with Z≥119. Fission is in fact a dominant decay channel for these isotopes and the survival probability of the isotope after formation of the compound nucleus in the fusion reaction is directly linked to the properties of the fission phenomenon.

The doctoral thesis of MSc. P.V. Kostryukov is presented in a lucid manner and composed of 186 pages, which are subdivided into 5 chapters, a summary, an abstract, an appendix and the bibliography.

Chapter 1 introduces the reader to the general topic of the dissertation, namely nuclear fission. After a historical introduction, the general principles of the phenomenon and the relevant terminology are presented. The main approaches to a theoretical description and modelling of the fission process, from the mean-field approximation to density-functional theory, are also discussed.

Chapters 2 to 4 provide an exhaustive and comprehensive summary of the methodologies adopted as fundaments for the model proposed in this dissertation.

Chapter 2 introduces possible ways to describe properties of the atomic nucleus relevant for the fission process. Particularly relevant are gross properties, like mass, charge and radius, as well as internal structure characteristics. The chapter starts with an overview of macroscopic models used for describing the binding energy of the nucleus, from the original liquid drop model of Weizsäcker to later descriptions that include deformation dependence and shell corrections to the binding energy, to conclude with the more sophisticated droplet and Lublin-Strasbourg models. The description of macroscopic models is followed by that of microscopic models, starting from the Hartree-Fock method to include then pairing corrections with the Hartree-Fock-Bogoliubov and Bardeen-Cooper-Shrieffer descriptions and later to include also Coulomb potential and energy corrections. The chapter concludes with a description of the macroscopic-microscopic method proposed by Strutinsky, which combines macroscopic, microscopic and collective aspects to determine the potential energy surface of nuclei, taking into account also the deformation of the nucleus, which is particularly relevant when attempting to describe the fission process, since the majority of fissioning nuclei are deformed.

Chapter 3 delves into one of the key fundamental properties of the nucleus, namely its shape. The understanding of basic properties of the nucleus, like its potential energy, depends on the choice of parametrisation used for the shape's description. Therefore different approaches are proposed and described in some detail, ranging from the traditional Nillson parametrisation to the Cassini method, to the Fourier parametrisation. A hydronymic description of nuclear properties is also considered.

Chapter 4 presents possible statistical approaches to the description of nuclear fission starting from the multivariate Langevin equations for describing the dynamics of fission. The Fokker-Planck approach is also illustrated as a way to describe the probability distribution of the motion of the nucleus. An important phenomenon associated with fission is the emission of light particles from the fissioning nucleus. This aspect is addressed at the end of the chapter, where a method to take this phenomenon into account is proposed.

In Chapter 5 the main results of the study are presented with the aid of an abundant and appropriate number of figures and plots. After having introduced all the necessary tools in the first part of the dissertation, the Author introduces in this chapter the model developed to describe the fission properties of heavy and super-heavy nuclei and then applies it to selected isotopes. The model aims at explaining a range of observables in the fission phenomenon, like mass distributions, charge distributions, kinetic energies and light-particle emission. Comparison with experimental data is provided, when available, and used to guide the model development and optimisation of its parameters. In the first three section of the Chapter the main components of the model are introduced and the choices made in the model construction explained. These include the selection of the optimal parameters when it comes to temperature effects and single particle energy spectra, but also the identification of optimal grid dimensions in multidimensional calculations of the fission dynamics or of the boundary conditions to be imposed on the solutions of the Langevin equations. The choices made are justified and explained by systematic studies and illustrated with ample aid of figures. In the last section the model is applied to predict properties of induced- and spontaneous- fission in heavy and super-heavy even-even nuclei ($90<Z<116$). These include mass and charge distributions for the fragments, as well as their kinetic energy following the separation of the two fragments from the fissioning nucleus. Heavy (actinides, $Z<104$) and super-heavy ($Z\geq104$) nuclei are addressed separately, since adjustments in the model are needed while switching from one set of nuclei to the other.

Several isotopic chains are considered in the actinides region chosen to cover different reactions, i.e. thermal-neutron-induced fission (Th, U, Pu, Cf, Fm), photo-fission (Th) and spontaneous fission (U, Pu, Cm, Cf, Fm, No). The model reproduces well the mass distributions – or at least their trend – for U, Pu and Cm, while for Cf, Fm and No the model predicts the presence of a symmetric fission channel which does not find its counterpart in the data for most of the isotopes, while in two cases, ^{256}Cf and ^{258}No the data show a symmetric distribution not fully explained by the model. In the case of Th isotopes, it is interesting that while the mass distribution is good for thermal-neutron-induced fission, in the case of photo-fission, which is studied at much higher excitation energies (>10 MeV), the important symmetric fission channel observed in the data is not reproduced by the calculations. Possible explanations are proposed for such discrepancy between data and predictions and are analysed in detail.

The model is then applied to predict fission properties of superheavy nuclei. The characteristics of fission for a super-heavy nucleus are key in order to predict the so-called *survival* of the system after fusion and therefore impact the production and possibility to observe and then study properties of such nuclei as well as to predict the possibility to create new elements. The choices made to adjust the boundaries of the deformation and the grid to include larger values are detailed. Such changes are needed since super-heavy nuclei not only show a symmetric fission channel, but present also decay channels with very large asymmetries, with the heavier fragments around ^{208}Pb. The comparison with experimental data, when possible, shows good agreement.

The last topic addressed is emission or evaporation of light particles from the fragments, phenomenon that would affect the measured mass and charge distribution and therefore impact the quality of the comparison between theory and experiment. Modelling of particle emission from the fragment and from the compound nucleus is proposed. Unfortunately, the limited amount of data available on the phenomenon does not allow for a systematic validation of the modelling.

A critical look at the results allows MSc. Kostryukov also to identify the parts of the model that will require further work in order to improve its prediction capabilities and to make suggestions in this respect.

The thesis is written in English. In portions of the text the language is rather colloquial with sometimes non-rigorous scientific terminology and expressions. There are also several typing and grammar imprecisions. Moreover, some references are reported as "[]" without quoting the actual reference. Acronyms should be defined once, when first met and later be used exclusively in the text. In Figures 5.1, 5.2 and 5.3 the color scale is missing, while Figure 5.4 is hard to read and there seems to be a mistake in the legend. In Figure 5.53 the lines in red and magenta are very hard to distinguish. These editorial comments do not affect the scientific quality of the work presented by M.Sc. Kostryukov in his doctoral dissertation.

Summarising, the work presented in MSc. Pavel V. Kostryukov's thesis comprises original results on the modelling of dynamics of induced and spontaneous fission in heavy and superheavy nuclei. The predictions of the model are in most of the cases considered in good agreement with the experimental data available. It would be interesting to see how the model will be developed further and what improvement in the predictive power can be achieved once the modifications suggested by the Author at the end of the summary will be implemented.

The doctoral dissertation "Dynamic description of low and middle energy nuclear fission" presented by MSc. Pavel Vladimirovich Kostryukov fulfils the requirements for doctoral thesis and I therefore ask for admission of MSc. Pavel Vladimirovich Kostryukov to the next steps of the doctoral proceedings and to public defence. (in Polish: *Rozprawa doktorska "Dynamic description of low and middle energy nuclear fission" przedstawiona przez mgr. Pavla Vladimirovicha Kostryukova spełnia wymagania stawiane pracom doktorskim i w związku z tym wnioskuję o dopuszczenie mgr. Pavla Vladimirovicha Kostryukova do dalszych etapów postępowania doktorskiego i do obrony publicznej.*)

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