Warszawa 08.09.2022

SZANOWNY PAN DYREKTOR INSTYTUTU FIZYKI UMCS
DR HAB. RYSZARD ZDYB, PROF. UMCS

Szanowny Panie profesorze posyłam recenzje pracy doktorskiej Pani mgr JIE YANG.

Z wyrazami Szacunku,
Michal Kowal

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PHD REFEREE REPORT

Title: *"Systematic Study of Exotic Nuclear Shape Symmetries and Isomers, Including Shape Evolution and Competition in Heavy and Super-Heavy Nuclei"*

Author: mgr JIE YANG

Supervisor: prof. dr hab. Jerzy Dudek

The reviewed dissertation contains 242 pages of the main text - six chapters, and eight appendices. An advanced group-theory apparatus was used in the study for the structural properties of atomic nuclei as; energy bands, rotational and vibrational states and reduced probabilities of electromagnetic transitions, including that inter-band: dipoles and quadrupoles. In addition, some exotic nuclear shapes bound at high symmetries have been studied.

At the very beginning, I would like to point out that this is an enormous theoretical material that can certainly be very useful for experimentalist. It is a considerable advantage of this job. The work is written very carefully, even in bookkeeping, and despite the vast number of formulas and texts, it does not contain typographical errors. The content is arranged logically, and the following chapters follow and relate to the preceding ones. Lastly, there are highly valuable A-H supplements.

Overview of the issues and the importance of the problems discussed in the individual chapters of the dissertation:

The author illustrates various octupole symmetry properties based on large-scale, systematic, potential energy calculations using a realistic phenomenological mean-field with newly adjusted parameters with the parametric correlations technique.

Chapter 1 contains a short introduction presenting the research motivation.

Chapter 2 is an introduction to the nuclear mean-field theory. The author recalls the essential aspects important from the point of view of the work, such as nuclear interactions, nuclear many-body Hamiltonian, phenomenological mean-field potentials, and symmetries of the mean-field Hamiltonian. Additionally, it is enriched by discussing model uncertainties with parametric correlations.

Chapter 3 discusses the technical aspects of solving the Schrödinger equation with the mean-field Hamiltonian.

Chapter 4 is a reminder of the well-known theory of superconductivity used to describe the pairing effect.

Chapter 5 also contains the known facts but is very interesting as it gives the link between quantum mechanics and group theory.

Chapter 6 is a critical chapter in which the results related to exotic shape symmetries in heavy and super-Heavy nuclei are discussed like: octupole magic number N = 136; Identification of exotic symmetries, results obtained from 4D octupole space, and exotic symmetries in super-heavy nuclei.

Whole dissertation is extensive and written very pedagogical in a way highly mature to a doctorate. The natural language used here is the group theory with their representation. Presented thesis is an excellent introduction to nuclear physics seen from the symmetry point of view and their relationship with nuclear shapes at equilibrium points and beyond. It feels like reading a fragment of a excellent textbook on the physics of the structure of the atomic nucleus.

The macroscopic-microscopic model applied here, due to the meticulous selection of the parameters of the single-particle potential and those occurring in the smooth part of the energy, has significant predictive power and may pretend to give reasonable predictions for the experiment.

The discussion of parameters and their correlation in the context of statistical errors is an essential point of the work, which proves the very high scientific maturity of the Ph.D. student.

Mastering not easy numerical methods prove the great independence of the person performing the work. In addition, the work was written in a very thoughtful, even bookkeeping manner.

Providing experimental criteria and suggesting systematic experimental identification criteria of the point group symmetries, I consider as a significant achievement of the Ph.D. student. This may be stimulating for the future work of experimental groups worldwide.

Although the dissertation is excellent, I have a number of specific questions that I would like to clarify/discuss during the defense.

GENERAL REMARK

It is quite complicated to find out the actual result of the doctoral student and separate it from the impact of the whole group, which has been working intensively and fruitfully on these issues for many years. Therefore, I kindly ask that individual contribution of a doctoral student be clearly said/bulleted during the defense.

SPECIFIC QUESTIONS:

1. How can angular momentum affect the studied states 1- or 3-? After all, it can significantly change the energy landscape, including "shift" the states in question. The cranking method was introduced, and it was meticulously derived. However, it is used only in the minima found, while the rotation energy can modify the entire map, shift the position of the minima and, above all, change their depth.

2. The details of the octupole symmetries related to the Y31, Y32, and Y33 harmonics are investigated, but what about other higher harmonics, non-axial and mass-asymmetrical, such as Y52 or Y54, etc.? Higher mode coupling significantly reduces vibrations with negative parity (M. Kowal and J. Skalski Phys. Rev. C 82, 054303 2010).

3. A figure like a Figure 6.8.4 comes from a 4DIM grid. Although much effort has already been put in, I am afraid that adding more variables will change this picture dramatically. In particular, I am convinced that tetrahedral minima will not survive as global (P. Jachimowicz, M. Kowal, and J. Skalski, Rev. C 95, 034329 2017). Of course, studying local and excited minima can also be interesting.

4. Similarly, the inference about the gap size (as in Fig. 6.2.1) is very uncertain. If the nucleus may deform freely in other directions, the received gap can be completely different from what the authors present. It can be relatively quickly checked by including Y40 and Y60 (only around the minimum). Therefore, it raises serious doubts about the generality of inference. The influence of additional degrees of freedom on the depth of the minima, which is derived from the Shell effect, which in turn depends on the energy gap, was shown in the work of Z. Patyk, A. Sobiczewski, Physics Letters B, Volume 256, Issues 3–4,

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14 1991). The author shows this already (minimum reduction of about 2 MeV) e.g. in Figure 6.7.4 by violet line. If Y60 were combined with Y80 (not shown), the effect would be even greater.

5. We have recently shown (M. Kowal, J. Skalski, Physical Review C 85 (6), 061302, 2013) that the dipole parameter (alpha10) has the character of a real shape variable. It is not only a technical parameter that allows the nucleus to be positioned in the center of the masses to diagonalize the potential. By introducing such a shape, we also get a new class of vibrations in the direction of mass asymmetry, unattainable using only lambda =3 in radius expansion. Moreover, since alpha10 is the first term in this expansion, it can consume a lot of energy. I am curious about the author's opinion on whether the variable related to Y10 spherical harmonic may influence tetrahedral vibration investigated here.

6. How the weakness of coupling of the octupole vibrations with the quadrupole was examined numerically/quantitatively? Since this coupling was omitted, I assume it was based on some investigations.

7. I consider using a spectrum for the central nucleus (not diagonalizing each of them separately) as a particular flaw in this work. The most exciting effects occur around self-magic shells and usually involve single-particle states around them. So the accuracy of the spectrum is essential. Therefore, today, in the era of supercomputing resources, such an approach seems a bit outdated to me.

8. I would like to ask how many shells were taken to diagonalize the deformed W-S potential. This is not just a technical problem as too few shells used in super heavy nuclei lead to serious errors by underestimating the microscopic energy. In particular, the masses are poorly described in such a case because the global minimums are not sufficiently deep. Since the work deals with competing minima, this problem becomes a key one. Similarly, I did not find information about the accuracy of integrating the deformation-dependent terms in the macroscopic part.

9. Tetrahedral minima in SHN were found for very neutron deficient nuclei ($N \sim 194$). Let me remind you that the heaviest nucleus - Og has only 176 neutrons. How could one check these predictions in this area of super-heavy nuclei?

10. As one of the conclusions, one can read: "A new exotic symmetry is deduced by combining the oblate-quadrupole deformation with octupole deformation." **This is not any new conclusion, either** - see: the discussion in

- International Journal of Modern Physics E Vol. 19, No. 04, pp. 508-513 (2010), where it is clearly stated: "Larger, pure oblate shapes are close to the g.s. for Z = 124; 126, where they compete with moderately oblate shapes combined with both octupole deformations mixed in the ratio b32c / b30 ~ Sqrt (3/5). This particular ratio corresponds to the Y33 symmetry with respect to the x-axis of the quadrupole shape."

- Or in Physical Review C 95 (3), 034329 (2017), where we have written: "The obtained minima, to moderately oblate shapes with octupole distortions in the ratio $\beta32$ / $\beta30$ ≈Sqrt (3/5), correspond to the octupole deformation $\beta33$ superimposed on the oblate shape along its symmetry axis. A result of this superposition is an oblate spheroid with a slightly triangular equator. "

11. The distinction between static and dynamic deformations seems important. Unfortunately, dynamic calculus is only one-dimensional with constant mass parameter, and, in my opinion, one cannot draw too far-reaching conclusions on its basis. It is a direction in which time can be invested in the future.

12. Prediction of octupole magic number N=136 was made many years ago by, e.g., S.Frauendorf, V.V.Pashkevich, see Physics Letters B Volume 141, Issues 1–2, 21 June 1984, Pages 23-27 where it is clearly stated: "In summary, octupole deformed rotational bands are expected for the N = 134 region".

JIE YANG is a co-author of ten papers published primarily in good, peer-reviewed journals. The author has mastered the difficult group-theoretical apparatus and has independently written many numerical programs needed to perform the analyzes presented here.

I conclude that the work entitled: "Systematic Study of Exotic Nuclear Shape Symmetries and Isomers, Including Shape Evolution and Competition in Heavy and Super-Heavy Nuclei," written by Jie YANG under the supervision of Professor Jerzy Dudek, meets all the requirements of the currently applicable law and I would like to strongly recommend this dissertation for admission to public defense.

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