SPECTROSCOPIC PROPERTIES OF ODD-MASS RARE-EARTH NUCLEI WITHIN A MEAN-FIELD APPROACH WITH TIME-REVERSAL SYMMETRY BREAKING

NURHAFIZA MOHAMAD NOR

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DEDICATION

For me,

and

those in their twenties

who are stuck between

dreams and responsibilities.

C’est la vie.

:)

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ABSTRACT

The study of nuclear structure within mean-field approach has been in spotlight in recent years. For odd-mass nuclei, the one unpaired nucleon causes time-reversal symmetry breaking at the mean-field level. One way to address this issue is by adopting the Hartree-Fock-plus-Bardeen-Cooper-Schrieffer (HF+BCS) approach with self-consistent blocking (SCB). In the present work, some spectroscopic properties of odd-mass nuclei in the rare-earth region with atomic mass number, A in the range of $157 < A < 181$ have been investigated within the HF+BCS framework with SCB using SIII Skyrme parameterization. The calculations were limited to nuclear shapes with axial and parity symmetries. In the BCS framework, seniority force was used to approximate the pairing interaction. The pairing strengths were determined by fitting the neutron and proton pairing strengths to reproduce experimental odd-even mass staggering and moment of inertia. The neutron and proton pairing strengths were found to be rather similar in both fitting procedures, with energy of 16 MeV and 15 MeV for neutron and proton, respectively. Calculations of odd-mass nuclei were performed starting from neighboring even-even nuclei. Spectroscopic properties that have been investigated are the spin and parity, charge radii, r, electric quadrupole moment, Q_{20}, spectroscopic quadrupole moment, $Q_{20}^{(s)}$, magnetic dipole moment, μ, moment of inertia, I and band-head energy spectra. Overall, a qualitative agreement was obtained between the calculated and experimental data of all the properties mentioned. It can be concluded that this approach is able to describe the ground-state nuclear properties and rotational band-head of the chosen rare-earth nuclei.

ABSTRAK

Kajian mengenai struktur nuklear dalam pendekatan medan-min telah menjadi tumpuan dalam tahun kebelakangan ini. Untuk nukleus jisim-ganjil nukleon yang tidak berpasangan menyebabkan pemecahan simetri pembalikan-masa di medan-min. Satu cara untuk menyelesaikan isu ini adalah dengan menggunakan pendekatan Hartree-Fock-dengan-Bardeen-Cooper-Schrieffer (HF+BCS) dengan penyekatan swa-konsisten (SCB). Dalam kerja ini, beberapa sifat spektroskopi nukleus jisim-ganjil di rantau nadir-bumi dengan nombor jisim atom, A dalam julat $157 < A < 181$ telah dikaji dalam rangka kerja HF+BCS dengan SCB menggunakan parameterisasi Skyrme SIII. Pengiraan adalah terhad kepada bentuk nukleus dengan simetri paksi dan pariti. Dalam rangka kerja BCS, daya kekananan telah digunakan untuk menganggar interaksi berpasangan. Kekuatan berpasangan telah ditentukan dengan pemadanan kekuatan pasangan neutron dan proton untuk menghasilkan semula jisim ganjil-genap berperingkat dan momen inersia daripada eksperimen. Kekuatan berpasangan neutron dan proton telah didapati agak serupa dalam kedua-dua prosedur pemadanan, masing-masing dengan tenaga 16 MeV dan 15 MeV untuk neutron dan proton. Pengiraan untuk nukleus jisim-ganjil telah dijalankan bermula daripada nukleus berjiran genap-genap. Sifat spektroskopi yang telah dikaji ialah spin dan pariti, jejari cas, r, momen kutub-empat elektrik, Q_{20}, momen kutub-empat spektroskopi, $Q_{20}^{(s)}$, momen dwi-kutub magnet, μ, momen inersia, I, dan spektrum tenaga kepala-jalur. Secara keseluruhan, persetujuan kualitatif telah diperolehi antara nilai yang dihitung dan data eksperimen bagi semua sifat yang dinyatakan. Dapat disimpulkan bahawa pendekatan ini dapat menerangkan sifat nukleus keadaan-asas dan kepala-jalur putaran bagi nukleus nadir-bumi yang dipilih.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

HF	-	Hartree-Fock
BCS	-	Bardeen-Cooper-Schrieffer
SCB	-	Self-consistent blocking
HF+BCS	-	Hartree-Fock-plus-Bardeen-Cooper-Schrieffer
OES	-	Odd-even Staggering
EFA	-	Equal Filling Approximation
HFB	-	Hartree-Fock-Bogoliubov
RMS	-	root mean square

LIST OF SYMBOLS

b	-	Oscillator parameter
q	-	Deformation parameter
G_n	-	Neutron pairing strength
G_p	-	Proton pairing strength
$\Delta_n^{(3)}$	-	Neutron OES
$\Delta_p^{(3)}$	-	Proton OES
r	-	Charge radii
Q_{20}	-	Electric quadrupole moment
$Q_{20}^{(s)}$	-	Spectroscopic quadrupole moment
$\mu_{intrinsic}$	-	Intrinsic magnetic moment
μ_{total}	-	Total magnetic moment
$g_s^{(eff)}/g_s^{(g)}$	-	Spin quenching factor
g_R	-	Gyromagnetic ratio
I	-	Moment of inertia

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Research

In nuclear structure, there are several approaches for description of ground and excited state of nuclei. The mean-field approach is one of the widely used method especially for mid to heavy nuclei region. Nucleus consists of protons and neutrons needs to be treated quantum mechanically. One can solve such a many-body problem within the mean-field approach with self-consistent Hartree-Fock (HF) method thereby reducing the many-body problem to a one-body problem. The Hartree-Fock method provides a reliable approximation to closed shell magic nuclei as shown in earlier study by Vautherin and Brink [1] on nuclear properties of ^{16}O and ^{208}Pb. Vautherin then extended the work to axially deformed nuclei [2]. For an open shell nucleus, pairing is important as it affects the deformation of nuclei. One can either treat the pairing correlation by using the Bardeen-Cooper-Schrieffer (BCS) or Bogoliubov framework. The HF-plus pairing approach was further improved by including a constraint to extend the study beyond the ground-state deformation to large nuclear deformation with axially symmetry such as in the work by Flocard et al. [3, 4] as well as in the case of including triaxial symmetrical shape (see e.g [5]).

While there are many studies on even mass nuclei [4, 6], there are only a few for odd-mass nuclei due to the complication on the breaking of time-reversal symmetry from the existence of unpaired nucleon at the mean-field level. Libert and Quentin calculate the properties of 23 odd-mass nuclei in the actinide region using rotor plus quasiparticle approximation [7]. However, other approaches are better in treating the unpaired nucleons such as the equal filling approximation (EFA) and self-consistent blocking (SCB). Within these two approaches, the single-particle state of the last unpaired nucleon is blocked and therefore does not participate in the BCS pairing calculation.

The study using EFA using a Gogny type force was done by Perez-Martin and Robledo on ^{235}U [8] and ^{239}Pu by De la Iglesia et al. [9]. In EFA approach, the time reversal-symmetry is maintained by "breaking" the unpaired nucleon into half and place one-half on a single-particle state and another half in its time-reversed conjugate state, treating it like an even-even nuclei. As it seems, the core polarization caused by the unpaired nucleon was not properly accounted for in this method. In contrast to EFA, the time-odd local densities are preserved for odd-mass nuclei in SCB. Pototzky et al. performed calculations on spherical and axially deformed odd-mass nuclei in the region between atomic number, Z of Z = 16 and Z = 72 using Skyrme HF with BCS pairing correlations and blocking [10]. They studied the effect of time odd mean field by breaking the time-reversal symmetry on the binding energy odd-even staggering and separation energy. Another recent studies on odd-mass nuclei using the same methods are by Bonneau et al. [11] on magnetic moments and Koh et al. [12] on fission barriers.

1.2 Problem Statement

The existence of the last unpaired nucleons in odd-mass nuclei breaks the time-reversal invariance at the mean-field level. In the previous work of Ref. [11], the study of magnetic dipole moment has been calculated within the HF+BCS framework for some odd-mass with $A \sim 100$ and $A \sim 180$ for rare-earth nuclei and $A \sim 236$ for actinide nuclei. Results shows a good comparison between calculated and experimental quenching factor for the spin gyromagnetic ratio which then yields a good agreement of magnetic dipole moment. The same approach was used in Ref. [12] on the study of band-head energy spectra for four odd-mass actinide nuclei namely ^{237}Np, ^{241}Am, ^{235}U and ^{239}Pu using seniority force to approximate the pairing interaction. The agreement to data was found to be good for odd-neutron well deformed heavy nuclei. It has thus been shown that the approach was able to be applied reasonably well for the calculations in both cases.

As it stands, calculation on rare-earth nuclei is still lacking. Currently to the best of the author's knowledge, there is no study on the spectroscopic properties of nuclei using the Skyrme HF+BCS with self-consistent blocking approach that covers a large sample of rare-earth nuclei. Other than that, aside of the study of magnetic moments and band-head spectra on rare-earth nuclei in both works, some other properties can also be studied such as the charge radii, r, electric quadrupole moment, Q_0 and moment of inertia, I. Thus, this research will be conducted on some chosen rare-earth nuclei using the Skyrme HF+BCS approach with self-consistent blocking considering the time-reversal symmetry breaking as had been used in Ref. [11, 12].

1.3 Research Aim and Objectives

The main objective of this research is to test the validity of the Skyrme HF+BCS approach with self-consistent blocking on the rare-earth odd-mass nuclei, by taking into account the effect of time-reversal symmetry breaking at the mean-field level. In this work, the approach will be applied to calculate some spectroscopic properties of rare-earth nuclei and compared to experimental data to assess the appropriateness of the approach. The calculation for odd-mass nuclei will first need the optimization of some parameters at which the calculations of even-even nuclei are needed. Hence, this report will also includ results of even-even nuclei. By using the Skyrme HF+BCS approach with self-consistent blocking, this research takes on the following steps to achieve the main purpose of the research:

a) Calculate the properties of even-even rare-earth nuclei namely the charge radii, r, electric quadrupole moment, Q_{20}, and moment of inertia, I, and compare them with experimental data.

b) Calculate the properties of odd-mass rare-earth nuclei nuclei namely the spin and parity, charge radii, r, spectroscopic quadrupole moment, $Q_{20}^{(s)}$, magnetic dipole moment, μ and moment of inertia, I, and compare them with experimental data.

c) Calculate and compare the band-head energy spectra of odd-mass rare-earth nuclei with those obtained from experimental data.

1.4 Scope of Research

In this research, the calculations are performed within Skyrme HF+BCS framework assuming axial and parity symmetric nuclear shape. The pairing interaction that will be considered in this research is the seniority force. For odd-mass heavy nuclei, this work will consider the effect of time reversal-symmetry breaking at the mean-field level. Nuclei in the rare-earth region are chosen as the background of the research.

1.5 Significant of Research

The significance of this research is to improve understanding on the structure of deformed nuclei. One would need to improve on the theoretical description in order to describe experimental data even better. This work tests the validity of the HF+BCS approach on the theoretical calculation for rare-earth nuclei. The results from this research can also provide a guide for future experimental study.

1.6 Thesis Structure and Organization

As of far, this chapter has described the motivation, objectives, scopes and significance of the research. In Chapter 2, this thesis will focus on the theoretical aspect and some literature review of the current work. Chapter 3 shall focus at the technical details of the calculation. This chapter will explain on the choice of nuclei and Skyrme parameter, the expansion of the single-particle wavefunction, the basis parameters as well as the methods on determining the pairing strengths. The code used in this research will also be explained at the end of Chapter 3. Calculations results are presented in parts namely in Chapter 4, 5 and 6. Results of the spectroscopic properties of even-even nuclei will be discussed in Chapter 4 while odd-mass nuclei will be presented in Chapter 5. The excitation energy spectra of odd-mass nuclei in the ground state deformation will be presented in Chapter 6. In the final Chapter 7, conclusions for the present work and suggestions for future research will be made.

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2. Koh, M., **Nurhafiza, M. N.**, Rezle, N, Kelvin, K., Quentin, P. and Bonneau, L. Skyrme-Hartree-Fock Approach for Descriptions of Static Nuclear Properties of Well-deformed Nuclei. (submitted to *Malaysian Journal of Fundamental and Applied Sciences, MJFAS*).

Non-Indexed Journal

1. **Nor, M. N.**, Koh, M. and Rezle, N. A. (2018). Preliminary Investigation of Band-Head Energies and Charge Quadrupole Moment of Some Rare-Earth Nuclei within Mean-Field Approach. *Jurnal Fizik Malaysia*. 39(2), 30033-30037.

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