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Microscopic description of low-lying $M1$ excitations in odd-mass actinide nuclei

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Abstract

A restoration method of a broken symmetry which allows self-consistent determination of the separable effective restoration forces is now adapted to odd-mass nuclei in order to restore violated rotational invariance (RI-) of the Quasiparticle Phonon Nuclear Model (QPNM) Hamiltonian. Because of the self-consistency of the method, these effective forces contain no arbitrary parameters. Within RI-QPNM, the properties of the low-lying magnetic dipole excitations in odd-mass deformed $^{229-233}$Th and $^{233-239}$U nuclei have been investigated for the first time. It has been shown that computed fragmentation of the $M1$ strengths below 4 MeV in these nuclei is much stronger than that in neighboring doubly even $^{228-232}$Th and $^{232-238}$U nuclei. For ^{235}U the summed $M1$ strength in the energy range 1.5–2.8 MeV is in agreement with the relevant experimental data where the missing strength was extracted by means of a fluctuation analysis.

Keywords: Actinide; Odd-mass; $M1$ excitations; Scissors mode; Rotational invariance; QPNM

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1. Introduction

The low-lying magnetic dipole ($M1$) excitations so-called scissors mode in heavy deformed even–even nuclei has been studied by both experimentalists and theorists (for a review see Refs. [1,2]) since the first experimental discovery of it in ^{156}Gd in 1984 [3]. The remarkable features of the scissors mode in deformed even–even nuclei are the quadratic dependence of the summed B($M1$) strength on the ground state deformation (δ) below 4 MeV and centered of the low-lying $M1$ strength distributions at about 3 MeV with an average total strength of about 3 μ_N^2 [1].

Theoretical as well as experimental interest also focused on the question whether scissors mode exists in odd-mass deformed nuclei. A first experiment on ^{165}Ho showed no strong excitations in the region around 3 MeV [4]. First clear signature for low-lying $M1$ strength in an odd-mass nucleus was observed in ^{163}Dy where distribution of the strength fitting into the systematics of the scissors mode in the neighboring even–even ^{160,162,164}Dy but more fragmented [5]. Later on, a sizable dipole strength whose distribution pattern follows closely the scissors mode spectrum of the nearby even–even nuclei was reported for other odd-mass nuclei (for a review see Ref. [1]).

Early theoretical descriptions of the scissors mode in odd-mass nuclei have been carried out using Interacting Boson Fermion Model (IBFM), Generalized Coherent-State Model, Sum Rule approaches, Group Theory approaches and microscopic models [5]. However, the schematic and phenomenological models are not adequate for describing the key features such as the fragmentation of the $M1$ strength in odd-mass nuclei [1,2]. A description of the fragmented structure of $M1$ states observed in the odd-mass nuclei requires a microscopic formalism in which the interplay between the single particle and collective vibrations of the core nucleus may be treated properly. The Quasiparticle Random Phase Approximation (QRPA) or more general Quasiparticle Phonon Nuclear Model (QPNM) offers such a microscopic formalism. However, there are only two QPNM studies [6,7] in which the results for the scissors mode in some odd-A rare-earth nuclei have been reported. For systematic investigation and to give some appreciable contribution to the solution of the puzzle for odd-mass nuclei it would be important to expand the microscopic calculations on other nuclei. On the other hand, it can be noted that the application of QRPA or QPNM to the study of the $M1$ excitations has met some problems. The single particle Hamiltonian in these microscopic models is not rotationally invariant, so that conservation of angular momentum is violated in all states [8–11]. Therefore, the excitation branch with $K^\pi = 1^+$ in even–even core contains admixture of a spurious state describing the rotation of the nucleus as a whole [8–11]. The existence of the spurious contribution in core states directly affects the low-lying excited states in odd-nuclei. In order to determine exactly the energies of the discrete states and the $M1$ transition probabilities between them in odd-mass nuclei the breaking rotational symmetry of the Hamiltonian has to be restored.

There are various techniques for this purpose [1,2]. However, the most powerful among them was originally introduced by Pyatov et al. [8–10]. According to Pyatov prescription, the rotational invariance of the Hamiltonian can be restored by adding to it residual isoscalar interactions. Later on, Kuliev et al. [11] showed that the single particle Hamiltonian is not invariant under the rotational transformation due to the axial symmetric isoscalar and isovector terms of the mean field potential. Therefore, for a correct description of the $M1$ excitations, it is very important to simultaneously restore breaking invariance of these terms [11]. It was used successfully in the past to describe magnetic dipole excitations in doubly even rare-earth [12], gamma-soft [13] as