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Quantum phase transitions and collective enhancement of level density in odd–*A* and odd–odd nuclei

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Abstract

The nuclear shell model assumes an effective mean-field plus interaction Hamiltonian in a specific configuration space. We want to understand how various interaction matrix elements affect the observables, the collectivity in nuclei and the nuclear level density for odd–*A* and odd–odd nuclei. Using the *sd* and *pf* shells, we vary specific groups of matrix elements and study the evolution of energy levels, transition rates and the level density. In all cases studied, a transition between a "normal" and a collective phase is induced, accompanied by an enhancement of the level density in the collective phase. In distinction to neighboring even–even nuclei, the enhancement of the level density is observed already at the transition point. The collective phase is reached when the single-particle transfer matrix elements are dominant in the shell model Hamiltonian, providing a sign of their fundamental role.

Keywords: Quantum phase transitions; Shell model

1. Introduction

In the framework of the nuclear shell model, an effective Hamiltonian is used in order to describe the nuclear properties in a certain region of the nuclear chart. The Hamiltonian can be derived either from a theory of a deeper level or by a phenomenological fit to experimental data;

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in practice one often has to combine these approaches. The good agreement with the data has rendered the shell model a powerful tool of nuclear spectroscopy.

The spectroscopic predictions in the framework of the shell model come from the large-scale diagonalization. Practical necessity to truncate the orbital space may require the corresponding renormalization of the interaction and transition operators. The truncation limits the excitation energy below which the shell model predictions can be reliable (even if we leave aside the continuum decay thresholds). However, the practically useful region in many cases already covers the excitations relevant for laboratory experiments and for astrophysical reactions. The shell model also correctly predicts statistical properties of nuclear states. Therefore it was used as a testing ground for many-body quantum chaos [1]. In the following, we explore the effects of specific components of the effective shell-model interactions on the properties of nuclear spectra, and identify the patterns related to the effects of certain parts of these interactions. In particular, we study the qualitative changes of nuclear observables similar to phase transitions which appear as a function of the interaction in the same shell-model framework. In this way we expect to better understand the relationship between the input effective Hamiltonian and the nuclear output.

The nuclear level density given by the shell model is sensitive to the specific features of the interaction. There are successful applications of the shell model to the prediction of the level density which is a necessary ingredient for the physics of nuclear reactions [2–7]. The traditional Fermi-gas models are based on the combinatorics of particle–hole excitations near the Fermi level [8–10], with the resulting level density growing exponentially with energy. In order to account for the effects of pairing [11,12] or other interactions of collective nature [13,14], various semi-phenomenological or more elaborate self-consistent mean-field approaches [15,16] have been developed. The shell model Monte Carlo approach, for example [17], is close in spirit with the shell model, but may have problems with specific interactions and keeping exact quantum numbers. The shell model Hamiltonian inherently includes pairing and other collective interactions. Along with that, matrix elements describing incoherent collision-like processes are present as well. Taking them into account consistently, we come to the level density that, in agreement with data, is a smooth function of excitation energy. Being still limited by truncated space, this approach does not require prohibitively large diagonalization. The regular calculation of the first statistical moments of the Hamiltonian is sufficient for reproducing the realistic level density.

In this work we study the evolution of simple nuclear characteristics under the variation of the values of certain groups of matrix elements in order to link these matrix elements to the emergence of collective effects in nuclei. This work can be considered as an extension of [18] where we limited ourselves to even–even isotopes. Here we study the behavior of odd–A and odd–odd nuclei in the same mass regions under the variation of interactions. This provides an additional insight on how the presence of unpaired fermions affects the changes of nuclear spectral observables and the level density. As will be seen, the effects of the variation of the matrix elements in nuclei with unpaired fermions change the nuclear observables in a strong and systematic way. As a result of the shift of rotational and vibrational excitations to lower energy, the level density reveals the collective enhancement.

2. Matrix elements responsible for collectivity

In the case of the sd shell-model space, there are three single-particle levels (orbitals), $1s_{1/2}$, $0d_{5/2}$, $0d_{3/2}$, and 63 matrix elements of the residual two-body interaction allowed by angular momentum and isospin conservation. Similarly, for the pf shell, there are four single-particle

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