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Angular momentum projection for a Nilsson mean-field plus pairing model

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Abstract

The angular momentum projection for the axially deformed Nilsson mean-field plus a modified standard pairing (MSP) or the nearest-level pairing (NLP) model is proposed. Both the exact projection, in which all intrinsic states are taken into consideration, and the approximate projection, in which only intrinsic states with $K = 0$ are taken in the projection, are considered. The analysis shows that the approximate projection with only $K = 0$ intrinsic states seems reasonable, of which the configuration subspace considered is greatly reduced. As simple examples for the model application, low-lying spectra and electromagnetic properties of ^{18}O and ^{18}Ne are described by using both the exact and approximate angular momentum projection of the MSP or the NLP, while those of ^{20}Ne and ^{24}Mg are described by using the approximate angular momentum projection of the MSP or NLP.

Keywords: Nilsson shell model; Angular momentum projection; Pairing interaction

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1. Introduction

It is well known that the spherical harmonic oscillator (HO) shell model is a well-established theory to elucidate the structure of atomic nuclei, at least in low-energy regimes [1,2]. Through the pioneering work of Bohr [3], Belyaev [4], and Elliott [5,6], it is commonly believed that the spherical shell model can be used to describe low-lying spectroscopy of nuclei, when the most important residual interactions, such as the quadrupole–quadrupole and pairing interactions, are taken into consideration. However, to date this approach has been limited to relativity light nuclei as computational resources are currently inadequate for medium mass and heavier nuclei since the size of the model space and computational requirements grow combinatorially with an increase in the number of particles and active orbitals. In order to reduce the dimension of the configuration subspace to make shell-model solutions more feasible, some innovative alternatives have been advanced. Examples include the SU(3) shell model developed mainly by Elliott for light nuclei [5,6], the pseudo SU(3) model for heavy nuclei [7], and its symplectic Sp(6, R) and pseudo-symplectic extensions [8–11], as well as the recently developed no-core symplectic shell model, NCSpM [12], and *ab initio* symmetry-adapted no-core shell model, SA-NCSM [13], which utilize an Sp(6, R)-based model space selection. These symmetry-adapted approaches employ only a subset of important shell-model states, within which the shell-model structures, once calculations converge, can be well understood. On the other hand, self-consistent methods for deriving the nuclear mean-field with density dependent effective interactions [14–16] or relativistic mean-field considerations [17–19] based on the HF and HFB approximations have been well developed [20].

Since the quadrupole–quadrupole interaction is an important part of the residual shell model interaction that tracks with nuclear deformation and rotational spectra as demonstrated by the Elliott model [5,6], Nilsson et al. [21,22] extended the spherical shell model to the deformed case by introducing a deformation-dependent oscillator length. This provides for a simple description of deformed nuclei and their rotational structure in a (deformed) shell-model basis. Not only ground-state properties of deformed nuclei can be correctly described within the framework of the Nilsson model as shown in [21,22], but also the deformed basis can be used to simplify spherical shell-model calculations through angular momentum projection [23–25] on the deformed basis through which the dimension of the shell-model subspace is greatly reduced, especially for well-deformed nuclei.

Because the deformation introduced in the Nilsson model is intrinsic, which is equivalent to a rotational symmetry-violating mean-field description, rotational symmetry restoration or angular momentum projection is required. The deformed description is reasonable since the long-range quadrupole–quadrupole interaction is taken into account [2]. It is therefore interesting to see whether low-lying spectra of deformed nuclei can indeed be described by the deformed Nilsson model after angular momentum projection. It should be emphasized that our approach is different from those shown in [23–25], in which the Hamiltonian used is rotationally invariant based on the spherical shell model, and only the product of the deformed Nilsson single-particle states, or quasi-particle states when pairing interaction is treated by the BCS approximation, are projected in the diagonalization. In the present study the Hamiltonian used is the intrinsic deformed Nilsson mean field plus pairing interaction, which breaks the rotational symmetry, and the angular momentum projection is carried out for the intrinsic deformed Hamiltonian, but not directly for the product of the single-particle states considered in the diagonalization.

In Sec. 2, we briefly review the Nilsson mean-field plus a modified standard pairing model and the nearest-level pairing model, which are all exactly solvable. The angular momentum