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Global properties of fp-shell interactions in many-nucleon systems ☆

K.D. Sviratcheva [a,*], J.P. Draayer [a], J.P. Vary [b,c]

[a] *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[b] *Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA*
[c] *Lawrence Livermore National Laboratory, Livermore, California 94551, Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA*

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Abstract

Spectral distribution theory, which can be used to compare microscopic interactions over a broad range of nuclei, is applied in an analysis of two modern effective interactions based on the realistic CD-Bonn potential for $0\hbar\Omega$ no-core shell model calculations in the fp shell, as well as in a comparison of these with the realistic shell-model GXPF1 interaction. In particular, we explore the ability of these interaction to account for the development of isovector pairing correlations and collective rotational motion in the fp shell. Our findings expose the similarities of these two-body interactions, especially as this relates to their pairing and rotational characteristics. Further, the GXPF1 interaction is used to determine the strength parameter of a quadrupole term that can be used to augment an isovector-pairing model interaction with Sp(4) dynamical symmetry, which in turn is shown to yield reasonable agreement with the low-lying energy spectra of ^{58}Ni and ^{58}Cu.

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Keywords: Comparison of interactions; Isovector pairing; Quadrupole features; Effective interactions; Realistic potentials; Spectral distribution theory; Sp(4) dynamical symmetry

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* Corresponding author. Tel.: +225 578 0351; fax: +225 578 5855.
E-mail address: kristina@baton.phys.lsu.edu (K.D. Sviratcheva).

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1. Introduction

Realistic NN potentials, whether derived from meson exchange theory (e.g., [1]) or chiral effective field theory (e.g., [2]), and their effective interaction derivatives, provide no a priori indication regarding how well they may or may not reproduce prominent features of nuclei, such as pairing gaps in nuclear energy spectra or enhanced electric quadrupole transitions in collective rotational bands, until actually employed in shell-model calculations. While such calculations are often laborious and model dependent, a simple and straightforward evaluation of an interaction can be made using spectral distribution theory [3,4]. Indeed, spectral distribution methods can yield a deeper understanding of the nature of an interaction and above all, its role in the development of collective and correlated many-nucleon motion [5–12]. In particular, spectral distribution theory can be used to show through correlation coefficient measures the similarity of interactions. Such analyses are independent of the averages of the interactions and yield an overall comparison across a broad domain of nuclei beyond what can be achieved by overlaps of nuclear states or detailed comparisons of two-body interaction matrix elements.

In this paper we examine three modern fp-shell interactions, specifically, two interactions denoted as "CD-Bonn" and CD-Bonn + 3terms [13] based on the CD-Bonn realistic potential [1] as well as GXPF1 [14]. The GXPF1 effective interaction is obtained from a realistic G-matrix interaction based on the Bonn-C potential [15] by adding empirical corrections determined through systematic fitting to experimental energy data in the fp shell. The CD-Bonn potential is a charge-dependent one-boson-exchange nucleon–nucleon (NN) interaction that is one of the most accurate in reproducing the available proton–proton and neutron–proton scattering data. Specifically, we use two-body matrix elements of an effective "CD-Bonn" interaction derived from the CD-Bonn potential for $0\hbar\Omega$ no-core shell model (NCSM) calculations in the fp shell. In addition, the CD-Bonn + 3terms interaction introduces phenomenological isospin-dependent central terms plus a tensor force with strengths and ranges determined in $0\hbar\Omega$ NCSM calculations to achieve an improved description of the $A = 48$ Ca, Sc and Ti isobars. In this regard, we use spectral distribution theory to provide an assessment of differences between the novel CD-Bonn + 3terms interaction and "CD-Bonn" as well as a comparison of these interactions with GXPF1, which has been shown to reproduce nuclear energy spectra throughout the fp shell [14].

The likely success of the three interactions for reproducing pairing and rotational spectral features is examined in a comparison to a pairing-plus-quadrupole model interaction, which combines a Sp(4) dynamically symmetric model interaction [16,17] for description of like-particle and proton–neutron (isovector) pairing correlations with a SU(3) symmetric term that governs a shape-determined dynamics. If the model and effective interactions are strongly correlated, then the latter will reflect the characteristic properties of the simpler model Hamiltonian, which in turn may be used as a good approximation.

The present study, which is complementary to a similar $1f_{7/2}$ analysis [18], focuses on the upper fp-shell domain, which includes neutron-deficient and $N \approx Z$ nuclei along the nucleosynthesis rp-path and unstable nuclei currently explored in radioactive beam experiments [19,20]. The analysis of the upper fp results reveals overall properties of the interactions under consideration different from those observed in the $1f_{7/2}$ orbit.

Several detailed reviews of the nuclear shell model and its applications have been published recently [21–23] that delve into related key physics issues that are explored in the present work. However, the spectral distribution analysis provided here is novel and sheds considerable light