A new covariant density functional with point-coupling and its application

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Abstract. The covariant density functional theory with a few number of parameters allows a very successful phenomenological description of ground state properties of nuclei all over the nuclear chart. The newly proposed point-coupling parametrization PC-PK1 [1] and its application is reported. In particular, the description of the nuclear ground state properties and the neutron single-particle spectrum in 132Sn is discussed in details.

1. Introduction
The density functional theory (DFT) is well known for its numerous applications to the description of nuclear ground and excited states. In particular, the covariant version of DFT takes the Lorentz symmetry into account in a self-consistent way. During the past years, the covariant DFT has received wide attention due to its successful description of lots of nuclear phenomena [2, 3].

There exist a number of attractive features in the covariant DFT, especially in its practical applications in the self-consistent relativistic mean-field (RMF) framework. The most obvious one is the natural inclusion of the spin degree of freedom and the resulting spin-orbit potential that emerges automatically with the empirical strength in a covariant way. The relativistic effects are responsible for the existence of approximate pseudospin symmetry in the nuclear single-particle spectra [4, 5, 6, 7] and spin symmetry in the anti-nucleon spectra [8]. Moreover, a covariant treatment of nuclear matter provides a distinction between scalar and four-vector nucleon self-energies, leading to a natural saturation mechanism.

The traditional RMF framework is based on the meson-exchange representation, i.e., the Dirac nucleons interact with each other via the exchange of mesons. In recent years, the RMF model with point-coupling interaction (RMF-PC) [9], in which the zero-range point-coupling interaction is used instead of the meson exchange, has attracted more and more attentions owing to the following advantages. First, it avoids the possible physical constraints introduced by explicit usage of the Klein-Gordon equation to describe mean meson fields, especially the fictitious σ meson. Second, it is possible to study the role of naturalness in effective theories for nuclear-structure-related problems [10]. Third, it provides more opportunities to investigate its relationship to the nonrelativistic approaches. Finally, it is relatively easy to study the effects beyond the mean-field for nuclear low-lying collective excited states [11].
In practical application of the RMF-PC model, the most widely used parametrizations include PC-LA [9], PC-F1 [12], and DD-PC1 [13]. However, the isospin dependence of the binding energy given by both PC-LA and PC-F1 along either the isotopic or the isotonic chain deviates from the data remarkably. The density-dependent parametrization DD-PC1 was proposed from the equation of state for nuclear matter and the masses of 64 deformed nuclei. Although it reproduces the binding energies, deformations, and charge radii of deformed nuclei quite well, the differences between the predicted binding energies and the corresponding data are somewhat large for spherical nuclei.

In the symposium, we presented the newly proposed point-coupling parametrization PC-PK1 [1] for covariant DFT and its application including the description of

- the nuclear ground state properties [1];
- the neutron single-particle spectrum in $^{132}$Sn [14];
- the magnetic rotation bands in $^{60}$Ni [15];
- the nuclear low-lying excitation states [1].

In this report, only the description of the nuclear ground state properties and the neutron single-particle spectrum in $^{132}$Sn will be discussed in details due to the limitation in length.

2. PC-PK1 parametrization

The parametrization of PC-PK1 is determined by a multiparameter fitting to both the binding energies and charge radii for 60 selected spherical nuclei with the Levenberg-Marquardt method. Meanwhile, the empirical neutron pairing gaps for 6 nuclei obtained with the five-point formula are also employed to constrain the pairing strengths. With the experimental observables and the calculated values, the ensemble of parameters can be obtained by minimizing the square deviation. More details for the fitting procedure and coupling constants of the parameter set PC-PK1 can be found in Ref. [1].

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Deviations of the calculated binding energies from the data [16] for Yb and U isotopes obtained by PC-PK1, DD-PC1, and PC-F1 (upper panel) as well as the corresponding calculated ground state deformations in comparison with data [17] (lower panel). The filled circles and squares in the upper panels correspond to the rotational corrected values given by PC-PK1 and PC-F1, respectively. Taken from Ref. [1].
3. Nuclear ground state properties

Taking Yb and U isotopes as examples, the binding energies and quadrupole deformations of the ground states are investigated. In the upper panels of Fig. 1, the deviations of the calculated binding energies with PC-PK1, DD-PC1, and PC-F1 from the data [16] are shown. When the rotational corrections are not taken into account, a systematic underestimation of the binding energies around 3 MeV for both Yb and U isotopes is found for PC-PK1. For PC-F1, the difference between the calculated and the observed binding energy decreases monotonically with the isospin values. As almost all the isotopes shown in Fig. 1 are used to adjust the parameters, the predictions with DD-PC1 are in good agreement with the data (within 1 MeV).

After taking into account the rotational correction energies with the cranking approximation [18], the calculated results by PC-PK1 reproduce the data quite well (within 1 MeV) for both Yb and U isotopes, while the differences between the corrected binding energies given by PC-F1 and data are still large. Since DD-PC1 is adjusted to the binding energies of well-deformed nuclei, the rotational correction energy is not considered in the corresponding calculations.

The calculated ground state deformations are shown in the lower panels of Fig. 1 in comparison with the data available [17]. It is found that PC-PK1 can provide also good performance in the description of the deformations as well as their corresponding evolutions with neutron number for both Yb and U isotopes.

4. Neutron single-particle spectrum in $^{132}$Sn

![Figure 2. Neutron-effective single-particle energies with respect to the orbital $2f_{7/2}$ in $^{132}$Sn calculated by the RMF theory with effective interactions PC-PK1, NL3*, DD-ME2, PK1, and PKDD. The experimental data and the results calculated by the Skyrme-Hartree-Fock theory with SkP, SkM*, BSK17, SLy4, and SIII are also shown for comparison. The shaded areas indicate the area beyond the neutron threshold. Taken from Ref. [14].](image)

The concept of magic numbers is one of the most fundamental ingredients for understanding the nature of atomic nuclei. Recently, by using the $^{132}$Sn(d,p)$^{133}$Sn reaction, the experiment performed at Oak Ridge National Laboratory revealed for the first time that the spectroscopic factors of the neutron single-particle states $3p_{1/2}, 3p_{3/2}, 2f_{5/2},$ and $2f_{7/2}$ outside the $N = 82$ core are consistent with $S \approx 1$ [19]. This is one of the critical pieces of evidence to conclude that $^{132}$Sn is a perfectly radioactive doubly magic nuclei, even better than the stable $^{208}$Pb.

In Fig. 2, the neutron-effective single-particle energies (SPE) with respect to the orbital $2f_{7/2}$ in $^{132}$Sn calculated by the RMF theory with PC-PK1, NL3*, DD-ME2, PK1, and PKDD are compared with the experimental data [19] and results calculated by the Skyrme-Hartree-Fock theory with typical effective interactions SkP, SkM*, BSK17, SLy4, and SIII. At the present
mean-field level, it is clearly shown that the overall structure of the neutron-effective SPE for such a neutron-rich doubly magic nucleus can be well reproduced in the relativistic framework, where both the spin-orbit and orbit-orbit potentials are described in a self-consistent way. In contrast, the nonrelativistic results overestimate nearly twice the single-particle energy spacing between the orbitals $3p_3/2$ and $2f_7/2$, where the reduction of the orbit-orbit potential plays the most important role.

Furthermore, one can extract the Nilsson spin-orbit parameter $C$ and orbit-orbit parameter $D$ by fitting to the single-particle energies. It is found that the RMF results agree quite well with the extracted Nilsson spin-orbit parameter $C$ and orbit-orbit parameter $D$ from experimental SPE of $^{132}$Sn, but remarkably differ from the traditional Nilsson parameters.

5. Conclusion
In summary, the newly proposed point-coupling parametrization PC-PK1 [1] for covariant DFT and its application are briefly reported. In particular, the description of the nuclear ground state properties with PC-PK1 is discussed in details. PC-PK1 is determined by fitting to the observables of 60 selected spherical nuclei, including the binding energies, charge radii, and empirical pairing gaps. It is found that PC-PK1 can provide very good descriptions for the binding energies as well as its isospin dependence along either the isotopic or the isotonic chains, which makes it reliable for application in exotic nuclei.

Investigations have also been applied to the single-particle spectrum of the neutron-rich doubly magic nucleus $^{132}$Sn. It is found that the RMF results agree quite well with the experimental single-particle spectrum in $^{132}$Sn as well as the Nilsson spin-orbit parameter $C$ and orbit-orbit parameter $D$ thus extracted, but remarkably differ from the traditional Nilsson parameters.

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