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There were 40 participants from different institutions in the symposium. This proceedings contain 17 papers which cover a wide range of subjects including topics in quark degreeds of freedom, microscopic problems, exotic nuclei, heavy ion collision, high spin, and nuclear astrophysics.

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New Effective Interactions, New Symmetry and New States in Atomic Nuclei*

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Abstract Recent works on the relativistic description of exotic nuclei and nuclear matter at extreme conditions are reviewed. New effective interactions, PK1, PK1r and PKDD in the relativistic mean field (RMF) theory, are proposed with the center-of-mass correction included in a microscopic way. They are able to provide an excellent description not only for the properties of nuclear matter and neutron stars, but also for the nuclei near or far from the beta-stability line, including halos and giant halos at the neutron drip line in nuclei and hyper-nuclei. Based on the solution of the RMF equations, good spin symmetry is found in anti-nucleon spectra.

Key words relativistic mean field, effective interaction, spin symmetry, exotic nuclei

1 Introduction

The relativistic mean field (RMF) theory [1] is a widely used and successful approach for describing properties of nuclear matter and finite nuclei. It has been used not only for describing the properties of nuclei near the valley of stability successfully[2], but also for predicting the properties of exotic nuclei with large neutron or proton excess[3, 4]. Based on the RMF theory and its generalization, some works on new effective interactions, new symmetry and new states in exotic nuclei have been done in Peking University, which are summarized in the following. The ground state properties for C, N, O, F and Na isotopes up to the neutron drip line have been systematically studied with the self-consistent microscopic relativistic continuum Hartree-Bogoliubov (RCHB) theory. With the nucleon density distribution thus obtained, the charge-changing cross sections for C, N, O, F and interacting cross section for Na isotopes are calculated using the Glauber model. Good agreement with the data has been achieved[5, 6]. The proton magic O, Ca, Ni, Zr, Sn, and Pb isotopes from the proton drip line to the neutron drip line are investigated with

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the RCHB theory. Halos and giant halos in Ca isotopes with $A > 60$ and Ne-Na-Mg drip line nuclei are predicted[7,8]. Based on a systematic investigation of the data available for nuclei with $A \geqslant 40$, a new isospin dependent $Rc/Z^{1/3}$ formula for the nuclear charge radius is proposed[9]. The Woods-Saxon basis is suggested to replace the widely used harmonic oscillator basis for solving the RMF equations in order to be generalized to study exotic nuclei[10, 11]. Based on the Schrödinger and Dirac equations, the energies and widths for single-particle resonant states in square-well, harmonic-oscillator and Woods-Saxon potentials have been investigated by analytic continuation in the coupling constant[12,13]. The structure and synthesis of superheavy nuclei are discussed based on the RMF theory and research on nuclides beyond the drip-line[14, 15], the hyperon-nucleon interaction, properties of neutron star [16—18] and the existence of hyperon halos and neutron halos in hyper-nuclei[19,20]. The pseudo-spin symmetry in the particle spectra and the spin symmetry in the anti-particle spectra are discussed[21—24]. The magnetic rotation and chiral doublets for nuclei in $A \sim 100$ and $A \sim 130$ regions have been studied with cranking RMF theory and the particle-rotor model[25,26].

In this paper, we will present a brief review on the new effective interactions for the Lagrangian density in RMF theory, their description for halos and giant halos at the neutron drip line, and the new spin symmetry in anti-nucleon spectra.

2 New effective interactions

In the mean field theory, the effective interactions are adjusted to reproduce various properties of nuclear matter and finite nuclei. A number of effective interactions of meson-baryon couplings based on the RMF theory have been developed, including nonlinear self-couplings for the σ-meson and/or ω-meson, such as NL1, NL2[27], NL3[28], NLSH[29], TM1 and TM2[30]. However, these nonlinear interactions have problems of stability at high densities, as well as the question of the physical foundation[27]. A more natural alternative is to introduce a density dependence in the couplings[31]. Based on the Dirac-Brueckner calculations, Typel and Wolter proposed the density-dependent effective interaction TW-99 and expected that the model could be reasonably extrapolated to extreme conditions of isospin and/or density[31]. Along this line, Nikšić et al. developed another effective interaction DD-ME1[32].

Along the β-stability line NL1 gives excellent results for binding energies and charge radii. Far away from the stability line the results are less satisfactory due to the large asymmetry energy $a \cong 44$MeV. In addition, the calculated neutron skin thickness shows systematic deviations from the data. NLSH produces an asymmetry energy $a \cong 36$MeV while giving a slight over-binding along the line of beta-stability. It also fails to reproduce the superdeformed minima in Hg-isotopes. For the nuclear matter incompressibility, NL1 predicts $K = 212$ MeV while $K = 355$MeV for NLSH. Both fail to reproduce the isoscalar giant monopole resonances for Pb and Zr nuclei. As an improvement, the effective interactions NL3 and TM1, provide reasonable incompressibility, $K_{NL3} = 271.1$MeV and $K_{TM1} = 281.2$MeV, and asymmetry energy ($a_{NL3} = 37.4$ MeV, $a_{TM1} = 36.9$MeV), but they give fairly small saturation density, $\rho_{NL3} = 0.148\text{fm}^{-3}$, $\rho_{TM1} = 0.145\text{fm}^{-3}$. NL2 and TM2 are mainly used for light nuclei. One should note that in all these parameterizations, the center-of-mass corrections are treated in a phenomenological way. In Fig.1, the microscopic center-of-mass correction from the RCHB calculation[3, 4] for proton magic isotopes is shown in comparison with usual phenomenological estimations. Systematic deviations can be seen.

As the effective interaction without nonlinear ω terms leads to strong repulsive potential for nuclear matter at high density, new effective interactions with nonlinear ω self-coupling (PK1) and also nonlinear ρ self-coupling (PK1r) have been developed. The microscopic estimation for the center-of-mass corrections has been improved by the fitting of new effective interactions. Following the density dependent interaction TW-99 and DD-ME1, PKDD is also proposed. These

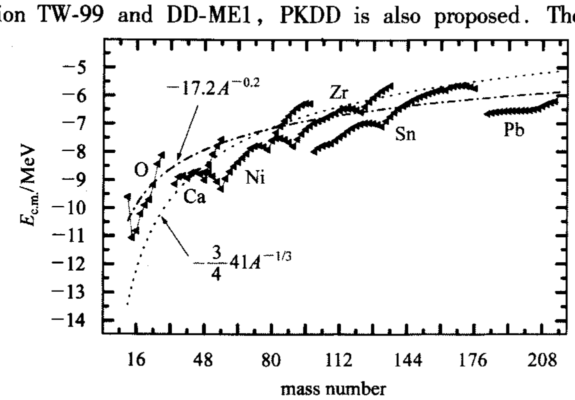

Fig.1. The microscopic center-of-mass correction from the RCHB theory(symbols) in comparison with the phenomenological ones(dotted and dot-dashed lines).

three new interactions are shown in Tables 1 and 2. In the parameterization, the masses of some spherical nuclei and the incompressibility K, the saturated density ρ_{sat} and the symmetry energy ρ_{sym} of nuclear matter are included; the details can be seen in Ref. [33].

Table 1. The nonlinear effective interactions PK1, PK1r and density-dependent effective interactions PKDD in comparison with TM1, NL3, and TW-99 and DD-ME1.

	PK1	PK1r	PKDD	TM1	NL3	TW-99	DD-ME1
M_n	939.57	939.57	939.57	938.00	939.00	939.00	938.50
M_p	938.28	938.28	938.28	938.00	939.00	939.00	938.50
m_σ	514.09	514.09	555.51	511.20	508.19	550.00	549.53
m_ω	784.25	784.22	783.00	783.00	782.50	783.00	783.00
m_ρ	763.00	763.00	763.00	770.00	763.00	763.00	763.00
g_σ	10.322	10.322	10.739	10.029	10.217	10.729	10.443
g_ω	13.013	13.013	13.148	12.614	12.868	13.290	12.895
g_ρ	4.5397	4.5500	4.2998	4.6322	4.4744	3.6610	3.8053
g_2	−8.169	−8.156	0	−7.233	−10.43	0	0
g_3	−9.998	−10.20	0	0.6183	−28.89	0	0
c_3	55.636	54.446	0	71.308	0	0	0
d_3	0	350	0	0	0	0	0

Table 2. Density-dependent parameters of PKDD for meson-nucleon coupling in comparing with TW-99 and DD-ME1.

	PKDD	TW-99	DD-ME1
a_σ	1.327423	1.365469	1.385400
b_σ	0.435126	0.226061	0.978100
c_σ	0.691666	0.409704	1.534200
d_σ	0.694210	0.901995	0.466100
a_ω	1.342170	1.402488	1.387900
b_ω	0.371167	0.172577	0.852500
c_ω	0.611397	0.344293	1.356600
d_ω	0.738376	0.983955	0.495700
a_ρ	0.183305	0.515000	0.500800

Using PK1, PK1r and PKDD together with NL1, NL2, NL3, NLSH, TM1, TM2, GL-97[34] and the density-dependent parameter sets TW-99, DD-ME1, the density dependence of various effective interaction strength in RMF are studied and carefully compared in nuclear matter and neutron stars[35, 36].

In Fig.2, the effective interaction strengths for g_σ (top), g_ω(middle) and g_ρ(bottom) in nuclear matter are shown as functions of the nuclear density. The curves in the

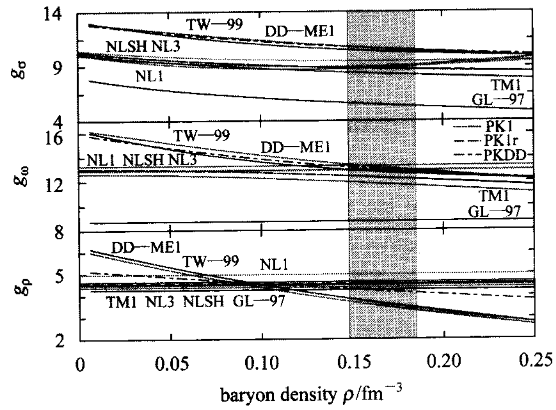

Fig.2. Density dependences of the effective interaction strengths for g_σ(top), g_ω(middle) and g_ρ(bottom) in nuclear matter as functions of the nuclear density. The shadowed area corresponds to the empirical value of the saturation point in nuclear matter(Fermi momentum $k_F = 1.35 \pm 0.05\text{fm}^{-1}$ or density $\rho = 0.166 \pm 0.018\text{fm}^{-3}$).

figures are labeled from top to bottom orderly from left to right. The shadowed area corresponds to the empirical value of the saturation point in nuclear matter, which is Fermi momentum $k_F = 1.35 \pm 0.05\text{fm}^{-1}$ or density $\rho = 0.166 \pm 0.018$ fm^{-3}. For the nonlinear effective interaction, the "equivalent" density dependence of the effective interaction strengths for σ, ω and ρ is extracted from the meson field equations according to:

$$g_\sigma(\rho) = g_\sigma + U'(\sigma)/\rho_s = g_\sigma + (g_2\sigma^2 + g_3\sigma^2)/\rho_s,$$
$$g_\omega(\rho) = g_\omega + U'(\omega)/\rho = g_\omega - (c_3\omega^3)/\rho,$$
$$g_\rho(\rho) = g_\rho.$$

For the σ-meson, TW-99 and DD-ME1 are quite different from the other strengths in either magnitude or slope. In particular, the strength in TW-99 and DD-ME1 for the density interval in Fig.2 is almost twice as large as that of GL-97. Quite different results can also be seen at the empirical nuclear matter densities. For the ω-meson, except TW-99, DD-ME1, TM1 and TM2, all the other strengths are density-independent. However, the strengths are close to each other at the empirical saturation density compared with those for the σ-meson, although large differences can also be seen at low density. For the ρ-meson which describes the isospin asymmetry, the strengths for TW-99 and DD-ME1 show strong density dependence in contrast with the other parameter sets. PK1, PK1r and PKDD are just in between.

The binding energy per nucleon, $E_B/A = \varepsilon/\rho - m$, is also investigated for pure neutron matter, symmetric nuclear matter and neutron stars; more details can be found in Refs. [33,35—37].

3 Halos and giant halos

We calculate the even-even nuclei of Pb isotope chains with the new effective interactions. Shown in Fig.3 are the differences between the predictions of PK1, PK1r and PKDD for Pb isotopes and the data[38]. For comparison, the results of TM1, NL3, TW-99 and DD-ME1 are also shown. All the results are calculated with RCHB theory[4]. The pairing correlations are treated self-consistently for zero-range δ-force. The microscopic center-of-mass correction is used in all the calculations. The new effective interactions PK1, PK1r and PKDD provide a good description of the masses for Pb isotope chains. In Fig.3, all the effective interactions overestimate the binding energy at the beginning of the isotope chain. While from ^{190}Pb to ^{210}Pb, the new interactions give better descriptions than all the others. Similar cases can also be seen for the other proton magic isotope chains.

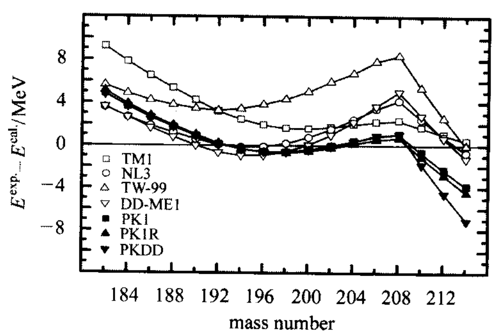

Fig.3. The deviation of the calculated energies for Pb isotopes in RCHB with PK1, PK1r and PKDD from the experimental values. The results with TM1, NL3, TW-99 and DD-ME1 are also included.

From the binding energies we can extract systematics in the two-neutron separation energies. In Fig.4, the systematic behavior of two-neutron separation energies with neutron number, predicted by the new effective interactions PK1 and PKDD, is shown. It can be seen from these figures that the new effective interactions give a good description for two-neutron separation energies. Here all the theoretical results are from RCHB theory. The interesting phenomena of the so called giant halo predicted in Ca and Zr isotopes near the neutron drip line[4, 7, 8, 19, 20], exist also for these new interactions.

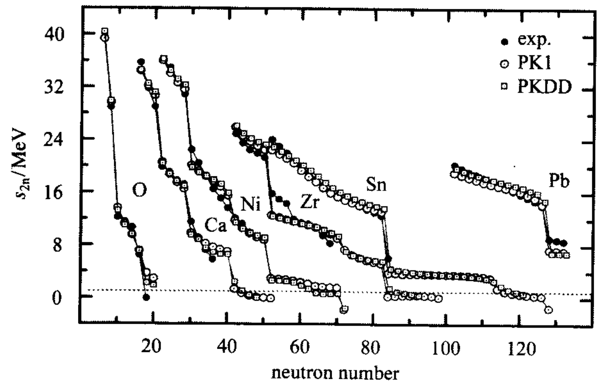

Fig.4. The two-neutron separation energy calculated with PK1, PK1r and PKDD for proton magic isotopes.

4 Spin symmetry in anti-nucleon spectra

Although the RCHB theory has achieved success in describing the exotic nuclei near the drip line, the deformation is not included there. It's well known that the harmonic oscillator (HO) basis is not suitable for studying exotic nuclei. For deformed nuclei, working in r space becomes much more difficult and numerically very sophisticated[10]. A reconciler between the HO basis and r space may be the Woods-Saxon (WS) basis. The spherical relativistic Hartree theory in the Woods-Saxon basis (SRHWS) is proposed in Ref. [11] where the Woods-Saxon basis is obtained by solving either the Schrödinger equation (SRHSWS) or the Dirac equation (SRHDWS). The WS basis in the SRHDWS theory is much smaller than that in the SRHSWS theory, which will largely facilitate the deformed problem. In SRHDWS calculations, negative energy states in the Dirac sea must be included in the basis in terms of which nucleon wave functions are expanded. We studied in detail the effects and contributions of negative energy states.

We find a very well developed spin symmetry in single anti-nucleon spectra. In Fig.5, we present the spin-orbit splitting in anti-neutron spectra of ^{16}O and ^{208}Pb. For ^{16}O, the spin-orbit splitting is around 0.2—0.5MeV for p states. With increasing particle number A the spin symmetry in the anti-particle spectra becomes even more exact. For ^{208}Pb, the spin-orbit splitting is about 0.1MeV for p states and less than 0.2MeV even for h states. The dominant components of the wave functions of the spin doublet are almost identical. This spin symmetry in anti-particle spectra and the pseudo-spin symmetry in particle spectra have the same origin[21—24].

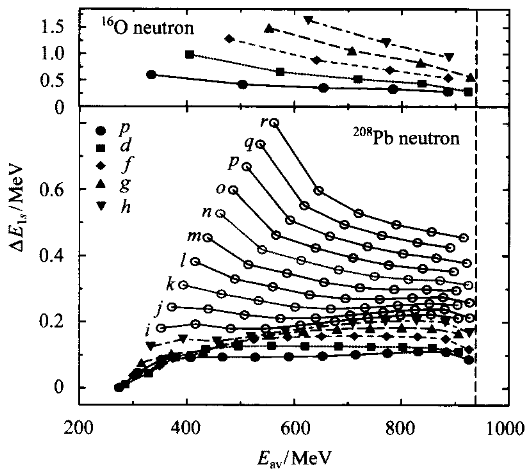

Fig.5. Spin-orbit splitting in anti-neutron spectra of ^{16}O and ^{208}Pb versus the average energy of a pair of spin doublets. The vertical dashed line shows the continuum limit.

However the spin symmetry in anti-nucleon spectra is much better developed than the pseudo-spin symmetry in normal nuclear single particle spectra[24].

5 Summary

The new effective interactions PK1, PK1r, and PKDD are proposed. They are able to provide an excellent description not only for the properties of nuclear matter and neutron stars, but also for nuclei in the nuclear chart from the proton to the neutron drip line, including halos and giant halos at the neutron drip line in nuclei and hyper-nuclei. To describe the deformed nuclei close to the drip-line, the Woods-Saxon basis has been suggested to replace the widely used harmonic oscillator basis for solving the RMF theory. We find spin symmetry in the single anti-nucleon spectra in nuclei. The origin of the spin symmetry in anti-nucleon spectra and that of the pseudo-spin symmetry in nucleon spectra are the same but the former is much more conserved in real nuclei.

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原子核中新的有效相互作用、新对称性及奇特核态*

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摘要 总结了近年来对奇特核和极端条件下核物质的研究结果,包括原子核的新有效相互作用、新对称性及奇特性质.在相对论平均场理论中,发现了反核子谱中的自旋对称性,提出了包含微观质心修正的新相互作用 PK1,PK1r 和 PKDD.这些新相互作用不但可以很好地描述核物质与中子星,还可以很好地给出靠近或远离 β 稳定线的原子核性质,包括中子滴线核与超核中的晕和巨晕现象.

关键词 相对论平均场 有效相互作用 自旋对称性 奇特核

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