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Nuclear Physics A 929 (2014) 191–201
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Relativistic mean-field study of time-odd fields and the effects on binding energies in light nuclei

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Received 17 April 2014; received in revised form 13 June 2014; accepted 27 June 2014

Abstract

The axially deformed relativistic mean field theory with the effective interaction PK1 has been applied to investigate the contributions of time-odd fields to the ground-state binding energies of 66 odd–odd nuclei and 140 odd-A nuclei in O–Ca isotopes. The results show that the ground-state deformation and configuration of 5 nuclei have been changed with considering the time-odd fields. The odd–odd nuclei have two unpaired valence nucleons and corresponding contribution of time-odd fields to binding energies (0.15–0.90 MeV) are larger than of the neighboring odd-A nuclei with only one unpaired valence nucleon (<0.4 MeV), and thus a staggering for this contribution appears in the isotones with odd number of neutrons. In addition, taking Al isotopes as an example, the contributions of time-odd fields to binding energies and corresponding configurations are studied in detail. Moreover, azimuthal components of neutron and proton currents in ^{22}Al, ^{24}Al and ^{26}Al, and the differences between the contributions of time-odd fields to ground-state binding energies of mirror nuclei, as well as the odd–even staggering of binding energies, are also investigated.

Keywords: Relativistic mean field; Time-odd fields; Binding energies; O–Ca isotopes; Odd–even staggering

1. Introduction

In the past decades, relativistic mean field (RMF) theory has been successfully applied to the analysis of nuclear structure over the whole periodic table, from light to superheavy nuclei with

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http://dx.doi.org/10.1016/j.nuclphysa.2014.06.015

a few universal parameters [1–4]. In the widely used version of RMF models, only the time-even components of vector meson fields are taken into account, while the time-odd components of vector fields, i.e., the time-odd fields (TOF), are neglected. In fact, the baryon current due to the unpaired valence nucleons in odd-A or odd–odd nuclei will lead to the time-odd fields. The time-odd fields together with the corresponding core polarization will modify the nuclear current, single-particle Dirac spinor, nuclear energies and magnetic moments, etc. The importance of the time-odd fields has been demonstrated in the successful descriptions of nuclear magnetic moment [5–8], moment of inertia for identical superdeformed bands [9], and M1 transition rates in magnetic rotation [10,11] as well as E2 transition rates in antimagnetic rotation [12]. In addition, the time-odd fields provide additional binding energies which also have important effect on nucleon separation energy [13], shell gap [14], pairing correlation [15] and so on.

Recently, the impact of time-odd fields on physical observables have been studied in detail in covariant density functional theory with non-rotating systems [16]. However, it mainly referred to the odd-mass nuclei. Thus, it is very interesting to study the effect of time-odd mean fields on odd–odd nuclei. In this paper, taking light nuclei as an example, we will systematically investigate the contributions of time-odd fields to the binding energies of odd-A nuclei and odd–odd nuclei in O–Ca isotopes using axially deformed RMF approach, and discuss the configuration of unpaired valence nucleons, and neutron and proton currents and contribution to mirror nuclei in detail, as well as the odd–even staggering (OES) of binding energies.

2. Theoretical framework

The starting point of the RMF theory is the standard effective Lagrangian density constructed with the degrees of freedom associated with the nucleon field ψ, two isoscalar meson fields σ and ω_μ, the isovector meson field ρ_μ, and the photon field A_μ [1–4]. Under “mean-field” and “no-sea” approximations, one can derive the corresponding energy density functional, from which one finds immediately the equation of motion for a single-nucleon orbital ψ_i by variational principle.

For even–even nuclei with time reversal symmetry, the time-odd components of vector mesons and photon fields do not contribute to the energy functional. In odd-A nuclei, the odd nucleon breaks the time-reversal invariance, and time-odd fields give rise to the nuclear magnetic potential. Then the Dirac equation with the time-odd fields can be obtained as

$$\big[\boldsymbol{\alpha}\cdot(-i\nabla-\boldsymbol{V})+V_0+\beta(M+S)\big]\psi_i=\varepsilon_i\psi_i, \tag{1}$$

where the scalar potential can be written as $S=g_\sigma\sigma$, the time-like component of vector potential $V_0=g_\omega\omega_0+g_\rho\tau_3\rho_0+e\frac{1-\tau_3}{2}A_0$, the space-like (time-odd) component of vector potential $\boldsymbol{V}=g_\omega\boldsymbol{\omega}$, while ρ and A are ignored since they turn out to be small compared with ω field in light nuclei [6]. This also can be seen for the corresponding calculations of $^{119\text{–}183}$Ce in Ref. [16].

The Klein–Gordon equations for σ, time-like components of vector mesons fields ω_0, ρ_0, and electromagnetic fields A_0 are the same as those in Ref. [8]. The time-odd components of vector meson fields $\boldsymbol{\omega}$ is determined by

$$\big(-\Delta+m_\omega^2\big)\boldsymbol{\omega}=g_\omega\boldsymbol{j}_B-c_3\omega^\nu\omega_\nu\boldsymbol{\omega}, \tag{2}$$

with $\boldsymbol{j}_B=\sum_{i=1}^{A}n_i\bar{\psi}_i\boldsymbol{\gamma}\psi_i$. Under “no-sea” approximations, the summation is confined to the particle states with positive energies. Following Ref. [16], pairing correlations are neglected for better isolation of the effects induced by time-odd fields, and the occupation numbers n_i take