Magnetic moments of $^{33}$Mg in time-odd relativistic mean field approach

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Abstract

The configuration-fixed deformation constrained relativistic mean field approach with time-odd component has been applied to investigate the ground-state properties of $^{33}$Mg with effective interaction PK1. The ground state of $^{33}$Mg has been found to be prolate deformed, $\beta_2 = 0.23$, with the odd neutron in $1/2[330]$ orbital and the energy $-251.85$ MeV which is close to the data $-252.06$ MeV. The magnetic moment $-0.9134 \mu_N$ is obtained with the effective electromagnetic current which well reproduces the data $-0.7456 \mu_N$ self-consistently without introducing any parameter. The energy splittings of time reversal conjugate states, the neutron current, the energy contribution from the nuclear magnetic potential, and the effect of core polarization are discussed in detail.

PACS numbers: 21.10.Ky, 21.10.Dr, 21.60.-n, 27.30.+t8

Keywords: Magnetic moment, Binding energy, Time-odd component, Configuration-fixed deformation constrained calculation, Relativistic mean field theory
I. INTRODUCTION

Nuclear magnetic moment, as one of the most important physical observables, provides key information to understand nuclear structure, and has attracted the attention of nuclear physicists since the early days [1, 2, 3]. Apart from the magnetic moments of stable nuclei [4], it is now even possible to measure the nuclear magnetic moments of many short-lived nuclei far from the stability line with high precision [5] with the development of the radioactive ion beam (RIB) technique.

Recently the nuclear magnetic moments of $^{33}$Mg has become a hot topic due to the following reasons: 1) it is a neutron-rich nucleus close to the so-called “island of inversion” [6]; 2) different spins and configurations for the ground state of $^{33}$Mg are assigned in a series of experiments [7, 8, 9, 10]. In order to remove the confusion, the spin and magnetic moment for the ground state in $^{33}$Mg have been directly measured in Ref. [11] with $I = \frac{3}{2}$ and $\mu = -0.7456(5)\mu_N$, which becomes a test for various theoretical approaches. In shell-model, the magnetic moment of the ground-state in $^{33}$Mg, can be reproduced only in the model space with $2p - 2h$ configuration [11]. With the assignment of configuration in Ref. [10], the simple Additivity Rules [12] can only account for half of the experimental magnetic moment.

For the last two decades, the relativistic mean field (RMF) theory [13] has achieved great success in describing many phenomena in the nuclei near and far from the line of $\beta$-stability [14, 15, 16]. In the widely used version of RMF models, only the time-even component of vector meson fields are taken into account. In odd-A or odd-odd nuclei, however, the baryon current due to the unpaired valence nucleons will lead to the time-odd components of vector fields, i.e., the time-odd fields. The time-odd fields together with the corresponding core polarization will modify the nuclear current, single-particle Dirac spinor, and magnetic moments, etc. The importance of the time-odd fields has been demonstrated in the successful descriptions of nuclear magnetic moments [17, 18, 19], moment of inertia for identical superdeformed bands [20], and $M1$ transition rates in magnetic rotation [21, 22], etc.

In this paper, the ground-state properties of $^{33}$Mg including the binding energy and magnetic moment will be investigated in axially deformed RMF approach with time-odd components of vector meson field [23]. In order to examine the magnetic moments for different valence nucleon configurations, both adiabatic and configuration-fixed deformation
constrained calculation [24] will be performed.

II. THEORETICAL FRAMEWORK

The basic ansatz of RMF theory is a lagrangian density [13, 14, 16, 25] where nucleons are described as Dirac particles which interact via the exchange of various mesons and photon. The lagrangian density is written in the form

\[ \mathcal{L} = \bar{\psi} \left( i \gamma^\mu \partial_\mu - M - g_\sigma \sigma - g_\omega \gamma^\mu \omega_\mu - g_\rho \gamma^\mu \vec{\tau} \cdot \vec{\rho}_\mu \right) \psi + \frac{1}{2} \bar{\psi} \left( \gamma^\mu \partial_\mu - M - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3} g_3 \sigma^3 \right) \psi + \frac{1}{2} \Omega^{\mu\nu} \Omega_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{1}{4} c_3 (\omega^{\mu} \omega_\mu)^2 \psi + \frac{1}{2} \bar{\rho} \cdot \vec{\rho}_\mu + \frac{1}{4} m_\rho^2 \vec{\rho} \cdot \vec{\rho}_\mu - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}. \] (1)

The meson fields contain the isoscalar \( \sigma \) meson, isoscalar-vector \( \omega \) meson and the isovector-vector \( \rho \) meson. \( M \) and \( m_i(g_i) (i = \sigma, \omega, \rho) \) are the masses (coupling constants) of the nucleon and the mesons respectively and

\[ \Omega^{\mu\nu} = \partial^\mu \omega^\nu - \partial^\nu \omega^\mu \] (2a)

\[ \vec{R}^{\mu\nu} = \partial^\mu \vec{\rho}^{\nu} - \partial^\nu \vec{\rho}^{\mu} \] (2b)

\[ F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu \] (2c)

are the field tensors of the vector mesons and the electromagnetic field. In this paper, we adopt the arrows to indicate vectors in isospin space and bold type for the space vectors.

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, i.e., the time-odd component of the vector potential. Then the equation of motion for nucleon can be obtained as:

\[ \{ \mathbf{\alpha} \cdot [ -i \nabla - \mathbf{V}(r)] + V_0(r) + \beta [M + S(r)] \} \psi_i = \varepsilon_i \psi_i, \] (3)

with the scalar potential \( S(r) = g_\sigma \sigma(r) \), the time-like component of vector potential \( V_0(r) = g_\omega \omega_0(r) + g_\rho \tau_3 \rho_0(r) + e \frac{1 - \tau_3}{2} A_0(r) \), and the time-odd component of vector potential \( \mathbf{V}(r) = g_\omega \omega(r) \), where \( \rho(r) \) and \( A(r) \) are neglected since they turn out to be small compared with \( \omega(r) \) field in light nuclei [17].
The Klein-Gordon equations for $\sigma$, time-like components of vector mesons fields $\omega_0$, $\rho_0$ and electromagnetic fields $A_0$ are the same as in the Ref \cite{16}. The time-odd component of $\omega$ meson is determined by

$$\{-\Delta + m_\omega^2\} \omega = g_\omega j_B - c_3 \omega^\nu \omega_\nu \omega,$$

with the baryon current $j_B = \sum_i n_i \bar{\psi}_i \gamma_\nu \psi_i$. The summation is confined to the particle states with positive energies in the no-sea approximation. As the pair correlation is neglected here, the occupation numbers $n_i$ take the value one (zero) for the states below (above) the Fermi surface. Restricting to an axially symmetric representation here, only azimuthal baryon currents $j_B^\phi (z, r_\perp)$ on circular lines around the symmetry axis are non-zero \cite{17}, i.e., only the azimuthal component of the $\omega$ vector field exists.

The total energy of the system, including the time-odd fields, is,

$$E = E_{\text{part}} + E_\sigma + E_\omega + E_\rho + E_\mu + E_{\text{c.m.}},$$

with

$$E_\omega = -\frac{1}{2} \int d^3 r \left[ g_\omega \bar{j}_B^0 (r) \omega_0 (r) - g_\omega \omega_\nu^\phi (r) j_B^\phi (r) \right]$$

and energy contributions from other parts, not shown here, are the same as given in Ref. \cite{19}.

To describe the nuclear magnetic moment, one needs the effective electromagnetic current which is defined as \cite{18,19}

$$\hat{j}^\mu (x) = \bar{\psi} (x) \gamma^\mu \frac{1 - \tau_3}{2} \psi (x) + \kappa \frac{2M}{\nu} \partial_\nu [\bar{\psi} (x) \sigma^{\mu \nu} \psi (x)],$$

where $\sigma^{\mu \nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$, and $\kappa$ is the free anomalous gyromagnetic ratio of the nucleon: $\kappa^p = 1.793$ and $\kappa^n = -1.913$. The spatial component of the effective electromagnetic current operator is given by

$$j(r) = \psi^+ (r) \alpha \frac{1 - \tau_3}{2} \psi (r) + \kappa \frac{2M}{\nu} \nabla \times [\psi^+ (r) \beta \Sigma \psi (r)],$$

where the first term is the Dirac current, and the second term is the so-called anomalous current.

From the effective electromagnetic current, the magnetic moment can be obtained by

$$\mu = \frac{1}{2} \int d^3 r r \times \langle \text{g.s.} | j (r) | \text{g.s.} \rangle.$$
III. NUMERICAL DETAILS

The Dirac equation for nucleons and the Klein-Gordon equations for mesons are solved by expansion in terms of the isotropic harmonic oscillator basis functions in cylindrical coordinates with 14 oscillator shells for both the fermion and the boson fields \[26, 27\]. The oscillator frequency is given by $\hbar \omega_0 = 41A^{-1/3}$ MeV. In odd A nuclei, as the time reversal invariance is broken by the odd nucleon, the Dirac equation for nucleons should be solved separately in two subspaces $\{\psi_j\}$ and $\{\psi_j^\dagger\}$, where $\psi_j$ and $\psi_j^\dagger$ are time reversal conjugate states \[19\].

The energy surface is obtained through the deformation constrained calculation. The quadratic constraint is adopted as in Ref. \[28\] by constraining the mass quadrupole moment $\langle \hat{Q}_2 \rangle$ to a given value $q$, i.e.,

$$
\langle H' \rangle = \langle H \rangle + \frac{1}{2} C (\langle \hat{Q}_2 \rangle - q)^2,
$$

(10)

where $\langle H \rangle$ is the total energy, and $C$ is the stiffness constant. The deformation parameter $\beta_2$ is obtained from the calculated $\langle \hat{Q}_2 \rangle$ for the protons and neutrons through

$$
\langle \hat{Q}_2 \rangle = \langle \hat{Q}_{2p} \rangle + \langle \hat{Q}_{2n} \rangle = \frac{3}{\sqrt{5\pi}} AR_0^2 \beta_2,
$$

(11)

with $R_0 = 1.2A^{1/3}$. In the following, both the adiabatic and the configuration-fixed deformation constrained calculation \[24, 29, 30\] will be performed.

The effective interaction parameter set PK1 \[31\] is used throughout the calculation and the center-of-mass (c.m.) correction is taken into account microscopically by

$$
E_{\text{c.m.}}^{\text{mic.}} = -\frac{1}{2MA} \langle \hat{P}_{\text{c.m.}}^2 \rangle,
$$

(12)

where $\hat{P}_{\text{c.m.}}$ is the total momentum operator of a nucleus with mass number $A$.

IV. RESULTS AND DISCUSSION

The energy surfaces for $^{33}\text{Mg}$ as a function of the quadrupole deformation parameter $\beta_2$ calculated by adiabatic, shown as open circles, and configuration-fixed, shown as solid lines, deformation constrained RMF approach with time-odd component using PK1 parameter set are presented in Fig. 1(a). As discussed in the Ref. \[30\], the configuration-fixed deformation
FIG. 1: (Color online) (a) The energy surfaces for $^{33}$Mg as a function of $\beta_2$ by adiabatic (open circles) and configuration-fixed (solid lines) deformation constrained RMF approach with time-odd component using PK1 parameter set. The minima in the energy surfaces for fixed configurations are represented as stars and respectively, labeled as A, B, C, D, E, F, and G of which A is the ground state with total energy $E = -251.85$ MeV and $\beta_2 = 0.23$, in comparison with the data $-252.06$ MeV [32] (dotted line). (b) Magnetic moments for the corresponding configurations in panel (a) as a function of $\beta_2$. The magnetic moment for the ground state is $\mu = -0.913 \mu_N$ in comparison with the experimental value $\mu = -0.7456(5) \mu_N$ [11] (dotted line).

constrained calculation gives a continuous and smooth curve for the energy surfaces as a function of $\beta_2$. The local minima in the energy surfaces for each configuration are represented by stars and labeled as ACG in ascending order of energy. The ground state A is found to be prolate deformed, $\beta_2 = 0.23$, with the total energy $-251.85$ MeV, which is close to the data $-252.06$ MeV [32]. Using Eq. [9], the effective electromagnetic current gives the nuclear
FIG. 2: (Color online) Neutron single-particle energies for $^{33}\text{Mg}$ as a function of $\beta_2$ obtained by configuration-fixed deformation constrained calculation for the configuration of ground state A. Positive (negative) parity states are marked by solid (dashed) lines. Each pair of time reversal conjugate states splits up into two levels with the third component of total angular momentum $\Omega > 0$ and $\bar{\Omega} < 0$ denoted by red and black lines respectively. The solid circle denotes that the corresponding orbitals are occupied in the ground state.

magnetic moment for given configurations in Fig. 1(b). It is found that the magnetic moment is sensitive to the configuration, but not so much to $\beta_2$. The magnetic moment for the ground state is $-0.913 \mu_N$ which is in good agreement with the data $\mu = -0.7456(5) \mu_N$, compared with the shell-model results $-0.675 \mu_N$ and $-0.705 \mu_N$ restricted to $2p-2h$ configuration using two different interactions designed specifically for the island of inversion.

In order to examine the evolution of the single particle level and compare with the results in Ref. [11], neutron single-particle energies for $^{33}\text{Mg}$ as a function of $\beta_2$ obtained by configuration-fixed deformation constrained calculation for the configuration of ground state A are presented in Fig. 2. The positive (negative) parity states are marked by solid (dashed) lines, and the occupied orbitals are represented by filled circles. The self-consistent calculation here gives the odd neutron in $1/2[330]$ orbital with $\beta_2 = 0.23$ for the ground state, while in Ref. [11], in a Nilsson-model picture, the odd neutron in $3/2[321]$ orbital with prolate deformation $0.3 < \beta_2 < 0.5$ is proposed to reproduce the spin and parity $I^\pi = \frac{3}{2}^-$. As the time reversal invariance is broken by the nuclear magnetic potential, each pair of time reversal conjugate states splits up into two levels with the third component of total
angular momentum $\Omega > 0$ and $\bar{\Omega} < 0$. The energy splittings of time reversal conjugate states range from 0.01 to 0.2 MeV, and the largest splitting occurs at the orbital occupied by the odd neutron. At $\beta_2 \approx 0.3$, the level crossing happens between $3/2[202]$ and $1/2[330]$ orbitals, and leads to the discontinuity of adiabatic energy surface at $\beta_2 \approx 0.3$ in Fig. 1(a) as explained in the Ref. [30].

In Fig. 3, as an illustration, the neutron current in $xy$ planes is plotted at $z = 0.40 \sim 4.48$ fm for the ground state of $^{33}$Mg. The direction and length of the arrows respectively represent the orientation and magnitude of current, which is in different scale for different panels. Take Fig. 3(a) as an example, since only azimuthal components of neutron current exist under the axial symmetry, the neutron current is on circular lines around the symmetry axis and peaks at $r_\perp = 3 \sim 4$ fm. From panel (a) to (f), one can see that, as $z$ increases, the neutron current gradually grows larger and there is a tendency of closing up to the center in the $xy$ plane. But in general, it peaks at $r \approx R_n = 3.4$ fm (the neutron rms radius), indicating

**FIG. 3:** Azimuthal components of neutron current in the $xy$ plane at $z = 0.40$ fm (a), $z = 1.20$ fm (b), $z = 2.0$ fm (c), $z = 2.81$ fm (d), $z = 3.63$ fm (e), and $z = 4.48$ fm (f) respectively for the ground state of $^{33}$Mg. The direction and length of the arrows respectively represent the orientation and magnitude of current which is in different scale for different panels.
FIG. 4: (Color online) The energy contributions due to the nuclear magnetic potential, \( E_j = -1/2 \int d^3 r g_\omega \phi_j(r) j_B^\omega(r) \), as a function of \( \beta_2 \) for different configurations.

that the current is mainly contributed from the old nucleon and flows around the nuclear surface \([19]\). It is interesting to note that for fixed \( z \), the neutron current can be clock-wise, anti-clock-wise or even a mixture.

In order to investigate the effect of the nuclear magnetic potential on the binding energy, in Fig. 4 the energy contributions for different configurations as a function of \( \beta_2 \) are given. In general, the nuclear magnetic potential makes the nucleus more tightly bound, and numerically, its contribution to energy is several hundred keV. Specially, the contributions for A, B, C, E are around \(-0.1\) MeV, while for D, F, G \(-0.5 \sim -0.8\) MeV, which is due to the breaking of proton pair shown in the following.

The total energy (\( E_{\text{cal}} \)), quadrupole deformation parameter (\( \beta_{\text{cal}} \)), valence nucleon configuration, the magnetic moments of the nucleus (\( \mu_{\text{total}} \)) and core (\( \mu_{\text{core}} \)) for different configurations are listed in Table. \( \Box \) It is obvious that the magnetic moments are sensitive to the valence nucleon configurations. For states A, C and E, the magnetic moments are negative, because the main component of corresponding valence nucleon wave function belongs to \( \nu 1f_{7/2} \) which has a negative Schmidt value. For state B, the main component of valence nucleon wave function belongs to \( \nu 1d_{3/2} \), and thus gives a positive magnetic moment. For states D and G, the total magnetic moments are remarkably large due to the breaking of proton pair and the enhanced Dirac current. For F, although there are three valence nucleons, the total magnetic moment is smaller than states D and G due to the strong cancelation
TABLE I: The energy ($E_{\text{cal}}$), the quadrupole deformation parameters ($\beta_{\text{cal}}$), the valence nucleon configuration, the magnetic moments of the nucleus ($\mu_{\text{total}}$) and the core ($\mu_{\text{core}}$), in comparison with experimental value of the ground-state energy ($E_{\text{exp}}$) [32] and magnetic moment ($\mu_{\exp}$) [11]. The energy is in MeV and the magnetic moment in $\mu_N$.

| State | $E_{\text{cal}}(E_{\text{exp}})$ | $\beta_{\text{cal}}$ | Valence nucleon configuration | $\mu_{\text{total}}(\mu_{\exp})$ | $\mu_{\text{core}}$ |
|-------|----------------------------------|-----------------------|------------------------------|----------------------------------|------------------|
| A     | -251.85(-252.06)                | 0.23                  | $\nu_{\frac{1}{2}}[330-]$   | -0.9134(-0.7456)                | -0.042           |
| B     | -251.37                         | 0.40                  | $\nu_{\frac{3}{2}}[202+]$   | 1.6380                          | -0.127           |
| C     | -250.69                         | 0.50                  | $\nu_{\frac{3}{2}}[321-]$   | -1.6750                         | -0.071           |
| D     | -250.58                         | 0.15                  | $\nu_{\frac{1}{2}}[330-] \otimes \pi \{\frac{3}{2}[211+], \frac{5}{2}[202+]\}$ | 7.8179            | -0.216           |
| E     | -250.33                         | -0.12                 | $\nu_{\frac{7}{2}}[303-]$   | -2.0198                         | -0.114           |
| F     | -250.18                         | -0.11                 | $\nu_{\frac{7}{2}}[303-] \otimes \pi \{\frac{3}{2}[211+], \frac{5}{2}[211+]\}$ | 1.4490            | -0.239           |
| G     | -249.34                         | 0.04                  | $\nu_{\frac{5}{2}}[312-] \otimes \pi \{\frac{3}{2}[211+], \frac{5}{2}[202+]\}$ | 7.0082            | -0.288           |

The core polarization effect can be investigated by examining the magnetic moments of the core ($\mu_{\text{core}}$). The baryon current of the valence nucleons is responsible for the polarization which results in the nonvanishing $\mu_{\text{core}}$. As it is seen from the Table, the $\mu_{\text{core}}$, which is caused by the polarization currents, is negative for all states. It is obvious that $\mu_{\text{core}}$ for states D, F and G are much larger than states ABC and E, due to the polarization effect of more valence nucleons.

V. SUMMARY

In summary, the configuration-fixed deformation constrained RMF approach with time-odd component has been applied to investigate the ground-state properties of $^{33}$Mg with effective interaction PK1. Using the configuration-fixed deformation constrained calculation, the ground state of $^{33}$Mg has been found to be prolate deformed, $\beta_2 = 0.23$, with the odd neutron in $1/2[330]$ orbital. The ground-state energy $-251.85$ MeV is close to the experimental value $-252.06$ MeV [32]. Using Eq. (9), the magnetic moment $-0.913 \mu_N$ is obtained with the effective electromagnetic current which well reproduces the data $-0.7456 \mu_N$ [11] self-consistently without introducing any parameter, in contrast with the shell-model re-
results $-0.675 \mu_N$ and $-0.705 \mu_N$ [11] restricted to $2p-2h$ configuration using two different interactions designed specifically for the island of inversion. The energy splittings of time reversal conjugate states, the nucleon current, the energy contribution, and the effect of core polarization due to the nuclear magnetic potential are discussed in detail.

Apart from the core polarization, the meson exchange current correction is also very important for the descriptions of nuclear magnetic moment, especially the isovector magnetic moment. Investigations along this line are in progress.

Acknowledgments

This work is partly supported by Major State Basic Research Developing Program 2007CB815000 as well as the National Natural Science Foundation of China under Grant Nos. 10775004, 10221003, 10720003 and 10705004.

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