Study of ground-state properties of neutron-rich Magnesium isotopes within covariant density functional theory

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Introduction

The covariant density functional theory (CDFT) is regarded as universal theory to study the structural properties of nuclei of the whole nuclear chart. These properties play a vital role in describing nuclear structure both experimentally as well as theoretically. Nakada et al. [1] studied the matter radii of $^{34-40}$Mg by employing semi-realistic interaction in axially-symmetric Hartree Fock Bogoliubov calculations and reproduced the neutron dependence of radii. Recently, the first spectroscopic study of $^{40}$Mg is performed by Crawford et al. [2]. In their paper, they experimentally found two peaks at two different energies which they term as the energies of first and second excited states of $^{40}$Mg. A careful study of nuclei in this region is of great interest as this region is connected to loss of magicity in these nuclei [3]. In this paper, by using density dependent point coupling (DD-PC1) interaction in the CDFT, ground state bulk properties like binding energy, root mean square radii, charge radii, two neutron separation energies and energies of first excited $(2^+)$ states of $^{36-42}$Mg are studied and compared with the available experimental data [4].

Theoretical framework

In the present work, axially symmetric relativistic Hartree-Bogoliubov model (RHB) with DD-PC1 interaction is employed to study the deformation and ground state properties of the neutron rich even-even $^{36-42}$Mg isotopes. For the details of formalism see refs. [5,6]. The potential energy surface calculations are made by using RHB model for the energy as a function of quadrupole deformation parameter $(\beta_2)$, by preserving axial symmetry. The $\beta_2$ is defined as

$$\beta_2 = \sqrt{\frac{4\pi}{5}} \frac{Q_{20}}{\langle r^2 \rangle}$$

where $\langle r^2 \rangle$ is mean square radius and $Q_{20} = (Z^2 - \frac{1}{2}(x^2 + y^2))$ is quadrupole moment. Both are computed by using HFB wavefunctions.

The charge radius is obtained by using

$$r_c = \sqrt{r_p^2 + 0.64} \text{ (fm)}$$

where, $r_p$ is root mean square proton radius and factor 0.64 is correction due to finite size of the proton.

Results and discussion

In Fig. 1, potential energy curves (PECs) for neutron-rich $^{36-42}$Mg isotopes are displayed. The PECs show the variation of the binding energy (MeV) with quadrupole deformation parameter ($\beta_2$), obtained by preserving axial symmetry in self-consistent RHB calculations and with the inclusion of DD-PC1 effective interaction. The $\beta_2$ values obtained from these PECs give an evidence about the prolate shape in neutron-rich even-even $^{36-42}$Mg isotopes. As $\beta_2 > 0$ corresponds to prolate shape and $\beta_2 < 0$ corresponds to oblate shape. The values obtained for the $\beta_2$ from PECs for $^{36-42}$Mg isotopes are presented in table 1. From the values presented in table 1, one finds that a well-deformed prolate minimum is observed in $^{36-42}$Mg isotopes. Besides this, the PECs, indicate second minimum on the oblate side, in all these isotopes. The presence of second minimum, predicts the phenomenon of shape coexistence in neutron-rich magnesium isotopes.
Fig. 1: Potential energy curves of $^{36-42}\text{Mg}$ isotopes as a function of quadrupole deformation parameter ($\beta_2$).

Table 1: Ground state properties of $^{36-42}\text{Mg}$ calculated by DD-PC1 interaction.

<table>
<thead>
<tr>
<th>A</th>
<th>Binding energy per nucleon (B.E./A) [MeV]</th>
<th>$\beta_2$</th>
<th>Root mean square radii [fm]</th>
<th>Charge Radii ($R_c$) [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Th.</td>
<td>Exp.</td>
<td>Th.</td>
<td>Exp.</td>
</tr>
<tr>
<td>36</td>
<td>7.333</td>
<td>7.240</td>
<td>0.430</td>
<td>3.43</td>
</tr>
<tr>
<td>38</td>
<td>7.015</td>
<td>6.928</td>
<td>0.450</td>
<td>3.53</td>
</tr>
<tr>
<td>40</td>
<td>6.713</td>
<td>6.628</td>
<td>0.462</td>
<td>3.62</td>
</tr>
<tr>
<td>42</td>
<td>6.357</td>
<td>0.424</td>
<td>3.71</td>
<td>3.317</td>
</tr>
</tbody>
</table>

Table 2: Comparison of calculated first excited $2^+$ energy ($E(2^+_1)$) with experimental data in $^{36-42}\text{Mg}$ isotopes.

<table>
<thead>
<tr>
<th>Mass Number (A)</th>
<th>$E(2^+_1)$ [KeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>753.76</td>
</tr>
<tr>
<td>38</td>
<td>617.71</td>
</tr>
<tr>
<td>40</td>
<td>528.90</td>
</tr>
<tr>
<td>42</td>
<td>569.57</td>
</tr>
</tbody>
</table>

In table 1, the calculated binding energies and root mean square radii for $^{36-42}\text{Mg}$ isotopes are compared with the available experimental data [4]. The calculated results show good agreement with the available experimental data. The binding energy value for $^{42}\text{Mg}$ is predicted. Besides, the charge radii are also predicted for $^{36-42}\text{Mg}$. In table 2, the energies of first excited $2^+$ state of $^{36-42}\text{Mg}$ are obtained from the $\beta_2$ by using empirical relation [7] and compared with experimental data [2,8]. The calculated values of $2^+$ energy reproduces the experimental data. The excitation energies of these isotopes will be studied by angular momentum projection techniques in future.

Two-neutron separation energies ($S_{2n}$) as a function of mass number (A) are displayed in fig. 2. The two neutron separation energies are calculated by the relation

$$S_{2n} = E(Z,N) - E(Z,N-2).$$

As the mass number increases the $S_{2n}$ energy decreases and it is minimum at $\text{A}=42$. The calculated results are compared with the theoretical results and experimentally available data [4]. From fig. 2, one can conclude that the calculated results with DD-PC1 parameter set are in better agreement with the available experimental data.

Fig. 2: Comparison of experimental (Exp.) and calculated (Th.) $S_{2n}$.

References