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Analyzing the Nuclear Structure of ^{13}O-^{13}B and ^{13}N-^{13}C Mirror Nuclei

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Abstract

In the context of the shell model, electromagnetic transitions were used to analyze the nuclear structure of a mirror nucleus with the same mass number, A = 13. The shell model investigation was performed by calculating the root mean square (rms) for the proton, neutron, matter and charge radii, occupancies, the excitation energies, as well as electromagnetic moments, using the elements of a body density matrix of the PSDMOD two-body effective interactions carried out in the psdpn-shell model space. The present results adopted the harmonic oscillator's single particle eigen functions and Hartree-Fock approximation. In addition, the effect of core polarization was added using the effective charge and effective g factors to calculate electromagnetic moments. To acquire a fair analysis of the information, the core polarization has to be present. The outcomes were compared with experimental data.

Keywords: Electric quadrupole moment, Energy level, Magnetic dipole moment, Mirror nuclei, Occupancies.

Introduction

Electron scattering is a useful method to study the structure of stable and exotic nuclei which transmits information about nuclear structure through single-particle configurations. The fundamental benefits of utilizing electrons as probes come from the properties of the electromagnetic interaction, which quantum electrodynamics fully describes. Because of the interaction's weakness, the scattering process can be approximated by the one-photon exchange approximation as a first-order perturbation. Moreover, it is possible to alter the energy and momentum carried by the virtual photons exchanged during the operation separately, which maps out the densities' Fourier transform [1, 2].

Recent research has shown exotic nuclei to be one of the largest issues in nuclear physics, along with stable nuclei, and has shown a wide variety of novel occurrences. Nuclear physics is developing swiftly as a result of the increased accessibility to uncommon isotopes that differ from stable nuclei in their neutron-proton ratios [3]. Hence, research on mirror nuclei provides a unique viewpoint on how coulomb interaction may affect single-particle wave functions[4]. As nuclear interactions are not reliant on the charge, similar series of excited quantum systems should exist in mirror nuclei. The energy difference between the ground states of mirror nuclei as well as the energy divergence between these nuclei's low-lying excited states should be easily quantified by a straightforward electrostatic and magnetic calculation [5].

Various studies of electron scattering were performed to study the mirror pair nuclear structure. By accounting for the impact of loosely bound

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nucleons, Kitagawa examined the quadrupole Q-moments in neutron-rich and lighter mirror nuclei near the dripline [6]. He has applied the Hartree-Fock wave functions to valence nucleons as well as core nuclei. Effective charges of the *p* and *sd* shell nuclei were determined separately. He has come to the conclusion that the valence proton wave function's spatial expansion corresponds to the enhancement.

The isospin-symmetry breakdown described by Smirnova[7] has been applied to real issues with the structure and decay of exotic neutron-deficient nuclei and nuclei along the N=Z, with results that are similar to those in their mirror nuclei.

Naito et al. [8] examined the effect of isospin symmetry breaking (ISB) in the charge radius difference ΔR_{ch} of mirror nuclei ^{48}Ca-^{48}Ni. They observed that while Coulomb corrections can be disregarded, nuclear ISB effects may change the anticipated value for the symmetry energy slope parameter L by more than ten MeV.

Caprio *et al.* studied the Q-moments of mirror *p* shell nuclei through the *ab initio* no-core configuration interaction, they came to the conclusion that it is important to examine how well mirror isospin symmetry holds for Q-moments across a mirror pair as well as how well the predictions for mirror Q-moments agree with the experiment [9].

In this work, the single particle wave functions of the harmonic oscillator (HO) and Hartree-Fock approximation (HF) of the shell model were adopted to calculate the rms of proton, neutron, matter and charge radii, energy levels, occupancies numbers, magnetic (μ) and quadrupole (Q)-moments of ^{13}O-^{13}B and ^{13}N-^{13}C mirror nuclei. The NuShellX@MSU shell model code was used to get the psdpn- shell model space [10], which computes the components of the proton as well as neutron formalism's one-body density matrix (OBDM). The core-polarization (CP) effectual are implemented through effective g-factors to calculate the magnetic (μ)–moments, and was also included through the effective charges (e_π, e_ν) using the Bohr-Mottelson formula (B.M) [11] and the modified surface delta interaction theory (MSDI) [12] to calculate the Q-moments. All these calculations aimed to find out the nuclear structure of these mirror nuclei.

Theoretical Formalism

The electromagnetic transition operator's nuclear matrix component ($\hat{O}$) between the first and last states is expressed as the single-particle matrix elements multiplied by the sum of the OBDM components[12]:

$$\langle \Lambda_f \| \hat{O}_{JT} \| \Lambda_i \rangle = \sum_{j_f j_i} OBDM\,(j_f, j_i, \Lambda_f, \Lambda_i)^{JT} \times \langle j_f t \| \hat{O}_{JT} \| j_i t \rangle, \quad 1$$

Where, states $|\Lambda_i\rangle$ and $|\Lambda_f\rangle$ are the shell model-space eigen functions of first and last states.

The Skyrme power interacts with both the second and third bodies in an efficient manner [13]. The two-body term can be written as a short-range expansion in the form:

$$V = \sum_{i<j} V_{ij}^{(2)} + \sum_{i<j<k} V_{ijk}^{(3)}, \quad 2$$

Where, $V_{Sk} = \sum_{i<j} V_{ij}^{(2)}$

$$V_{Sk} = t_0(1 + x_0\hat{P}_\sigma)\delta_{12} + \frac{t_1}{2}(1 + x_1\hat{P}_\sigma)(\hat{k}'^2\delta_{12} + \delta_{12}\,\hat{k}^2) + t_2(1 + x_2\hat{P}_\sigma)\hat{k}^2.\delta_{12}\ \hat{k} + \frac{t_3}{6}(1 + x_3\hat{P}_\sigma)\rho^\alpha(\vec{R})\delta_{12}) + it_4\hat{k}'(\hat{\sigma}_1 + \hat{\sigma}_2) \times \hat{k}\delta_{12}, \quad 3$$

Where, $\vec{R} = \frac{r_1 + r_2}{2}$, and the $\hat{k}$ and $\hat{k}'$ are the operators for relative momentum acting on the eigen function, $\hat{k}$ acts to the right and $\hat{k}'$ to the left. They have the form:

$$\hat{k} = -\frac{i}{2}(\nabla_1 - \nabla_2) \quad \Rightarrow \quad \hat{k}^2 = -\frac{1}{4}(\nabla_1^2 + \nabla_2^2 - 2\nabla_1 \cdot \nabla_2)$$
$$\hat{k}' = \frac{i}{2}(\nabla_1' - \nabla_2') \quad \Rightarrow \quad \hat{k}'^2 = -\frac{1}{4}(\nabla_1'^2 + \nabla_2'^2 - 2\nabla_1' \cdot \nabla_2') \quad 4$$

In the equation (3), $\delta_{12} = \delta(r_1 - r_2)$ is the Dirac delta function, $\hat{\sigma}$ the Pauli (spin) operator and the Skyrme power parameters are t_0, t_1, t_2, t_3, t_4, x_0, x_1, x_2, x_3 and α. At $J = 2$, the Q-moments are given by [12]:

$$Q = \begin{pmatrix} J_i & J & J_i \\ -J_i & 0 & J_i \end{pmatrix} \sqrt{\frac{16\pi}{5}} \langle J \| \hat{E}(E2) \| J \rangle \quad 5$$

The occupations (occ#) for each subshell is indicated by:

$$occ\#(j, t_z) = OBDM(i, f, t_z, J = 0)\sqrt{\frac{2j+1}{2J_i+1}} \quad 6$$

The mean square radius $\langle R^2 \rangle_\lambda$ for matter, proton, and neutron is defined as [12]:

$$\langle R^2 \rangle_\lambda = \frac{1}{\lambda} \sum occ\#\, b^2\,(N + \tfrac{3}{2}) \quad 7$$

N, is the total amount of oscillator quanta that have been excited and λ represents the mass, proton, and neutron number.

The formula for the mean square charge radius is [14, 15]:

$$\langle R_{ch}^2\rangle = \langle R_p^2\rangle + 0.769 - \frac{N}{Z}0.1161 + 0.033 \qquad 8$$

The charge radii of a free proton are 0.769; R_p is the radius of a nucleus's point proton dispersion, a free neutron's charge radii are -0.1161, and the so-called Darwin-Foldy term is 0.033. For J=1, the μ–moments is given by [12]:

$$\mu = \begin{pmatrix} J_i & 1 & J_i \\ -J_i & 0 & J_i \end{pmatrix} \sqrt{\frac{4\pi}{3}} \langle J||\hat{O}(m1)||J\rangle \mu_N \qquad 9$$

$\langle J||\hat{O}(m1)||J\rangle$ is the magnetic transition operator, where the nuclear magnetrons is $\mu_N = \frac{e\hbar}{2m_p c} = 0.1051\, e.fm.$

Results and Discussion

In this paper, the qualities of ^{13}O-^{13}B and ^{13}N-^{13}C mirror nuclei are investigated using large-scale shell model simulations using the single-particle wave functions of the PSDMOD interactions in the psdpn -shell model space [16], it adopted the harmonic oscillator with size parameter value obtained from a global formula[17] b = 1.685fm, and with Skyrme interactions are utilized to produce a one-body potential using SkXs25 parameterizations [18] in the Hartree-Fock approximation it is an appropriate representation of Skyrme power.

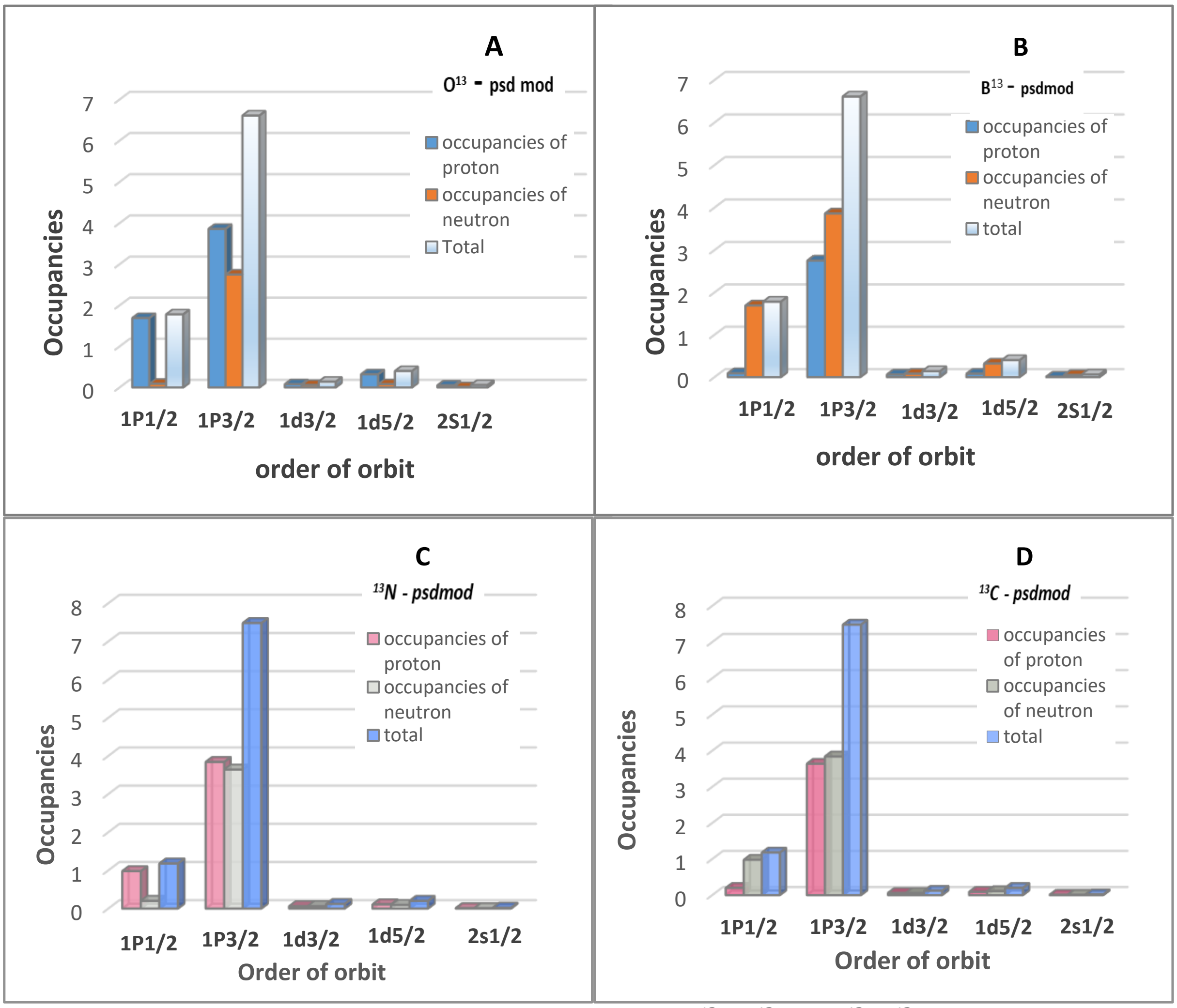

Figure 1. The occupancies for the ground states of ^{13}O -^{13}B and^{13}N-^{13}C mirror nuclei

Currently, self-consistent mean field models are the most appropriate framework [19]. Due to its zero-range interaction, the Skyrme interaction is the one that is most frequently utilized in computations of

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nuclear structure that depend on the momentum thus making computations in many-body systems much simpler.

The main characteristics of mirror nuclei can be represented when computing the occupancies of the nucleus. The occupancy of pair mirror ^{13}O-^{13}B nuclei are composed with configuration $(1s)^4$ inert core, and valence particles moving in $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ proton and neutron orbital as shown in Fig.1 (A&B). The contribution of protons occupancy from $1p_{1/2}$ is dominant for the pair mirror but the contribution of occupancy from $1p_{3/2}$, $1d_{3/2}$, $1d_{5/2}$, and $2s_{1/2}$ is smaller in comparison to that from $1p_{1/2}$ orbital. This contribution and distribution of nucleons in every state determines any nuclear quantity. Similarly, the same result was obtained for the results of ^{13}N-^{13}C mirror nuclei, the occupation number that reflected the property of the reciprocal nuclei is shown in Fig.1 (C&D).

The calculations of energy levels of each isobar are shown in Fig. 2. It is noticeable that the calculated results are close to the experimental value [16] of the ground state and its deviation is larger than the measured value at higher energy levels, especially at the ^{13}N-^{13}C mirror nuclei. The deviation results from a high energy gap for the ^{13}N-^{13}C mirror nuclei and for coulomb effect.

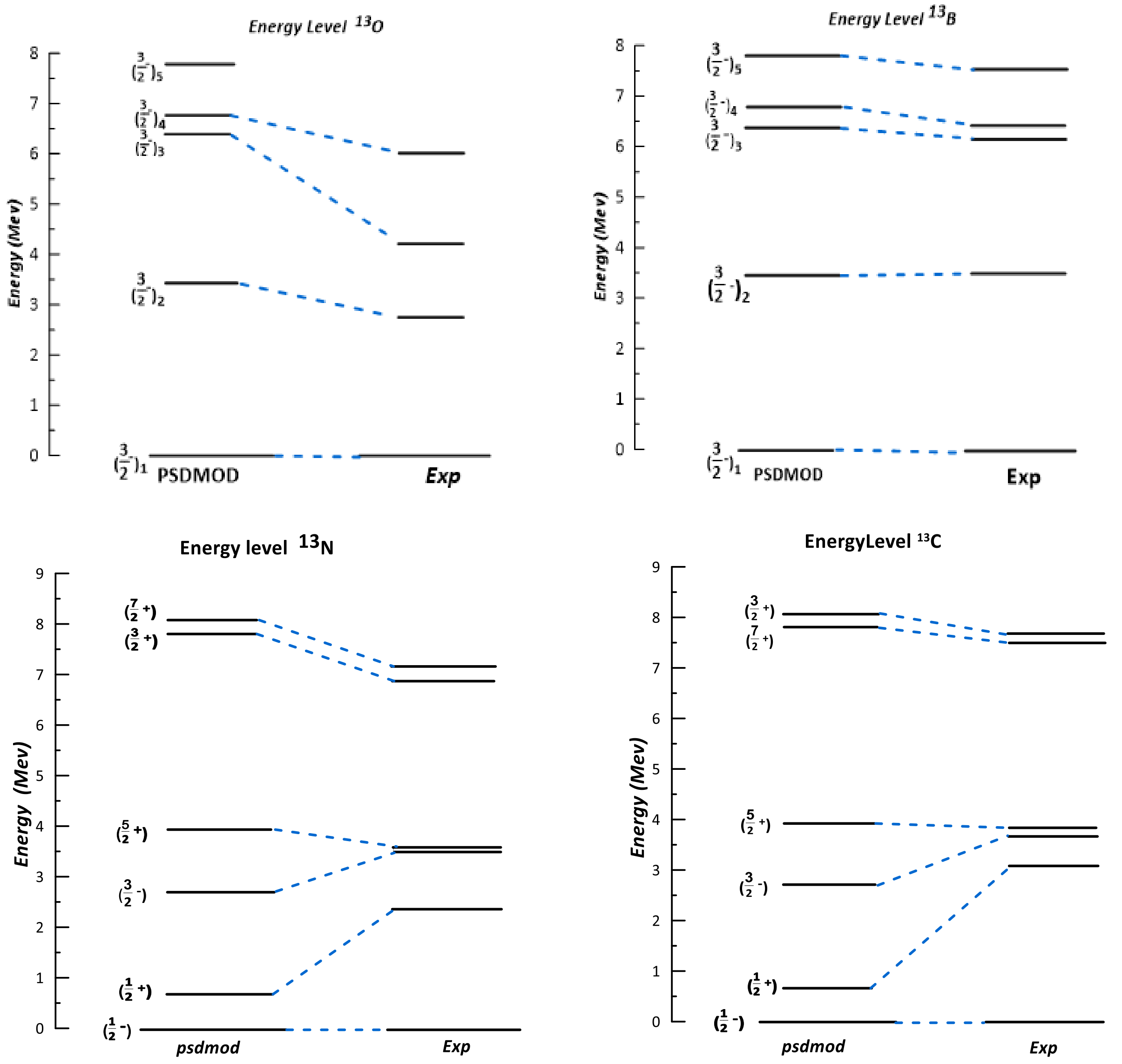

Figure 2. The energy level of ^{13}O -^{13}B and ^{13}N-^{13}C mirror nuclei, compared results with experimental data[16]

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Nuclear radii like the proton (R_p), neutron (R_n), matter (R_m) and charge (R_{ch}) radii, are one of several static properties of atomic nuclei, they observable and can clearly reflect the significant features of the nuclear structure. The R_{ch} can be measured from the isotope shift using a laser spectroscopy experiment[20]. These results of size parameter 1.685fm and the R_{ch} with available measured charge radii of some odd mirror nuclei are shown in Table 1. For mirror nuclei, the result of spatial transformation effect of protons and neutrons with the HO and HF eigen functions appear when calculating the nuclear radii values, because only the diagonal matrix components of the single particle eigen function, which contributes to the nuclear radii, are present in the nuclear radii. For the results, the root mean square values were slightly less than the experimental results when using the HO eigen function and slightly more than the experimental value when using the HF eigen function.

Table 1. Calculate the rms of proton, neutron, matter and charge radii of ^{13}O-^{13}B and ^{13}N-^{13}C using HO and HF eigen functions. The calculated R_c are compared with the experimental data [21, 22].

Nuclei	$J^{\pi}T$	HO eigenfunction				HF eigen function				R_{ch} (exp) (fm)
		R_p (fm)	R_n (fm)	R_m (fm)	R_{ch} (fm)	R_p (fm)	R_n (fm)	R_m (fm)	R_{ch} (fm)	
$^{13}_{8}O$	$\frac{3}{2}^{-}\ \frac{3}{2}$	2.454	2.371	2.422	2.533	2.892	2.478	2.741	2.960	2.68(5)[a]
$^{13}_{5}B$	$\frac{3}{2}^{-}\ \frac{3}{2}$	2.442	2.572	2.495	2.513	2.494	2.799	2.686	2.568	
$^{13}_{7}N$	$\frac{1}{2}^{-}\ \frac{1}{2}$	2.507	2.480	2.495	2.578	2.683	2.514	2.607	2.753	2.45(4)[a]
$^{13}_{6}C$	$\frac{1}{2}^{-}\ \frac{1}{2}$	2.480	2.507	2.495	2.556	2.454	2.629	2.591	2.623	2.4614(34)[b]

a. Ref. [21]
b. Ref. [22]

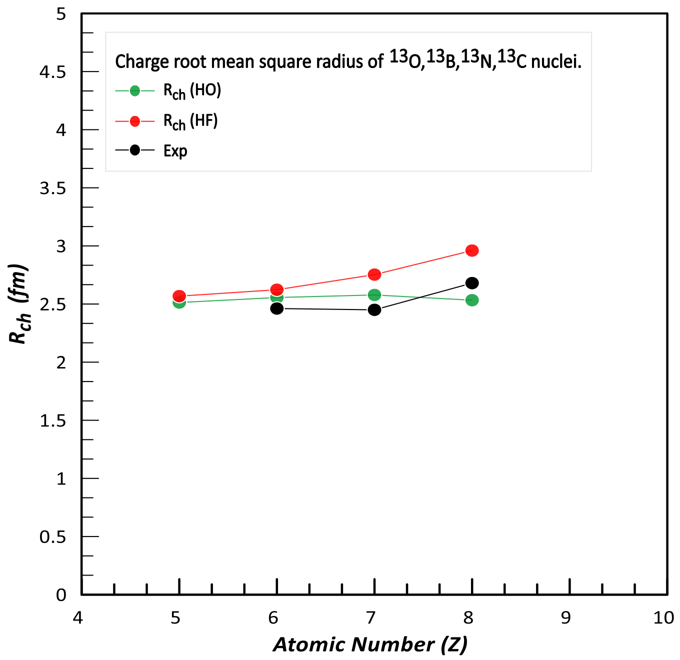

Figure 3. Comparison between the calculated root mean square charge radius using HO (green curve) and HF (red curve) wave functions with the experimental [21,22] (black curve).

The magnetic dipole moments (μ) are also calculated for two pairs of mirror nuclei with the HF and HO eigen functions with the bare single-nucleon *g*-factors orbital and spin are:" g_{ℓ}^{p}= 1, g_{s}^{p} = 5.585, g_{ℓ}^{n}= 0, g_{s}^{n}= - 3.826" [12] and with the efficient *g1*-factors for solitary nucleons, with typical values for the *sd* shell [23] equal "g_{ℓ}^{p}= 1.06,

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g_s^p = 5.055, g_ℓ^n= 0.0, g_s^n= - 3.19" and *g2*-factors equal " g_ℓ^p= 1.15, g_s^p = 4.748, g_ℓ^n= - 0.15 g_s^n= - 3.252" [24]. The present results calculated μ using HO and HF functions and are displayed in Table 2 and Fig. 4 in contrast with the experimental data from reference [25].

The results for ^{13}O-^{13}B mirror nuclei, especially of the proton-rich nucleus does not reproduce the value and the sign of the experimental data using effective nucleon *g1* and *g2* factors. The values of μ agrees with the experimental data [25] for $^{13}_{5}$B and is improved using effective *g1* factors.

The anomaly remains the same for the ^{13}N-^{13}C pair mainly for proton rich nucleus. The calculated values is less than the measured 0.3222(4) nm and with a minus signal that clearly shows the opposite direction of projection to the z-components. For neutron rich-nucleus, $^{13}_{6}$C, the use of effective factors *g1* and *g2* did not improve the values of μ and it remained lower than the practical value but with the same sign. To reduce the difference in the calculated values it seems necessary to consider other effects theoretically.

Table 2. The calculated magnetic dipole moments μ (nm) for ^{13}O-^{13}B and ^{13}N-^{13}C using HO and HF eigen functions in compared to experimental data provided for Ref. [25].

Nuclei	HO eigen function			HF eigen function			$\mu_{exp.}$ (nm)
	μ_{bare} (nm)	μ_{g1} (nm)	μ_{g2} (nm)	μ_{bare} (nm)	μ_{g1} (nm)	μ_{g2} (nm)	
$^{13}_{8}$O	0.579	-1.114	-1.154	-1.207	-0.982	-1.154	1.3892 (3)
$^{13}_{5}$B	2.975	2.846	2.829	2.975	2.856	2.829	3.1778 (5)
$^{13}_{7}$N	-0.2158	-0.1212	-0.3227	-0.2158	-0.1156	-0.3227	0.3222(4)
$^{13}_{6}$C	0.5721	0.4933	0.4385	0.5721	0.4933	0.4385	0.7024118(14)

Effective g_1 factors: "g_ℓ^p= 1.06, g_s^p = 5.055, g_ℓ^n= 0.0, g_s^n= -3.19".
Effective g_2 factors: "g_ℓ^p= 1.15, g_s^p = 4.748, g_ℓ^n= -0.15 g_s^n= -3.252".

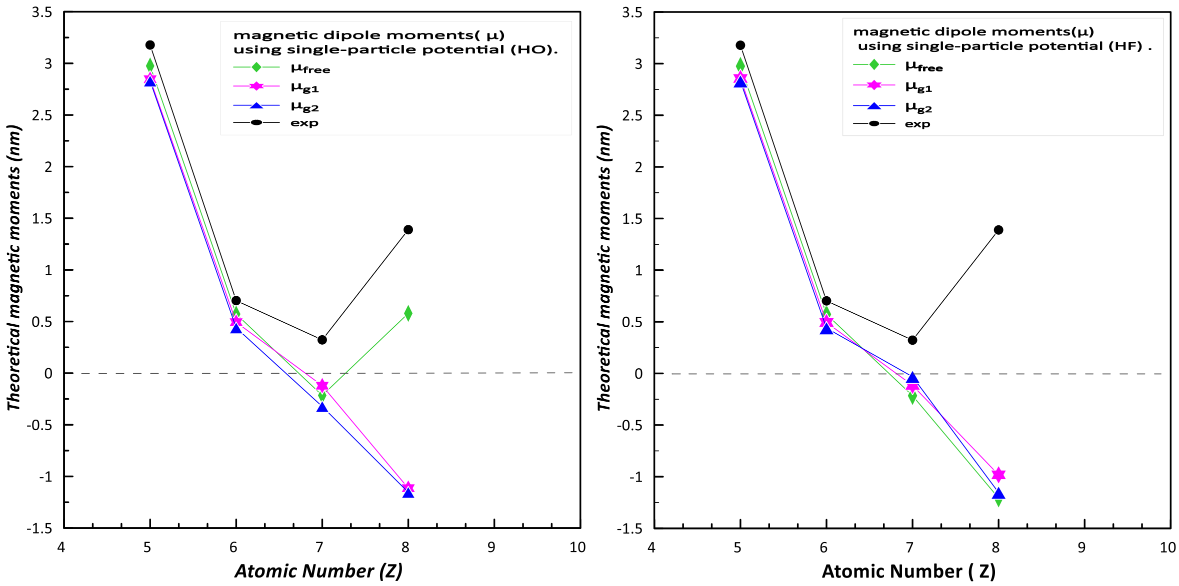

Figure 4. Comparison in present results of magnetic dipole moments using HO and HF eigen functions with the experimental data [26].

The calculation of the nuclear electric *Q*- moments explains how the nuclear charge is distributed within the nucleus and the actual form of the ellipse, it is one of the most crucial aspects of researching nuclear structure. The values of the quadrupole moments determine the form of the nucleus, which is spherical for Q equal zero, blate for Q less than zero and prolate for Q larger than zero. In order to achieve the best results, we investigated the usefulness of the current method in computing the electric quadrupole moments utilizing two different single-particle wave functions. The Bohr-Mottelson formula (B.M. formula) and the modified surface delta interaction theory (MSDI theory), which computes the effective charges of the protons and neutrons as well as the Q -moments, used to determine the core-polarization (CP) effects. Table 3 and Fig. 5 show the results for Q moments in comparison to the existing experimental data from reference [26].

The results for Q-moments of proton-rich nucleus, ${}^{13}_{8}O$, are close the experimental values [26]. The present results were obtained with HO and HF wave functions using the MSDI theory with effective charges e_π= 1.166e, e_ν= 0.166e. Using B.M formula the effective charge e_π= 1.3e, e_ν= 1.07e increases the values of Q-moments and approaches the experimental values [26] after adding the error. For neutron rich nuclei, the effect of the spatial expansion of the wave functions in the ${}^{13}_{5}B$ nucleus is what produces the significant improvement in the system after utilizing the effective charge. The theoretical values of the HO wave functions using B.M formula with effective charge e_π= 1.06e, e_ν= 0.56e are more consistent with the experimental value 3.65(8) [26] when compared to the HF eigen functions.

Table 3. The calculated effective charge and electric quadrupole moments (Q) for ${}^{13}O$-${}^{13}B$ mirror nuclei using HO and HF eigen functions in compared to experimental data provided for Ref. [26].

Nuclei	Effective charge		HO eigen function			HF eigen function			$Q_{exp.}$ (e fm^2)
	e_π, e_ν (B.M)	e_π, e_ν (MSDI)	Q_{bare} (e fm^2)	$Q_{B.M}$ (e fm^2)	Q_{MSDI} (e fm^2)	Q_{bare} (e fm^2)	$Q_{B.M}$ (e fm^2)	Q_{MSDI} (e fm^2)	
${}^{13}_{8}O$	1.3, 1.07	1.166 , 0.166	0.499	0.8674	1.11	0.466	0.898	1.102	1.11(8)
${}^{13}_{5}B$	1.06, 0.56	1.098, 0.098	2.976	3.587	3.474	2.912	3.348	3.243	

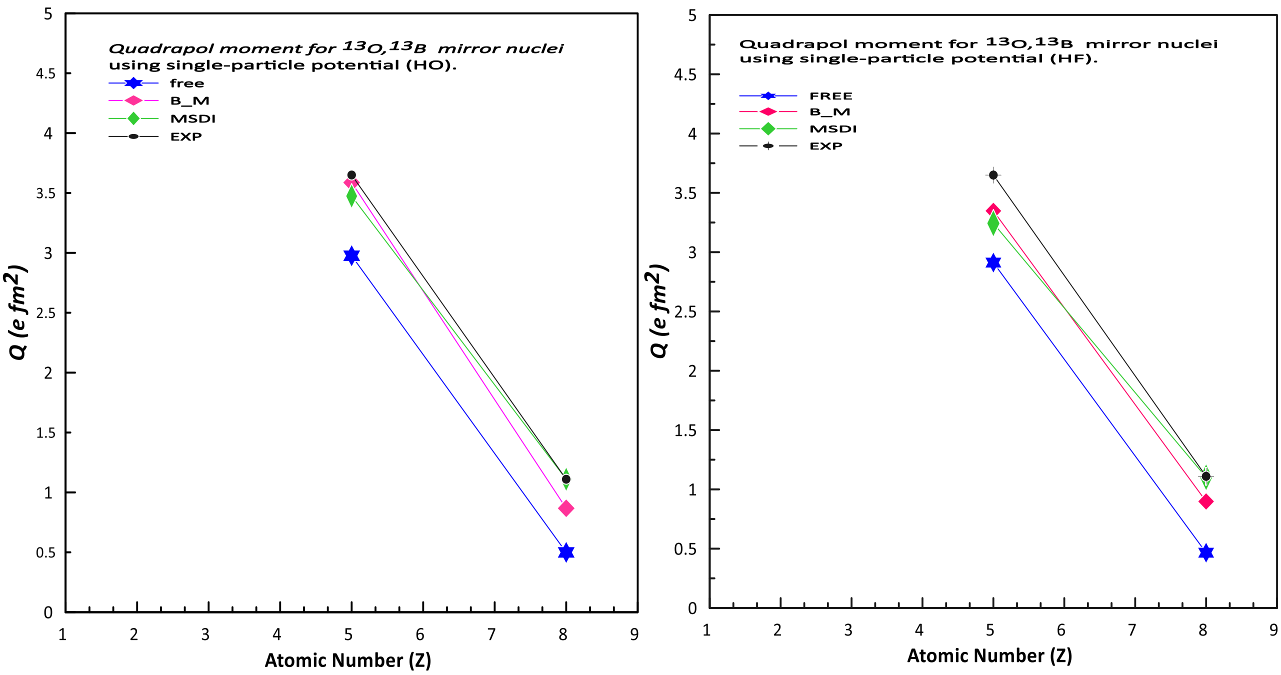

Figure 5. Comparison in electric quadrupole moments using HO and HF wave functions among the experimental data [26]. Effective charges presented are deduced from MSDI theory and with B.M formula.

Conclusion

The nuclear structure of a mirror nucleus with mass number 13 was studied in this work using a large scale of model spaces. The current analysis of the ^{13}O-^{13}B and ^{13}N-^{13}C mirror nuclei showed a considerable contribution of lp$1_{/2}$ orbit. For all chosen mirror nuclei, the neutron and proton occupancy from $1p_{1/2}$ makes up the majority of the contributions. For ^{13}O-^{13}B pair nuclei, the calculated findings of energy levels are in accord with the experimental values, however for ^{13}N-^{13}C pair nuclei, the calculated value does not agree with the measured value, especially at higher energy levels. These variations in findings are brought on by the mirror nuclei's and the coulomb effect's large energy gaps. The calculated R_{ch} results with HO eigen function agree with the observational results with the error rate present.

When the μ- moments are calculated, there is a significant disparity between the calculations and the empirical values but when using the effective *g*-factors, the results are enhanced especially the value of μ- moments for the neutron rich nuclei using the HF eigen function.

When employing HO wave function, the effective charges are found to be successful in describing the *Q* moments for ^{13}O-^{13}B and ^{13}N-^{13}C mirror comparing with the most recent experimental values.

Author's Declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Besides, the Figures and Images, which are not ours, have been given the permission for republication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at University of Baghdad.

Authors' Contributions Statement

R H H and B S H both contributed in visualizing and designing the study, obtaining data, in addition to analyzing and interpreting the results, and writing the manuscript.

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تحليل التركيب النووي لنوى المرأتية ^{13}B-^{13}O و ^{13}C-^{13}N

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الخلاصة

في سياق نموذج القشرة ، تم استخدام التحولات الكهرومغناطيسية لتحليل التركيب النووي للنوى المرآتية ذات نفس العدد الكتلي ، A = 13. تم التحقق من نموذج القشرة من خلال حساب جذر متوسط مربع نصف القطر(rms) للبروتون والنيوترون، أنصاف أقطار المادة والشحنة، اعداد الإشغال، طاقات الإثارة، وكذلك العزوم الكهرومغناطيسية، باستخدام عناصر مصفوفة كثافة الجسم للتفاعلات الفعالة ثنائية الجسم PSDMOD في فضاء نموذج psdpn -shell. النتائج الحالية تمت باستخدام جهد الجسيم المفرد للمتذبذب التوافقي وتقريب هارتري- فوك. تمت إضافة تأثير استقطاب القلب باستخدام الشحنة الفعالة وعوامل g الفعالة لحساب العزوم الكهرومغناطيسية. النتائج الحالية تتوافق مع البيانات التجريبية مع مراعاة تأثير استقطاب القلب.

الكلمات المفتاحية: عزم رباعي القطب الكهربائي، مستويات الطاقة، عزم ثنائي القطب المغناطيسي، النوى المرآتية ، اعداد الاشغال.