Effect of the Exact Center of Mass Correction on the Longitudinal Form Factors for Neutron Rich $^{12,14,18}$N Isotopes

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Abstract. The nuclear structure of the ground state for even $^{12,14,18}$N isotopes are studied within the shell model framework through the longitudinal elastic electron scattering. The generate wave functions from two-body interaction of Cohen and Kurath in the p-shell for $^{12,14}$N, and psdsu3 interaction for $^{18}$N nucleus. The exact value of the center of mass correction in the translation invariant shell model (TISM) are re-examined for longitudinal form factors. The contribution of a higher 2p-shell configuration resolves some discrepancies with the experiments for the form factors at q-values. The inclusion of the core polarization effects through an effective nucleon charge gives a reasonable agreement for the present results with available data. The occupancy percentage with respect to the valance nucleons is also calculated.

Keyword: Exotic nucleus, Longitudinal electron scattering, quadrupole moment, $p$ and psd-shell model

1. Introduction

In the studies of nuclear structure, electron scattering played a key role. To get a reliable and deep information about the structure of atomic nuclei, electron scattering was used. This is due to the fact that the electron probes the nuclei through the electromagnetic interaction without serious distortion in the target nucleus, since this interaction is relatively weak. The quantum electrodynamics are given a good description for this process [1].

The nuclei which contain extraordinary ratio protons and neutrons are called the exotic nuclei. These nuclei were unstable and have a thin cloud of nucleons orbiting at big distances from the others, forming the core and weakly bound with slightly excited states. One of the most important goals in nuclear physics is to investigate the properties of exotic nuclei and it is now possible thanks available for radioactive beam production and heavy-ion accelerators by the development of modern technologies [2].

Several theoretical studies of elastic scattering of the electron in exotic nuclei have been reported in recent year. A few of these works are concerned with analyzing electron scattering in light nuclei. The form factors of charge to distributions of density proton in some nuclei of exotic, such as $^{19,17}$B,$^{14}$Be, $^3$Li, and $^6$He are calculated by Antonov et al [3]. Their results display the effect of the neutron halo or skin on proton distributions in exotic nuclei.

The elastic (longitudinal + transverse) electron scattering from isotopes (Li) and ($^3$B) and (He) are studied by Karataglidis and Amos [4]. Where the precise distribution of the neutron excess has a small effect on the calculated-form factor and there is mass dependence in the charge density. The structure of $^{19-22}$N isotopes are investigated by Soehler et.al [5] using the fragmentation reaction of both stable
and radioactive beams. The level schemes are constructed for the neutron-rich N nuclei. They compared their results with that of shell model.

Roca-Maza et al.[6,7] studied of the development of the charge form factors with proton and neutron numbers in the nuclear chart. They concluded that the elastic scattering of electron experiments in isotopes can provide priceless information about occupation of the single-particle levels of protons and the loading order. The quadrupole transition moment data for nuclei of exotic provide a qualitative directory to the structure of associated nuclear states which afford serious tests of nuclear structure studies. Huffman et al. [8] determined the neutron configurations of some low-lying states in $^{18}$N from the $^{17}$N(d,p)$^{18}$N reaction at 13.6 MeV/amu in inverse kinematics. Spectroscopic factors and orbital angular momentum assignments were determined from the measured angular distribution during a distorted wave Born approximation (DWBA) analysis by shell model calculations with different interactions.

The calculation of effective charges and quadrupole moments for $^{7,8,9,11}$Li and $^{8,10,11,12,13,14,15}$B isotopes are performed by Radhi et al. [9], p and spd$pf$ - shell model space.

Karataglidis [10] considered the scattering of the electron from nuclei of exotic at high energies to survey short-range correlations in specific reaction. He noted that the nuclei of exotic are governed primarily by binding energy. Where the results agreed with the experimental data. Liu et. al.[11] investigate the contributions of proton holes to the nuclear quadrupole moments Q and magnetic moments μ by the multiple Coulomb and magnetic scattering for odd-A nuclei ($^{14}$N, $^{27}$Al, and $^{39}$K). The relativistic mean-field models (RMF) can be represented by the deformed charge of nuclear densities. They compared their results with the experimental data. From the scattering of electron, The nuclei (odd-A) can be tested by wave functions for proton holes, which can also reflect the validity of the nuclear structure model. Fortune [12] examined the history and current state knowledge of the structure nuclei of exotic with (Z = 2-4), from (7He) to (10Be). He presented the models that have been applied in these nuclei, and information of the available experimental and pointed out contradictions inside the data.

Ziliani et al.[13] investigated the excited states of ($^{17}$N, $^{18}$N and $^{19}$N) nuclei through the measurement of gamma rays. In $^{15}$N nucleus, two states de-exciting around (4-5) MeV, clearly pointed with a short lifetime. In $^{18}$N nucleus, three states are observed at energies, 2073.4(8) KeV, 2300.9(8) KeV and 1662.3(3) KeV.. They found two other new transitions around 1566KeV and 1720KeV, also new transition in $^{18}$N with energy 2489.7(8)KeV is observed.

The static properties are well described employing shell model. The inclusion of the effective charges [14] is essential to reproduce the experimental data. In the present work, were studied effect for the center of mass correction to longitudinal form factors. The exact center-of-mass correction of Mihaila and Heisenberg [15] has been adopted to generate the longitudinal form factors in the Born approximation picture. The quadrupole moment and the charge form factors are calculated with Cohen-Kurath interaction (CKI) [16] in p-shell model $^{12}$N isotopes, and psdu3 interaction [17] for $^{18}$N nucleus.

2. Theory
The longitudinal form factor of a given momentum transfer $q$ and multipolarity $J$ can be written in term of isospin spaces ad matrix elements reduce both in angular momentum as [14]:

$$\left| F_{J}^{\text{isosp}}(q) \right|^2 = \frac{4 \pi}{Z^2 (2J_i + 1)} \left| J_J \left| \hat{T}_J^{\text{isosp}}(q) \right| J_i \right|^2 \times \left| F_{e.m.}(q) \right|^2 \times \left| F_{Jx}(q) \right|^2$$

(1)

Where: $F_{Jx}(q) = \left[ 1 + (q/4.33)^2 \right]^{-2}$ is the finite size for the nucleon. And $F_{e.m.} = (A/m) \frac{q^2 \hbar^2}{2}$ is the center of mass correction [18,19]. The reduced matrix elements for the longitudinal scattering of electron operator $\hat{T}^{\text{isosp}}$ is expressed is given by:
\[
\left\langle f \right| \hat{T}_{jT}^{L} \left| i \right\rangle = \sum_{\alpha, \beta} \chi_{\alpha, J_f}^{T} (\alpha, \beta) \left\langle \alpha \right| \hat{T}_{J_f}^{L} \left| \beta \right\rangle
\]

(2)

Where \((\alpha \text{ and } \beta)\) is label single-particle states isospin is included for the model space. We use the OXBASH shell model code [20], where the OBDM in (spin-isospin) formalism is obtained.

The longitudinal form factor with the exact value of the center of mass correction in TISM \(F_{\text{int}}\) [15] can be written as:

\[
|F_j^L (q)|^2 = \frac{4\pi}{Z^2 (2J_i + 1)} \left| \langle J_f \left| \hat{T}_J^L (q) \right| J_i \rangle \right|^2 \times |F_{\text{int}} (q)|^2 \times |F_{j} (q)|^2
\]

(3)

\[
F(q) = F_{\text{c.m.}} (q) F_{\text{int}} (q)
\]

(4)

When the (1p-shell) model space is extended to include the 2p-shell model space, the wave functions of the initial \((i)\) and final \((f)\) states will be written as:

\[
\left| i \right\rangle = \alpha \left| i \right\rangle (1p) + \sqrt{1 - \alpha^2} \left| i \right\rangle (2p)
\]

(5)

\[
\left| f \right\rangle = \gamma \left| f \right\rangle (1p) + \sqrt{1 - \gamma^2} \left| f \right\rangle (2p)
\]

(6)

Where \(\alpha\) and \(\gamma\) are mixing parameters. Since the C-K interaction [depends on the angular parts only, the same OBDM is used for both 1p and 2p shells. The electric quadrupole moment in a state \(|J = 2 \text{ M} = 0 >\) for \(I_i = I_f\) is [9]:

\[
Q(J = 2) = \left( \begin{array}{cc} J_i & J_f \end{array} \right) \left( \begin{array}{cc} J_i & J_f \end{array} \right) \sqrt{\frac{16\pi}{5}} \left\langle j \left| \hat{O} (E2) \right| j \right\rangle = \left( \begin{array}{cc} J_i & J_f \end{array} \right) \left( \begin{array}{cc} J_i & J_f \end{array} \right) \sqrt{\frac{16\pi}{5}} M(E2)
\]

(7)

Where, \(\left\langle j \left| \hat{O} (E2) \right| j \right\rangle\) is the nuclear matrix element of the electromagnetic operators between the initial \((J_i)\) and final \((J_f)\) nuclear states.

The occupation numbers of average in each subshell \(j\) is given by [22]:

\[
\text{occ} \#(j, t) = \text{OBDM} (a, b, t, J = 0) \frac{2J + 1}{2J_i + 1}
\]

(8)

3. Results and Discussion

The longitudinal form factors for the elastic electron scattering from \(^{12,14,18}\text{N}\) nuclei have been performed. The multi-nucleon shell model with a mixed configuration is adopted. The calculations are carried out with OXBASH shell model Code [20]. Cohen-Kurath interaction CKI [16] is used to find the OBDM given in equ.(2) for \(^{12,14,18}\text{N}\) nuclei with 1p-shell model space and 2p-shell extended model. The psdus3 [17] interaction is used for \(^{18}\text{N}\) nucleus with psd-shell model space. The calculations incorporated the single – particle wave functions of harmonic oscillator potential with size parameter \(b\). The size parameter \(b\) for the nuclei under consideration is calculated as:

\[
b = \sqrt{\frac{\hbar}{M_p \omega}} ; \quad \hbar \omega = 45 A^{-1/3} - 25 A^{-2/3} , M_p \text{ is the mass of proton [23]}
\]

The exact value of the center of mass corrections in the translation invariant shell model TISM is also examined. The experimental data of Dally et. al. [24] is available only for the stable \(^{14}\text{N}\) nucleus to be compared with the present results.
Table 1. The percent work occupation numbers of the ground (gs) states of \( l_p_{1/2}, l_p_{3/2}\) and orbits outside the \(^4\)He core for \(^{12,14}\)N isotopes and for the \( l_p_{1/2}, l_p_{3/2}, l_d_{3/2}, l_d_{5/2}, 2s_{1/2}\) orbits outside the \(^4\)He core for \(^{16}\)N isotope.

| Nucleus | Average no. of particles in each j-level | Occupation number % |
|---------|----------------------------------------|---------------------|
| \(^{12}\)N | \( l_p_{1/2} \) | 3 | 5 | --- | --- | --- | 15.435 |
|         | \( l_p_{3/2} \) | 2 | 6 | --- | --- | --- | 14.929 |
|         | \( l_d_{3/2} \) | 1 | 7 | --- | --- | --- | 69.570 |
| \(^{14}\)N | \( l_p_{1/2} \) | 3 | 7 | --- | --- | --- | 6.889 |
|         | \( l_p_{3/2} \) | 2 | 8 | --- | --- | --- | 93.111 |
| \(^{16}\)N | \( l_p_{1/2} \) | 3 | 4 | 4 | 3 | 0 | 100 |

3.1. The \(^{14}\)N stable nucleus (\( J^+ T= 1^+ 0 \))

According to the many-particle shell model, the configuration mixing in the ground state of \(^{14}\)N nucleus with inert \(^4\)He core is mainly from; 93.111\% \( (l_p_{1/2})^2 (l_p_{3/2})^6 \) and 6.889\% \( (l_p_{1/2})^3 (l_p_{3/2})^7 \) as shown in table (1). The elastic scattering from the ground state \( J^+ T = 1^+ 0 \) is purely isoscalar. The calculated longitudinal form factors for the ground state of \(^{14}\)N with bare charge using the size parameter \( b = 1.699\text{fm} \) are presented in figure (1) (solid black curve) and were compared with the experimental data [24] for \( q > 2.7\text{fm}^{-1} \). The C2 contribution (dashed-dot curve) is much smaller than C0 (dashed curve). It is clear that the spherical contributions C0 are dominant at most regions of momentum transfers. The diffraction minimum of C0 multipole is located at \( q = 1.5 \text{ fm}^{-1} \), where the C2 multipole is peaked around, which is reasonable compared with the measured region (at \( q = 1.8\text{fm}^{-1} \)). The model space form factors (solid black curve) give a good behavior in general, but underestimate the experimental data at \( q < 1.5 \text{fm}^{-1} \), and overestimate the data at (\( q > 1.5\text{fm}^{-1} \)). The inclusion of the exact value of center of mass correction decreased this discrepancy especially at high \( q \)-value (\( q > 2.2 \text{fm}^{-1} \)) as shown in figure (2) (green curve). The core polarization effect is included through the valance model in which the valence nucleon is given an extra charge to form effective charge chosen to reproduce the measured quadrupole moment. The calculated quadrupole moment for this transition with bare charge is \( Q_{\text{cal}} = 0.781\text{e}^2\text{fm}^2 \), which is less than the measured value \( Q_{\text{exp}} = 2.044\pm0.03\text{e}^2\text{fm}^2 \) [25]. The inclusion of higher \( 2p\)-shell contribution with \( \alpha = \gamma = 0.93 \) together with the effective charge (with \( e_c = 1.35e \) and \( e_e = 0.35e \)) are displayed in figure (3) (red curve). No change on the calculated form factors, but these contributions increased the predicted value to be \( Q_{\text{cal}} = 2.046\text{e}^2\text{fm}^2 \), which reproduced very well the measured value, and close to that of Refs. [26,27]. This comparison is presented in table (2). The inspection of figure (4) (blue curve) reveals that the shape of the total longitudinal form factors is in qualititative agreement with the experimental data. The little discrepancy can be noticed, where the predicted results enhanced overall at high \( q \)-data. The same behavior is given by Dally et al.[24] and Liu et al.[11], but their results reproduced very well the low \( q \)-data and slightly underestimated the second maximum of the data.
Fig.(1): The longitudinal form factors for $^{14}$N ground state calculated in $p$-model space only. The individual multipole contributions of $C_0$ and $C_2$ are shown and were compared with the experimental data [24].

Fig.(2): Comparison between the total form factors of $^{14}$N nucleus with $1p$-model space only (black curve), and with ($1p+e_{c.m}$ corr.) (green curve) and were compared results with the experimental data [24].

Fig.(3): Comparison between the total form factors of $^{14}$N nucleus in $1p$-model space only (black curve), and with ($1p+e_{c.m}$ corr.+$2p$) (red curve) and were compared results with the experimental data [24].

Fig.(4): Comparison between the total form factors of $^{14}$N nucleus in $1p$-model space only (black curve), with ($1p+e_{c.m}$ corr.+$2p$) (red curve) and with ($1p+e_{c.m}$ corr.+$2p$+$c.m$ corr.) (blue curve).
3.2. $^{12}\text{N}$ nucleus ($^{12}\text{N}$, $T=1^+, I=11.0\text{ms}$)

The longitudinal form factors calculated for the ground ($g_s$) state of the exotic $^{12}\text{N}$ nucleus with size parameter $b = 1.669$ fm and free nucleon charges are shown in figure (5) (solid curve). The $C_0$ form factor (dashed curve) is dominated at low $q$-region, with diffraction minimum located at $q \sim 1.5$ fm$^{-1}$, where the $C_2$ multipole is peaked around at $\sim 10^{-3}$ value. The $C_2$ form factor (dashed-dotted curve) has minor effect. Exactly, the same behavior can be noticed to that of $^{14}\text{N}$ nucleus. The effect of the center of mass correction slightly reduced the total form factor, especially at high $q$-regions as shown in figure (6) (green curve). The predicted quadrupole moment from the model space of $1p$-shell with bare effective charges is $Q_{\text{cal.}} = 0.172e^2\text{fm}^2$, his value indicates lower the measured value by a factor of more than five is $Q_{\text{exp.}} = 0.98 \pm 0.09e^2\text{fm}^2$[25]. This discrepancy between the measured and theoretical $Q$-values is modified by introducing the effective charge with $e_p=1.35e$ and $e_n=0.35e$ together with higher $2p$-shell contribution (with $\alpha = \gamma = 0.49$) to be $Q_{\text{cal.}} = 1.318 e^2\text{fm}^2$. This value is closed to that of Ohtsubo[28]. The core polarization effects adjusted only the predicted quadrupole moment as shown in figure (7) (red curve). In figure (8) (blue curve) one can see that at high momentum transfers the predicted form factors are slightly modified by introducing the exact center of mass correction, without any change in the location of the diffraction minimum. The major contribution of $1p_{3/2}$ orbit for valence nucleons is listed in the table (1), where the occupation numbers percentages are calculated and presented for the ground state of $1p_{3/2}$ and $1p_{1/2}$ orbits.

![Fig.5](image1.png)

Fig.(5): The longitudinal form factors for $^{12}\text{N}$ ground state calculated in $p$-model space only. The individual multipole contribution of $C_0$ and $C_2$ are shown.

![Fig.6](image2.png)

Fig.(6): Comparison between the total form factors of $^{12}\text{N}$ nucleus with $1p$-model space only (black curve), and with ($1p+c.m$ corr.) (green curve).
3.18 \textsuperscript{N} nucleus (F T = 1/2, \tau = 624ms)

The \textsuperscript{18}N ground state is purely dominated by; (1p\textsubscript{1/2})\textsuperscript{3}, (1p\textsubscript{3/2})\textsuperscript{4}, (1d\textsubscript{5/2})\textsuperscript{4} (1d\textsubscript{5/2})\textsuperscript{3} configurations as shown in table(1), and considered as a proton hole (1p\textsubscript{1/2})\textsuperscript{4} coupled to the sd- neutron configuration.

The elastic longitudinal form factors for sd-shell model space with the size parameter \(b=1.751\text{fm}\) using psdus\textsubscript{3} interaction[17] exhibit two diffraction minimum (due to the contribution of sd-neutron configuration) located at (q~1.6) \text{fm}\textsuperscript{-1} and (q = 3.0) \text{fm}\textsuperscript{-1} respectively as shown in figure (9) (solid curve). The C0 component (dashed curve) is dominant and in accordance with the total form factor (solid curve) along all regions of q. While the C2 component of height \(\sim 10^{-5}\) value is peaked around q~1.5\text{fm}\textsuperscript{-1} region, with the diffraction minimum located at q ~ 1.9 \text{fm}\textsuperscript{-1}. The sd-model space results with the exact center of mass correction slightly enhanced the form factors for q > 2.0 \text{fm}\textsuperscript{-1} as shown in figure (10) (green curve). The predicted quadrupole moment for (sd-shell) model space with bare charges is \(Q_{\text{cal}} = 0.197e^2\text{fm}^2\), while the inclusion of the core polarization effect (with effective charge \(e_{p}=1.35e\) and \(e_n=0.35e\)) gives the value \(Q_{\text{cal}}=0.678e^2\text{fm}^2\). In comparison with that of the experimental result, this value is a factor of more than three lower than the measured value \(Q_{\text{exp}}= 2.7 \pm 0.04e^2\text{fm}^2\) [25] and underestimates the \(Q_{\text{exp}}= 1.23 \pm 0.012e^2\text{fm}^2\) of Ref.[29]. This comparison is given in table (2). No change in the calculated form factors with core polarization effect as shown in figure (11)(red curve) and figure (12) (blue curve).

The comparison of the predicted longitudinal form factors of \textsuperscript{12}N (red curve), \textsuperscript{14}N (black curve) and \textsuperscript{18}N (blue curve) as well as with the experimental data of stable nucleus \textsuperscript{14}N [24] are shown in Figure (13). No experimental data are available for \textsuperscript{12,14}N nuclei. From the general point of view, the form factors of \textsuperscript{12,14}N nuclei are close to each other for all q-regions. They have the same behavior with a reasonable description of the experimental data especially at low q-region (q \leq 1.5 \text{ fm}\textsuperscript{-1}), and still slightly overestimate the data at q > 1.5 \text{ fm}\textsuperscript{-1}. They reproduce the same location of the diffraction minimum (q \sim 1.5 \text{ fm}\textsuperscript{-1}). The closer form factors (in shape) of \textsuperscript{12,14}N nuclei in all q- regions mean that the tail part of the wave functions of the last neutron in \textsuperscript{12,14}N nuclei are close to each other when the last neutron occupies the same orbital (here \(P_{3/2}\) orbit, see table 1), and there is no contribution of sd-neutron configuration. The form factor of \textsuperscript{18}N (blue curve) has also good behavior and underestimates the data of \textsuperscript{14}N nucleus at q > 1.0 \text{ fm}\textsuperscript{-1}. 

Fig.(7): Comparison between the total form factors of \textsuperscript{12}N nucleus in 1p-model space only(black curve),and with (1p+e\textsubscript{eff}+2p) (red curve).

Fig.(8): Comparison between the total form factors of \textsuperscript{12}N nucleus in 1p-model space only(black curve), with (1p+e\textsubscript{eff}+2p+c.m corr.) (blue curve).
Fig.(9): The longitudinal form factors for $^{18}$N ground state calculated in psd-model space only. The individual multipole contribution of C0 and C2 are shown.

Fig.(10): Comparison between the total form factors of $^{18}$N nucleus with psd-model space only (black curve), and with (psd + c.m corr.) (green curve).

Fig.(11): Comparison between the total form factors of $^{18}$N nucleus in 1$p$-model space only (black curve), and with (1$p$+c.m eff) (red curve).

Fig.(12): Comparison between the total form factors of $^{18}$N nucleus in 1$p$-model space only (black curve), with (1$p$+c.m eff) (red curve) and with (1$p$+c.m eff+ c.m corr.) (blue curve).
Table 2. The calculated Quadrupole moments \( Q \) of \( ^{12,14,18}\text{N} \) isotopes are compared with the experimental results of Ref.[25] and other results.

| Nucleus | \( J^T \) | \( b \) (fm) | \( Q_{\text{cal.}} \) (e\(^2\)fm\(^2\)) | \( Q_{\text{cal.}} \) (e\(^2\)fm\(^2\)) | \( Q_{\exp.} \) (e\(^2\)fm\(^2\)) | Other results |
|---------|---------|------------|----------------|----------------|----------------|----------------|
| \( ^{12}\text{N} \) | \( 1^+ \) | 1.669 | 0.172 | 1.318\(^{(a)}\) | 0.98±0.09 | 1.03±0.024\(^{(28)}\) |
| \( ^{14}\text{N} \) | \( 1^0 \) | 1.699 | 0.781 | 2.046\(^{(b)}\) | 2.044(3) | 2.0±0.03\(^{(26)}\), 3.2[11], 2.07±0.04\(^{(27)}\) |
| \( ^{18}\text{N} \) | \( 1^- \) | 1.751 | 0.197 | 0.678 | 2.7±0.04 | 1.23± 0.12\(^{(29)}\) |

\(^{(a)}\gamma = \alpha = -0.49\)
\(^{(b)}\gamma = \alpha = -0.93\)

4. Conclusion

In the present work, for all C2 transitions, the inclusion of effective charges (\( e_p=1.35e \) and \( e_n=0.35e \)) are adequate to obtain a good agreement between the predicted and measured quadrupole moment. The inclusion of the exact value of c.m. correction has a minor on \( q \) dependence form factors and on the quadrupole value. Two-body interaction plays an important role in the study of nuclear structure. The second diffraction minimum in psd-form factor is due to the contribution of sd-neutron configuration. The quadrupole moment (\( Q \)) of \( ^{18}\text{N} \) was calculated by polarization charge. The contribution of the proton to the \( ^{18}\text{N} \) ground (\( g_s \)) state Q-value is very small because of the \( P_{1/2} \) major orbit for proton hole. The results from Q calculated and experimental indicates that the effective charges for neutrons in \( ^{18}\text{N} \) nucleus is substantially smaller than in nuclei close to stability.
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