Elastic and Inelastic Magnetic Electron Scattering Form Factors of Neutron- Rich ^{19}C Exotic Nucleus

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Abstract
The elastic magnetic electron scattering form factors and the magnetic dipole moments have been studied for the ground state of ^{19}C (halo) ($J^{\pi}T= 1/2^{+}$ 7/2) nucleus carried out using *psd*-shell Millener-Kurath (PSDMK) interactions. The single-particle wave functions of harmonic-oscillator (HO) potential are used with two different oscillator parameters b_{core} and b_{halo}. According to this interaction, the core nucleons of ^{18}C nucleus are assumed to move in the model space of *spd*. The outer halo (1-neutron) in ^{19}C is assumed to move in the pure $2s_{1/2}$ orbit. The elastic magnetic electron scattering of the stable ^{13}C and exotic ^{19}C nuclei are investigated through Plane Wave Born Approximation (PWBA). It is found that the difference between the total form factors of unstable isotope (^{19}C halo and non-halo) and stable isotope ^{13}C is in magnitude. The magnetic dipole moments of excited states ^{19}C ($J^{\pi}T= 3/2^{+}$ 7/2) and ($J^{\pi}T= 5/2^{+}$ 7/2) nucleus and the transverse inelastic electron scattering form factors for ^{19}C ($J^{\pi}T= 5/2^{+}$ 7/2) are also calculated using the Reehal-Widenthal (REWIL) interactions.

Keywords: Exotic nucleus, Halo nucleus, Magnetic electron scattering form factors**,** Magnetic dipole moment**.**

عوامل التشكل المستعرضة للأستطارة الألكترونية المرنة وغير المرنة للنواة ^{19}C الغريبة الغنية بالنيوترونات

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الخلاصة
تم دراسة عوامل التشكل المغناطيسية للأستطارة الألكترونية المرنة و العزم المغناطيسي للحالة الأرضية لنواة الهالة ^{19}C ($J^{\pi}T= 1/2^{+}$ 7/2) بأستخدام تفاعل PSDMK. استخدمت الدوال الموجية للجسيمة المفردة لجهد المتذبذب التوافقي مع قيمتين مختلفتين للثابت التوافقي واحد للقلب (b_{core}) والأخرى للهالة (b_{halo}). بناءاً على هذا التفاعل، تم أفتراض نيكلونات القلب لنواة ^{18}C تتحرك في فضاء *spd*. تم أفتراض نيترون الهالة لـ ^{19}C بانه يسبح في المدار الصرف $2s_{1/2}$. تم تحقيق عوامل التشكل المغناطيسية للأستطارة الألكترونية المرنة للنواتين المستقرة ^{13}C والغريبة ^{19}C بواسطة تقريب بورن للموجة المستوية. لقد وجد هناك أختلاف لقيم عوامل التشكل المرنة للنواة الغريبة ^{19}C والنواة المستقرة ^{13}C. تم كذلك حساب العزم المغناطيسي للحالتين المثارة لنواة ^{19}C ($J^{\pi}T= 3/2^{+}$ 7/2) و($J^{\pi}T= 5/2^{+}$ 7/2) و عوامل التشكل المستعرضة للأستطارة الألكترونية غيرالمرنة للحالة ($J^{\pi}T= 5/2^{+}$ 7/2) بأستخدام تفاعل REWIL.

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Introduction:

Structural evolution of atomic nuclei towards the neutron and proton drip lines in the nuclear chart is one of the most important and intriguing issues in current nuclear physics. In particular, the location of the neutron drip line is the key to understand the stability of atomic nuclei around the bound limit of neutron-proton quantum system. In spite of such importance, the neutron drip line has been determined only up to the oxygen isotopes. The drip-line nuclei exhibit peculiar feature of nuclear structures as in neutron halo nuclei found in the vicinity of the neutron drip line. However, the neutron halo nuclei so-far known have been limited to the light system, and the heaviest neutron halo nucleus experimentally known had long been ^{19}C [1] .

Until the middle of 1980's, nuclear physics had been developed by investigating primarily stable nuclei which exist in nature. Many facets of atomic nuclei had been revealed, which include a mass, density distribution, radius, shell structure, collective excitations, and various decay modes[2].The field of halo nuclei has generated much excitement and many hundreds of papers since its discovery in the mid-1980s. While early β- and γ-decay studies of many of these nuclei yielded information about their lifetimes and certain features of their structure, credit for their discovery should go mostly to Tanihata [3,4] for the work of his group at Lawrence Berkeley Laboratory's Bevalac in 1985 on the measurement of the very large interaction cross sections of certain neutron-rich isotopes of helium and lithium, along with Hansen and Jonson for their pioneering paper two years later in which the term 'halo' was first applied to these nuclei [5]. The halo nuclei are an extreme case of exotic nuclei with almost zero binding energy.

The quadrupole and magnetic moment of exotic nuclei are serious tests for these new developed nuclear patterns. They contain a lot of information about the structure of the nuclear state: the magnetic dipole moment is sensitive to the orbitals of nucleons that are not dual to zero spin. The electric quadrupole moment shows information on the deformation of the charge distribution of the nucleus.

For one-neutron halo nucleus ^{19}C, Bazin et al, [6] measured the longitudinal momentum distribution of ^{18}C, ^{17}C, and ^{16}C after the one-neutron breakup of ^{19}C, ^{18}C, and ^{17}C, respectively. The observed narrow width of $44.3 \pm 5.9 MeV/c$ for the ^{18}C fragments indicated that ^{19}C is a new example of a one-neutron halo. The consequences of the obtained results on the structure of the three isotopes ^{19,18,17}C were discussed together with shell-model calculations.

The structure of the ^{19}C ground state and the last neutron separation energy S_n are still very uncertain. A naive shell model suggests a nodeless $1d_{5/2}$ orbit for the least bound neutron. More detailed calculations however predict a $1/2^+$ ^{19}C ground state due to a lowering of the $2s_{1/2}$ orbital [7].

Stanoiu et al [8] studied the drip line nuclei through two-step fragmentation and concluded that the neutron-rich $^{17-20}$C and $^{22-24}$O nuclei have been performed by the in-beam γ-ray spectroscopy using the fragmentation reactions of radioactive beams. The 2^+ energy of ^{20}C is determined. Its low-energy value hints for a major structural change at N = 14 between C and O nuclei. Evidence for the non-existence of bound excited states in either of the ^{23,24}O nuclei has been provided, pointing to a large subshell effect at N = 16 in the O chain.

The electron scattering was studied on halo nuclei by Bertulani [9]; he used the inelastic scattering of electrons on weakly-bound nuclei to study with a simple model based on the long range behavior of the bound state wave functions and on the effective-range expansion for the continuum wave functions. It was shown that the cross sections for electro-dissociation of weakly-bound nuclei reach ten milibarns for 10 MeV electrons and increase logarithmically at higher energies.

Dong et al [10] calculated the elastic magnetic electron form factors of ^{23}O, ^{15,17,19}C, and ^{17}F in the relativistic impulse approximation. Great differences the form factors were found when the last nucleon of a given nucleus occupies different orbitals. Therefore, one can determine immediately the orbital of the last nucleon of odd-A exotic nuclei when the form factors of these nuclei are determined.

The aim of the present work is to study the magnetic elastic and inelastic electron scattering form factors and to calculate the magnetic dipole moments of exotic nucleus ^{19}C (neutron-rich) using the *psd* and *ZBM* model space (*ZBM* valence space was composed of the active orbital's $0p_{1/2}$, $0d_{5/2}$ and $1s_{1/2}$ with a ^{12}C core, allowing 1 to 4 nucleon jumps. Again in *ZBM* space, a similar calculation was performed to describe the normal and intruder states in nuclei with A = 18–20) [11, 12]. The shell model calculations are carried out for core nucleons using the *psd*-shell Millener-Kurath (PSDMK) interactions [13]. The elastic and inelastic magnetic electron scattering of the exotic ^{19}C nuclei are also investigated through plane wave born approximation (PWBA).

Theory

The interaction of the electron with the spin and currents distributions of nuclei can be considered as an exchange of a virtual photon with angular momentum ± 1 along momentum transfer $\vec{q}$ direction. This is called transverse scattering [14]. From the parity and angular momentum selection rules, only electric multipoles can have longitudinal components, while both electric and magnetic multipoles can have transverse components [14, 15].

The squared magnetic form factors for electron scattering between nuclear states J_i and J_f involving angular momentum transfer J are given by [16]:

$$\left|F_J^{\eta}(q)\right|^2 = \frac{4\pi}{Z^2(2J_i+1)} \left| \sum_{T=0,1} (-1)^{T_f - T_{zf}} \begin{pmatrix} T_f & T & T_i \\ -T_{Zf} & M_T & T_{Zi} \end{pmatrix} \left\langle \Gamma_f \left\| \hat{T}_{J,T}(q) \right\| \Gamma_i \right\rangle \right|^2 , \qquad (1)$$

where $\hat{T}_J(q)$ is the magnetic electron scattering multipole operator. For a magnetic operator T_{JT} the reduced matrix elements are written as the sum of the product of the one-body density matrix elements (OBDM) times the single-particle transition matrix elements [17]:

$$\left\langle \Gamma_f \left\| \hat{T}_\Lambda \right\| \Gamma_i \right\rangle = \sum_{\alpha,\beta} OBDM\left(\Gamma_i, \Gamma_f, a, b\right) \left\langle a \left\| \hat{T}_\Lambda \right\| b \right\rangle \qquad (2)$$

where $\Lambda = JT$ is the multipolarity and the states $\Gamma_i \equiv J_i T_i$ and $\Gamma_f \equiv J_f T_f$ are initial and final states of the nucleus. While α and β denote the final and initial single-particle states, respectively (isospin is included). The nuclear shell model calculations were performed using the OXBASH Shell model code [18], where the one body density matrix (*OBDM*) elements of the core and halo parts in spin-isospin formalism are obtained.

The single-nucleon form factor [19] and the center-of-mass form factor [20] are given by:

$$F_{fs}(q) = [1 + (q/4.33)^2]^{-2}, \qquad F_{cm}(q) = e^{q^2 b^2 / 4A} \qquad (3)$$

where A is the nuclear mass number and b is the harmonic-oscillator size parameter, for halo nuclei b equal to the average of b_{core} and b_{halo}. Introducing these corrections into Eq. (1), we obtain:

$$\left|F_J^{M}(q)\right|^2 = \frac{4\pi}{Z^2(2J_i+1)} \left| \sum_{T=0,1} (-1)^{T_f - T_{zf}} \begin{pmatrix} T_f & T & T_i \\ -T_{Zf} & M_T & T_{Zi} \end{pmatrix} \left\langle \Gamma_f \left\| \hat{T}^{M}_{J,T}(q) \right\| \Gamma_i \right\rangle \right|^2 \times \left|F_{c.m}(q)\right|^2 \times \left|F_{f.s}(q)\right|^2 \qquad (4)$$

The single particle matrix element in spin- isospin state is given by [17]:

$$\left\langle a \left\| \hat{O}_T(m1 \right\| b \right\rangle = \left\langle n_a l_a \left| r^{J-1} \right| n_b l_b \right\rangle f_T^{m1}(a,b) \qquad (5)$$

where

$$f_T^{m1}(a,b) = (-1)^{\ell_a}(2J+1)\sqrt{\frac{J(2J-1)(2\ell_a+1)(2\ell_b+1)(2j_a+1)(2j_b+1)}{4\pi}}$$
$$\times\begin{pmatrix} \ell_a & J-1 & \ell_b \\ 0 & 0 & 0 \end{pmatrix}\sqrt{2T+1}[\frac{g_p^{\ell}+(-1)^T g_n^{\ell}}{J+1}(-1)^{\ell_b+j_b+1/2}\sqrt{2\ell_b(\ell_b+1)(2\ell_b+1)}$$
$$\times\begin{Bmatrix} \ell_a & \ell_b & J \\ j_b & j_a & 1/2 \end{Bmatrix}\begin{Bmatrix} J-1 & 1 & J \\ \ell_b & \ell_a & \ell_b \end{Bmatrix}+\frac{1}{2}\{g_p^s+(-1)^T g_n^s\}\sqrt{3}\begin{Bmatrix} \ell_a & 1/2 & j_a \\ \ell_b & 1/2 & j_b \\ J-1 & 1 & J \end{Bmatrix}]\mu_N \tag{6}$$

for $J=1$ equation (5) become:

$$\left\langle a \left\| \hat{O}_T(m1) \right\| b \right\rangle = f_T^{m1}(a,b) \tag{7}$$

The reduce matrix element of the magnetic transition operator $\hat{O}_k(m1)$ is expressed as the sum of the product of the elements of the one-body density matrix (*OBDM*) times the single-particle matrix elements, and is gives by:

$$\left\langle J_i \left\| \sum_{k=1}^{n} \hat{O}_k(m1) \right\| J_i \right\rangle = \sum_{a,b,T}(-1)^{T_i-T_z}\begin{pmatrix} T_i & T & T_i \\ -T_z & 0 & T_z \end{pmatrix} OBDM(a,b,J=1,T)\left\langle a \left\| \hat{O}_T(m1) \right\| b \right\rangle \tag{8}$$

The magnetic dipole moment μ of a state of total angular momentum J is given by [17]:

$$\mu = \sqrt{\frac{4\pi}{3}}\begin{pmatrix} J_i & 1 & J_i \\ -J_i & 0 & J_i \end{pmatrix}\left\langle J_i \left\| \sum_{k=1}^{n} \hat{O}_k(m1) \right\| J_i \right\rangle \tag{9}$$

Results and Discussion

The shell model has been used successfully in reproducing the magnetic moments by the spin and orbital *g*-factors for free nucleons. The differences between the single particle *g*-factors and the measured values have been explained by the configuration mixing: the core nucleus composed of an even number of nucleons is excited into the 1^+ state, which contributes to the magnetic moment of the nucleus.

^{19}C (exotic neutron-rich system) with $\tau_{1/2}$=49(4) ms [21] is of particular interest since it lies at the drip line, has a small single neutron separation energy, S_n= 0.53 MeV, and most likely can be classified as a one-neutron halo nucleus [22]. However, the spin-parity of its ground state is still uncertain. A standard shell model (SM) gave a $1/2^+$ assignment making the nucleus a candidate to be a $1s_{1/2}$ neutron-halo nucleus. The spectrum of ^{19}C [23] has a ground state with $J^{\pi}T=1/2^+$ 7/2. Then there are two excited states at 72 and 197 keV excitation. Those were assigned spins of 3/2 and 5/2 based on the assignments to states in ^{17}C.

Recent experiments performed at the GSI fragment separator (FRS) have brought further insight into the structure of this nucleus. The results reveal an extended neutron density distribution, corroborating the assumption of a ^{18}C-core surrounded by a one-neutron halo. The study of the neutron-rich nucleus ^{19}C has attracted much attention since narrow momentum distributions, measured for ^{18}C breakup fragments as well as for neutrons [24], were taken as evidence for a one-neutron halo around a ^{18}C core—similar to the structure of the well established one-neutron halo nucleus ^{11}Be. According to Heisenberg's uncertainty principle, a narrow momentum distribution implies a large spatial extent of the valence nucleon's wave function. The one-neutron separation energy of ^{19}C is comparable to that of ^{11}Be, which further suggests a core-plus-halo neutron structure of this isotope [22].

For ^{19}C non-halo the calculations of the proton, neutron, and matter rms radii and magnetic form factors are carried out using REWIL interactions [25] and *ZBM* the shell model point of view, (Zuker-Buck-McGrory) in the basis of $0p_{1/2}$, $1s_{1/2}$ and $0d_{5/2}$ orbital's [11, 12] but by ^{19}C halo the calculations of the proton, neutron, and matter rms radii and magnetic form factors are carried out using PSDMK interactions and *psd* model space. The single-particle wave functions of harmonic oscillator potential with oscillator size parameter b=1.94fm chosen to reproduce the experimental matter rms radius 3.13 ± 0.07 [26] which is consisting with measured value as in table-1. In table-1 the calculated matter rms radii with experimental values for this nucleus are displayed.

Table 1- The present and experimental values of $(\text{rms})_{matt.}$ radii and the proton and neutron (rms) values in fm for ^{19}C ground state ($J^{\pi}T= 1/2^{+}$ 7/2) nucleus.

rms radii (fm)		**$(\text{rms})_p$ radius(fm)**	**$(\text{rms})_n$ radius (fm)**
Present work	Experimental value [26]	Present work	Present work
3.13	3.13 ± 0.07	2.8571	3.2482

The difference between the neutron and proton rms radii is $R_n - R_p = 3.2482 - 2.8571 = 0.3911$ fm, which provides an additional evidence for the exotic structure of this nucleus.
The elastic magnetic form factors of unstable nucleus ^{19}C non-halo with $J^{\pi}T= 1/2^{+}$ 7/2 is calculated with size parameter b_{rms}=1.94 fm as shown in figure-1. The comparison of the M1 multipole with the free g-factors (solid curve), g_s(eff)=0.9 g_s (free)(dashed curve) and with the chi square fittings to all M1 even –even sd- shell nuclei (cross curve) are shown. All the results are close to each other and have the same diffraction minimum at q=1.1 fm^{-1} and the same diffraction maximum located at q=0.4 and 1.9 fm^{-1}.

The ground state of ^{19}C halo can be described is a one-neutron halo nucleus, composed of the core ^{18}C nucleus $\left(J^{\pi}T = 0^{+}3,\ t_{1/2} = 95\ s\right)$ [21], plus one loosely bound neutron surrounding the core; this neutron must be in the $2s_{1/2}$-orbit. The oscillator size parameter for the core (b_{core}) in the present work is fixed at 1.784 fm. The oscillator size parameter for the one-neutron halo (b_{halo}) is assumed as a free parameter to be adjusted to reproduce the experimental matter rms radius of the halo nucleus ^{19}C and is taken to be 3.505 fm as shown in figure-2. The magnetic form factors for ^{19}C halo (solid curve) is comparison with that of ^{19}C non-halo (dash curve) and with the experiment data of stable isotope ^{13}C are displayed in figure-3. The location of the minimum of ^{19}C non-halo has forward shift as compared with the minimum of ^{19}C halo. The significant difference between the form factors of the ^{19}C halo and non-halo is the difference in the center of mass correction which depends on the mass number and the size parameter b which is assumed in this case of halo equal to the average of b_{core} and b_{halo}.

The calculated magnetic dipole moment of g_s(free) for ^{19}C non-halo μ= -1.91316 n.m which is greater than the calculated values of Ref. [27]. Using g_s(eff)=0.9g_s(free) and chi square fittings to all M1 even –even *sd*- shell nuclei decreases the μ value to become -1.7218 and -1.72184n.m respectively. When using PSDMK interactions the magnetic dipole moment of g_s(free) for ^{19}C halo μ=-1.691 n.m. The calculated magnetic moments of the ground state ^{19}C ($J^{\pi}T= 1/2^{+}$ 7/2) nucleus are tabulated in table-2 together with available theoretical data.

Table 2- The values of the magnetic dipole moments (μ) of ^{19}C ($J^{\pi}T= 1/2^{+}$ 7/2) nucleus of the present work compared with the other important results.

AUTHORS		**TECHNIQUE**	**μ (n. m)**	**Ref.**
Present work	**non-halo**	g_s(free)	-1.91316	
		g_s(eff.)=0.9 g_s(free)	-1.7215	
		g_l, g_s=chi square fittings	-1.72184	
	halo	g_s(free)	-1.691	
Theoretical results		WBP interaction	-1.305	[27]
		MK interaction	-1.374	[27]
		Skyrme interactions SGII Skyrme interactions SIII	-1.795 -1.780	[27]

The magnetic dipole of the excited state ($J^{\pi}T= 3/2^{+}\ 7/2$) of ^{19}C nucleus are also calculated and carried out by using REWIL interactions [25] and *ZBM* the shell model. The different values of g_s-factors are used previously, which give different values for magnetic moment. Our choice for free g_s-factors gives $\mu = -0.49627$n.m. Using $g_s(eff)=0.9g_s$ (free) and chi square fittings to all M1 even –even *sd*- shell nuclei decreases the μ value to become -0.44665 and -0.50685 n.m respectively. The calculated magnetic dipole moments of ^{19}C ($J^{\pi}T= 3/2^{+}\ 7/2$) isotope are tabulated in table-3 together with available theoretical data.

Table 3- The values of the magnetic dipole moments (μ) of ^{19}C ($J^{\pi}T= 3/2^{+}\ 7/2$) nucleus of the present work compared with the other important results.

AUTHORS	TECHNIQUE	μ (n. m)	Ref.
Present work	g_s(free)	-0.49627	
	g_s(eff.)=0.9 g_s(free)	-0.44665	
	g_l, g_s=chi square fittings	-0.50685	
Theoretical results	WBP interaction	0.284	[27]
	MK interaction	0.421	[27]
	Skyrme interactions SGII Skyrme interactions SIII	1.071 0.975	[27]

The transverse inelastic electron scattering form factors are displayed in figure-4 for ^{19}C ($J^{\pi}T= 5/2^{+}\ 7/2$) and size parameter b_{rms}=1.94 fm and with free spin g_s-factor. The individual multipoles contributions E2 and M3 are denoted by cross and dashed curves respectively. The results have the diffraction minimum at q=1.6 fm^{-1} and the diffraction maximum located at q=1.0 and 2.1 fm^{-1}. The magnetic dipole moment of this state μ= -1.9148 is greater than the calculated value of Ref. [27]. The calculated magnetic moments of the ^{19}C ($J^{\pi}T= 5/2^{+}\ 7/2$) nucleus are tabulated in table-4 together with available theoretical data.

Table 4- The values of the magnetic dipole moments (μ) of ^{19}C ($J^{\pi}T= 5/2^{+}\ 7/2$) nucleus of the present work compared with the other important results.

AUTHORS	TECHNIQUE	μ (n. m)	Ref.
Present work	g_s(free)	-1.92307	
	g_s(eff.)=0.9 g_s(free)	-1.73076	
	g_l, g_s=chi square fittings	-1.81831	
Theoretical results	WBP interaction	-1.126	[27]
	MK interaction	-0.831	[27]
	Skyrme interactions SGII Skyrme interactions SIII	-1.138 -1.138	[27]

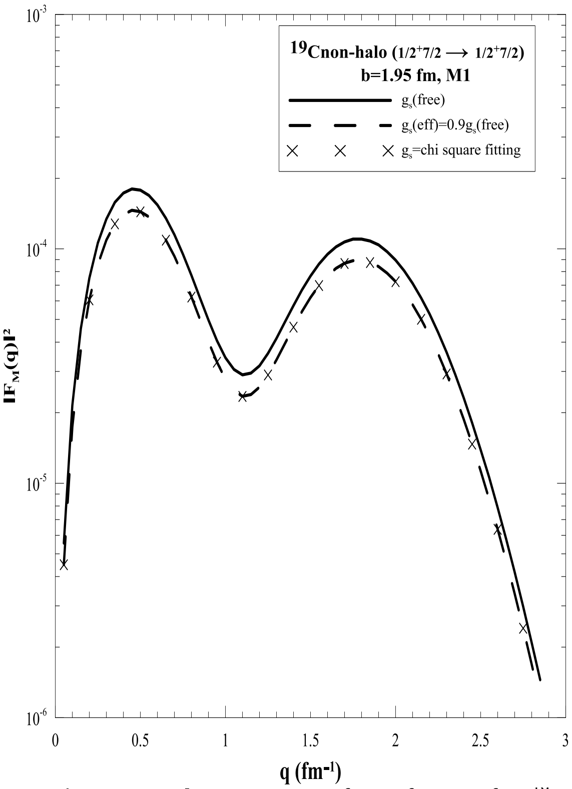

Figure 1- The transverse form factors for ^{19}C (non-halo) ground state ($J^{\pi}T = 1/2^{+}$ 7/2) calculated in *ZBM* model space. Comparison between the total form factors of ^{19}C with g_s is free (solid curve), g_s(eff)=0.9 g_s(free) (dashed curve) and with chi square fittings (cross curve).

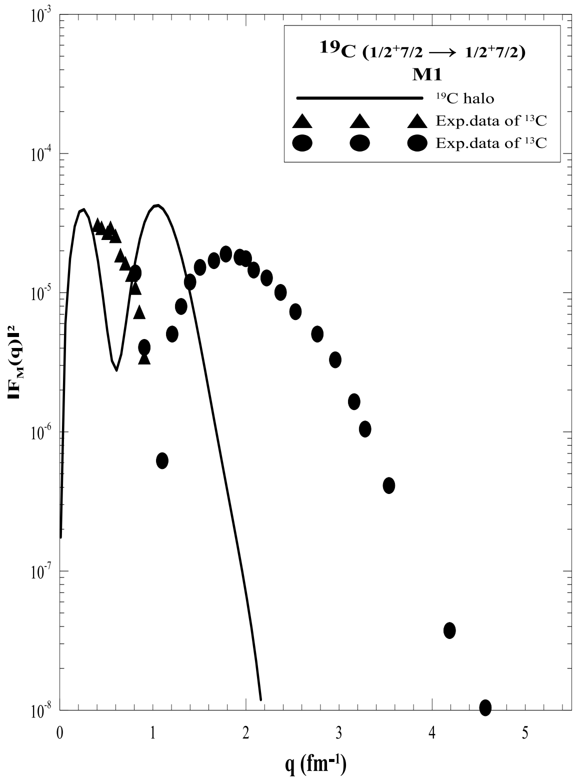

Figure 2- The transverse form factors for ^{19}C halo ground state ($J^{\pi}T = 1/2^{+}$ 7/2) calculated in *spd* model space.

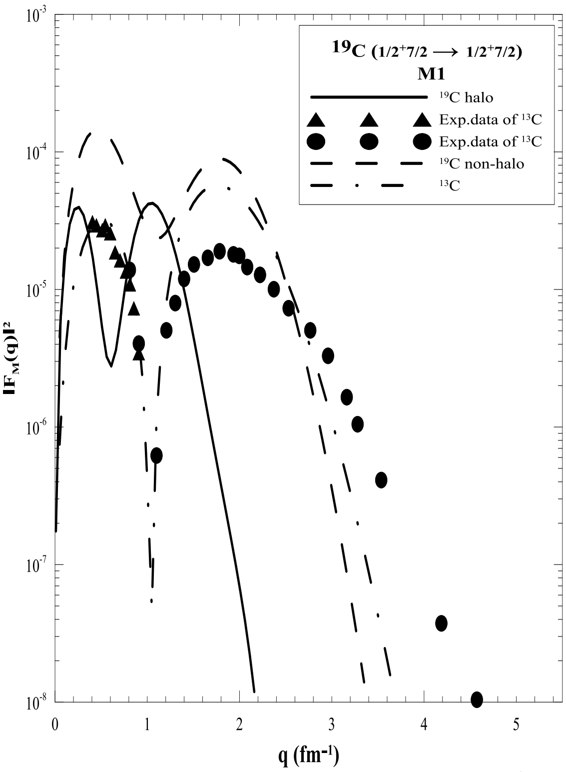

Figure 3- Comparison between the total form factors of ^{19}C halo (solid curve), ^{19}C non halo (dashed curve) and ^{13}C (dash-dot curve) with the experimental data of ^{13}C nucleus**.**

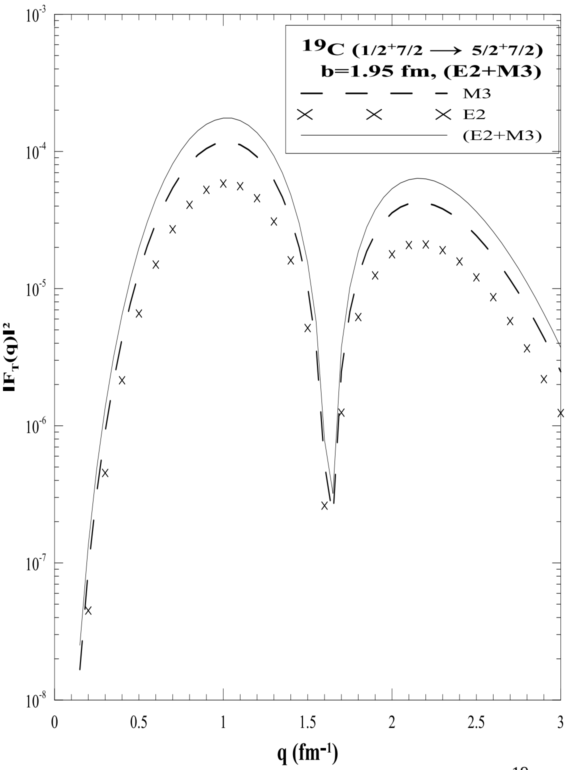

Figure 4- The transverse form factors for ^{19}C excited state ($J^{\pi}T = 5/2^{+}$ 7/2) calculated in *ZBM* model space. The individual multipole contribution of E2 and M3 are shown.

Conclusions

1. In the present work, it is possible to draw the following conclusions:
2. The total form factors of ^{19}C (halo) have the same behavior as the calculated form factors of ^{19}C (non-halo) and ^{13}C but they are different in magnitude.
3. For neutron-halo nuclei, it is found that the form factors are not dependent on detailed properties of the neutron halo. The only difference between form factors of the unstable nucleus and that of stable is attributed to the difference in the center of mass correction.
4. The calculated elastic magnetic form factors for neutron-rich nuclei ^{19}C (halo) showed a backward shifts in comparison with ^{19}C (non-halo) and with stable one ^{13}C.
5. The result of magnetic dipole moments calculations based on *psd* model space (^{19}C halo) is less than that calculation in *ZBM* model space (^{19}C non-halo).
6. The magnetic dipole moments did not depend on the size parameter (b_{core} and $b_{halo)}$.

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