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ELECTRIC CHARGE FORM FACTOR OF ^{6}LI IN HADRON-QUARK HYBRID MODEL

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Abstract- The contribution of the multi-quark cluster states have been invoked in the wave function of ^{6}Li. The Hadron-Quark Hybrid (HQH) model used here combines hadronic (traditional nuclear) and quark-cluster wave functions. The hadronic wave function is based on realistic nuclear wave functions. Variational Monte Carlo method is used for the calculation of the hadronic wave function. The quark-cluster wave function is based on a relativistic harmonic oscillator. The effect of multi-quark clusters on the charge form factor of ^{6}Li at large momentum transfer region has been investigated. The existing experimental data is in good agreement with the results that have been obtained.
Keywords- Nuclear Physics, Nuclear Charge Form factor, Elastic Electron Scattering, Few Nucleon Systems, Relativistic Harmonic Oscillator, Realistic Nuclear Potentials

Introduction

The high energy electron scattering has been a successful tool in providing vital information concerning charge and current distribution admixtures in nuclei, high momentum components of the nucleus wave functions, short range correlation effects, meson exchange currents, quantum chromodynamics, and quark degrees of freedom in nuclei.
Shell model has been quite successful in analyzing electron scattering data particularly in the low momentum transfer region. In the case of ^{6}Li, however, unlike other p-shell nuclei, one has to introduce some modification to the pure shell approach in order to obtain an agreement with the observed data , as in Lodhi [1]. The attempt to invoke an α-d cluster wave functions, as in Bergstrom [2], and the introduction of αNN clusterization, as in Ryzhikh [3], brought some improvements in the form factor of ^{6}Li. The conventional nuclear physics form factors, where hadrons (nucleons and mesons) dominate the dynamics of interaction, fall down more rapidly as function of the invariant momentum transfer squared, q^2 , than the experimental results for increasing q^2, McCarthy [4], Li [5], F. P. Juster [6], and D. H. Beck [7]. Ordinary nuclear physics assumes that nuclei are loosely bound systems of elementary particles, namely, structureless neutrons and protons. Accordingly, in impulse approximation, the scattering off a nucleus is treated as a simple superposition of scattering off free nucleons at rest. The deviation of the form factors under this model from experimental data has led to several approaches. One of the assumptions that could be made is that there were clustering phenomenon of quarks as integral multiple of three-quark configurations in addition to the neutron-proton bound states of nuclei in ordinary nuclear physics, Kizukuri [8], Namiki [9], Vary [10], P. Hoodbhoy [11], and L. Kisslinger [12]. The European Muon Collaboration Effect (EMC), Aubert [13], has revealed a difference in the structure functions of bound nucleons compared to that of free nucleons, thus leading to believe in a quark structure manifesting in the nucleus. In the light of the Quark Degrees of Freedom (QDF), multi-quark clustering model for understanding the nuclear structure has been seen as important, Butler and Miller [14]. Recently, an experiment on inclusive electron-proton and electron-deuteron inelastic cross sections has been done at Jefferson Lab to confirm the hadron-quark duality in the resonance region, at large momentum transfers by S. P. Malace [15].
At low momentum transfer region, the conventional hadron wave function dominates and the multi-quark clusters effect is almost totally insignificant. On the other hand, in the large momentum transfer region, the conventional hadron physics contribution to the form factor decreases rapidly and multi-quark cluster effect becomes dominant.
These ideas were independently applied to ^{6}Li charge form factor using a multi-quark cluster configuration. Khalil [16] used a phenomenological model for ^{6}Li charge form factor in terms of multi-quark cluster configuration in the region of 4 fm^{-2} < q^2 < 32 fm^{-2} . These calculations predict no diffraction minimum in the expected region of momentum transfer around $q^2 \approx 8$ fm^{-2}. Instead, they seem to over-correct the charge form factor when compared with the experimental data, Frosch [17] and Li [5]. In a previous paper, Lodhi [1], the multi-quark cluster effect on the charge form factor of some light nuclei was presented in which preliminary results for ^{6}Li were also reported. They showed good agreement with the observed data and the first diffraction minimum and the second maximum in the experimentally observed region. In this paper, somewhat detailed calculations of the charge form factor of ^{6}Li in the Hadron-Quark Hybrid (HQH) model are presented up to the momentum transfer squared,
Q^2 = 100 fm^{-2}. In this model, the quark part of the wave function of ^{6}Li have been chosen to be the relativistic harmonic oscillator, Namiki [9].

Wave Function of ^{6}Li in the HQH Model

In this model of ^{6}Li nucleus, the conventional nuclear physics wave function dominates in the low momentum transfer region. In this region, the ^{6}Li can be further split into ^{4}He and deuteron and treat their densities as overlaps as done by G. Z. Krumova [18]. This approach is similar to a recent treatment of ^{4}He as four cluster channels, i.e., p-^{3}H , n-^{3}He, d-^{2}H, and d-^{2}H as proposed by H. M. Hofmann and G. M. Hale [19]. It is also similar to the approach proposed for exotic nuclei such as many exotic nuclei, such as ^{6}He (= $\alpha + n + n$) or ^{11}Li(= ^{9}Li + n + n) by A. Damman and P. Descouvemont [20]. Recently, a study of α-cluster structure above doubly closed shells has been done based on the generalized density-dependent cluster model by Dongdong Ni and Zhongzhou Ren [21].

The contribution of the multiquark cluster configurations to the total wave function is small. However, the multiquark cluster configurations dominate in the high momentum transfer region. The total wave function, including both hadronic (nuclear) part and quark part, is given by

$$\left|\Psi_A\right\rangle = \alpha_1 \left|\Psi_A^{r>r_o}\right\rangle_{\mathbf{Hadronic}} + \alpha_2 \left|\Psi_A^{r\le r_o}\right\rangle_{\mathbf{Quark}} \qquad (1)$$

where

A = 6 for ^{6}Li, $\alpha_1 >> \alpha_2$, $\left|\alpha_1^2\right| + \left|\alpha_2^2\right| = 1$ and $r_o \approx 0.50$ fm is the cut-off radius, i.e. the boundary that separates the hadronic and quark regions. It is assumed that the hadronic part of the above wave function has non zero value only outside the hard core region of the ordinary nucleon-nucleon interaction, while the quark part exists only inside the hard core region.

For the hadronic part of the wave function, two wave functions have been considered. The first one is the nuclear shell-model harmonic oscillator bases with a Jastrow-type correlation function S. E. Massen [22]:

$$f(r) = 1 - j_o(kr)$$

satisfying both the short-range and long range properties of the nuclear such that

$$\lim_{r\to\infty} f(r) = 1 \quad \text{and} \quad \lim_{r\to 0} f(r) = 0$$

$j_O(kr)$ is a spherical Bessel function and $r \equiv r_{ij} = \left|\vec{r}_i - \vec{r}_j\right|$. The most common approach of invoking the short-range correlation is to multiply the single particle density by the above Jastrow-type function which satisfies the properties of a nucleon-nucleon interaction. The correlated wave function is, therefore:

$$\Psi\left(\vec{r}_1, \vec{r}_2, \ldots\ldots\ldots, \vec{r}_A\right) = \psi\left(\vec{r}_1, \vec{r}_2, \ldots\ldots\ldots, \vec{r}_A\right) \prod_{i<j=2}^{A} f\left(r_{ij}\right)$$

where A = 6 for ^{6}Li and $\psi\left(\vec{r}_1, \vec{r}_2, \ldots\ldots\ldots, \vec{r}_A\right)$ is the harmonic oscillator basis given by:

$$\psi_{nlm}\left(\vec{r}\right) = R_{nl}(r) Y_l^m(\Omega)$$

where

$$R_{nl}(r) = N(\alpha r)^l \exp\left(-\frac{1}{2}\alpha^2 r^2\right) L_n^{l+\frac{1}{2}}\left(\alpha^2 r^2\right)$$

The second wave function considered is a variational wave function derived from the realistic Argonne v$_{18}$ and Urbana IX potentials. Variational Monte Carlo technique is used for the derivation of the wave function. The general format of the wave function is provided by Wiringa and Schiavilla [23] and it is as follows:

$$\left|\Psi_V\right\rangle = \left[1 + \sum_{i<j<k}\left(U_{ijk} + U_{ijk}^{TNI}\right) + \sum_{i<j} U_{ij}^{LS}\right]\left|\Psi_P\right\rangle \qquad (2)$$

where the pair wave function , $\left|\Psi_P\right\rangle$, is given by

$$\left|\Psi_P\right\rangle = \left[S\prod_{i<j}\left(1 + U_{ij}\right)\right]\left|\Psi_J\right\rangle \qquad (3)$$

The U_{ij} , U_{ij}^{LS} , U_{ijk} , and U_{ijk}^{TNI} are non-commuting two- and three-nucleon correlation operators, and the S is a symmetrization operator. Ψ_J is an anti-symmetric Jastrow wave function, R. B. Wiringa at. al [24], Pudliner [25], R. B. Wiringa et. al [26], and Muslema Pervin [27].

In the multi-quark cluster configuration ^{6}Li wave function can be written as:

$$\left|{}^6Li\right\rangle = c_1\left|Hadronic\right\rangle + c_2\left|6q-3q-3q-3q-3q\right\rangle + c_3\left|9q-3q-3q-3q\right\rangle$$
$$+$$
$$c_4\left|12q-3q-3q\right\rangle + c_5\left|9q-6q-3q\right\rangle + c_6\left|6q-6q-3q-3q\right\rangle$$
$$+$$
$$c_7\left|6q-6q-6q\right\rangle + c_8\left|12q-6q\right\rangle + c_9\left|9q-9q\right\rangle + c_{10}\left|15q-3q\right\rangle + c_{11}\left|18q\right\rangle \qquad (4)$$

The first term in Equation (4) is the hadronic part of the wave function represented by Ψ_V in Equation (2). The remaining terms represent the multiquark cluster wave functions which can be written symbolically as:

$$\left|\Psi_{quark}\right\rangle = \left|c_2\Psi_2 + c_3\Psi_3 + c_4\Psi_4 + c_5\Psi_5 + c_6\Psi_6 + c_7\Psi_7\right\rangle$$

$$+ \left|c_8\Psi_8 + c_9\Psi_9 + c_{10}\Psi_{10} + c_{11}\Psi_{11}\right\rangle \qquad (5)$$

The coefficients c_2, c_3, c_4, etc., are yet to be determined. The quark part of the wave function is calculated from a relativistic harmonic oscillator (RHOM) model:

$$\left[\sum_{i=1}^{n} p^{(i)^2} + k^2 \sum_{i>j=1}^{n}\left(x^{(i)} - x^{(j)}\right)^2\right]\Psi_{nq} = 0 \quad (6)$$

which leads to n-quark cluster a wave function of

$$\Psi_{nq}\left(r^{(1)},....,r^{(n-1)};P\right) = \left(\frac{\alpha_n}{n\pi}\right)^{n-1} \times \exp\left[\frac{\alpha_n}{2n}\left(g^{\nu\mu} - \frac{2P^\mu P^\nu}{M_n^2}\right)\left(\sum_{i=1}^{n-1} r_\mu^{(i)} r_\nu^{(i)}\right)\right] \quad (7)$$

A transformation matrix is used to get the expression

$$\sum_{i>j=1}^{n}\left(x^{(i)} - x^{(j)}\right)^2 = n\sum_{i=1}^{n-1} r^{(i)^2} \quad (8)$$

where the parameter α_n is given for the n-quark bound state system by the relation $\alpha_n = n^{\frac{3}{2}}k$. The coupling constant κ in the RHOM is to be determined as to give the Regge slope for a three quark bound system (nucleon); specifically it is given by $\alpha_3 = 3^{\frac{3}{2}}\kappa$ so that κ = 0.096 (Gev/c)^2 = 2.4fm^{-2} , Namiki [9].

These expressions thus provide values for α_n for n-quark cluster system. The values of α_n thus generated and the parameter M_n, which is the physical mass of an n-quark cluster system in a bound state, are listed in the following table (Table 1). P^μ and P^ν are four-momenta vectors and $g^{\mu\nu}$ is the metric tensor.

Since the n-quark sub-system occurs as a cluster configuration in a given system, the parameter M_n is treated as the so-called symmetric mass of the corresponding multiplets, Namiki [9]. Like nuclear masses, the mass of a 3*n*-quark cluster is assumed to be less than the mass of the corresponding n nucleons forming that cluster, Koch and Miller [28]. The values of M_3 and M_6 are chosen from the earlier work on electron-deuteron elastic scattering of Kizikuri et al. [29] and Namiki [9]. The values of M_9 and M_{12} are used from the work of Namiki et al. [9] obtained from the electron-helium scattering. The effective mass parameter belonging to larger values of *n* like M_{15} and M_{18} are determined from the assumption that the ratio of the number of quarks in a given cluster to that of the preceding cluster is equal to the ratio of their respective masses.

In other words, it establishes the relation as

$$\frac{n+3}{n} = \frac{M_{n+3}}{M_n} \quad (9)$$

In the analogy of nuclear cluster model, Lodhi [30] and Wildermuth [31], a quark cluster wave function consisting of, say, two clusters of *m* and *n* quarks can be written in the symbolic form

$$\Psi_{m-n} = N\phi_i(nq)\phi_j(mq)X\left(\left|\mathbf{R}_n - \mathbf{R}_m\right|\right) \quad (10)$$

where ϕ_i and ϕ_j describe the *n* and *m* quark clusters respectively, $X\left(\left|\mathbf{R}_n - \mathbf{R}_m\right|\right)$ refers to the relative motion between the two clusters and *N* is the normalization constant which antisymmetrizes the wave function completely with respect to the exchange of all pairs of particles involved. Specifically, the wave function of a system consisting of two clusters of two quarks each is written in the RHOM as:

$$\Psi_{2q-2q}(\mathbf{X};\mathbf{P},R,r_1,r_2) = N\phi_i(r_1,P)\phi_j(r_2,P)X(R;P)\exp(-i\mathbf{P}.\mathbf{X}) \quad (11)$$

where **X** and **P** are the center of mass coordinate and momentum respectively, R is the relative coordinate between the two clusters and r_1 and r_2 are the relative coordinates inside each cluster, Kizukuri [29].

The Admixture Coefficients

There are variety of definitions found in the literature for the probability of formation of quark clusters in a given nucleus. One can define in a most straightforward manner as the probability of a nucleus to be found in a certain quark cluster configuration. This probability corresponds to the square of the amplitude in a cluster expansion of the nuclear wave function. Accordingly, the squares of the coefficients c_i^2 in the expansion of the wave function given by Equation (5) correspond to those probabilities. A slightly different definition than the preceding one may be given as the probability that a quark chosen at random in a given nucleus is obtained from an n-quark cluster where n = 3, 6, 9, ... Obviously, this probability is not in general the square of the coefficients in the expansion of Equation (5) but certainly related. These probabilities can be transformed in terms of the squares of the admixture coefficients. If we let p_i represent the probability that a quark is chosen at random from an i-quark cluster where i-quark cluster appears in several channels with amplitudes c_i in Equation (5). The relation between various p_i and c_i can readily be written for ^{6}Li as follows:

$$p_3 = c_1^2 + \frac{2}{3}c_2^2 + \frac{1}{2}c_3^2 + \frac{1}{3}c_4^2 + \frac{1}{6}c_5^2 + \frac{1}{3}c_6^2 + \frac{1}{6}c_{10}^2$$

$$p_6 = \frac{1}{3}c_2^2 + \frac{1}{3}c_5^2 + \frac{2}{3}c_6^2 + c_7^2 + \frac{1}{3}c_8^2$$

$$p_9 = \frac{1}{3}c_3^2 + \frac{1}{2}c_5^2 + c_9^2$$

$$p_{12} = \frac{2}{3}c_4^2 + \frac{2}{3}c_5^2$$

$$p_{15} = \frac{5}{6}c_{10}^2$$

$$p_{18} = c_{11}^2$$

These equations can be inverted to express c_i^2 in terms of p_i. By the same reasoning as in Namiki et al. [9], the 6q-6q and 9q-3q cluster configurations are equally probable. Likewise, $c_3^2 = c_4^2$, $c_5^2 = c_6^2$, $c_7^2 = c_8^2 = c_9^2 = c_{10}^2$. With this assumption, The previous equations are converted as follows:

$$c_1^2 = p_3 - 2p_6 + 3p_9 - \frac{7}{2}p_{12} + \frac{11}{5}p_{15}$$

$$c_2^2 = 3p_6 - 6p_9 + \frac{9}{2}p_{12} - \frac{6}{5}p_{15}$$

$$c_3^2 = \frac{3}{2}p_{12} - \frac{6}{5}p_{15}$$

$$c_5^2 = 2p_9 - \frac{3}{2}p_{12} - \frac{6}{5}p_{15}$$

$$c_7^2 = \frac{6}{5}p_{15}$$

$$c_{11}^2 = p_{18}$$

The quark cluster probabilities have been evaluated for light nuclei, namely ^{2}H and ^{3}He by M. Sato [32]. For heavier nuclei, only qualitative estimates have been used. For this work, those admixture coefficients have been evaluated from a hydrodynamical approach based on the flucton theory, Burov [33]. A more recent approach invokes the effect of nuclear surface fluctuations and thermodynamic influences on the charge form factor of light nuclei. S .E. Massen [34] and X. J. Wen [35].

Let these probabilities be denoted c_k^2 where k = 1 corresponds to three-quark cluster (i.e. ordinary hadronic component of the wave function), k = 2 corresponds to six-quark cluster, and so on. The probability of finding k nucleons of the nucleus of mass number A in the flucton volume $V_\xi = \frac{4}{3}\pi r_\xi^3$ is given by:

$$c_k^2 = \binom{A}{k}\left(\frac{V_\xi}{AV_o}\right)^{k-1} B_k \qquad (12)$$

V_o is the nuclear volume given by $V_o = \frac{4}{3}\pi r_o^3$. Here B_k allows for the isotopic composition of a function with k_N neutrons and k_Z protons, and is given by:

$$B_k = \frac{1}{Z}\binom{N}{k_N}\binom{Z}{k_Z}\binom{A}{k}^{-1} \qquad (13)$$

The other parameters r_ξ and r_o are chosen to be 0.75 fm and 1.2 fm, respectively [29]. The calculated admixture coefficients are listed in the following table.

^{6}Li Charge form Factor

With the separation of hadron and quark parts of the wave function

Described earlier, the charge form factor of ^{6}Li can be written in Hadron-Quark Hybrid (HQH) model as:

$$F(q^2) = \alpha_1^2 F_N(q^2) + \alpha_2^2 F_q(q^2) \qquad (14)$$

with the conditions that $F(0) = F_N(0) = F_q(0) = 1$.

With the wave function given by Equation (5), the form factor can be written as:

$$\sum_{i=1}^{11} c_i^2 F_i(q^2) \qquad (15)$$

where $F_i(Q^2)$ correspond to the cluster configuration terms respectively given by Equation (4). The first term in the above equation is recognized as:

$$c_1^2 F_1(q^2) \equiv c_1^2 F_{3-3-3-3-3-3}(q^2) = \cos^2\theta \, F_N(q^2)$$

Is the contribution from the hadron part. The remaining ten terms are contributed by various quark clusters. In the first Born approximation, the elastic nuclear charge form factor is given by:

$$F(q^2) = \frac{1}{Z}\sum_{i=1}^{Z}\int_0^\infty \Psi^*(\vec{r}_1,\vec{r}_2,....,\vec{r}_A)\exp(i\vec{q}.\vec{r}_i)\Psi(\vec{r}_1,\vec{r}_2,....,\vec{r}_A)d^3r_1....d^3r_A \qquad (16)$$

The wave function Ψ is the realistic wave function. We used variational Monte Carlo method similar to the one used earlier by R. B. Wiringa and R. Schiavilla [23].

The hadron part of the wave function distributing over a wide range in the exterior region does not overlap with that of the quark-cluster components, confined with a narrow range in the interior region, as far as their main parts are concerned. In the zeroth order of approximation, the orthogonality of the hadron and quark-cluster components can be assumed. Therefore, no cross terms over hadron and quark cluster parts are included in these calculations. The charge form factor for the multi-quark cluster channel is calculated in the RHOM basis which governs their relativistic bound systems. It should depend on the center-of-mass momentum. Because of this dependence, the final inner wave function is different from the initial one.

Using the first Born approximations, the form factor for the quark-cluster part is found to be:

$$F_{nq}(q^2) = \left[1 + \frac{q^2}{2M_n^2}\right]^{-n+1} \times \exp\left[-\frac{(n-1)q^2}{4\alpha_n\left(1+\frac{q^2}{2M_n^2}\right)}\right] \qquad (17)$$

One feature of Equation (17) is that the form factor $F_{nq}\left(q^2\right)$ obeys the asymptotic behavior, i.e., $F_{nq}\left(q^2\right) \propto \left(q^2\right)^{1-n}$ in the region of high momentum transfer, which is in agreement with the experimental data in Brodsky and Chertok [36].

An overlapping integral that takes various *n*-quark clusters into consideration, as in Namiki et al [9], is given by:

$$G_{nq}\left(q^2\right) = \int_0^\infty \Psi_{nq}^*\left(r; P_f\right)\Psi_{nq}\left(r; P_i\right) d^4 r = \left(1 + \frac{q^2}{2M_n^2}\right)^{1-n} \quad (18)$$

where *r* stands for the four-dimensional relative coordinate, P_i and P_f for the initial and final center-of-mass four momenta, respectively. In the above equations, the term $\frac{q^2}{2M_n^2}$ would become $\frac{\hbar^2 q^2}{2\ c^2 M_n^2}$ if $\hbar$ and *c* are not taken as one.

Equations (17) and (18) are used to calculate the quark-cluster contributions to the total charge form factor of ^{6}Li as follows:

$$F_{6-3-3-3-3}\left(q^2\right) = \frac{1}{3}\left[F_{6q}\left(q^2\right)\left(G_{3q}(q^2)\right)^4 + 2F_{3q}\left(q^2\right)\left(G_{3q}(q^2)\right)^3 G_{6q}(q^2)\right] \times F_{5c}$$

$$F_{9-3-3-3}\left(q^2\right) = \frac{1}{2}\left[F_{9q}\left(q^2\right)\left(G_{3q}(q^2)\right)^3 + F_{3q}\left(q^2\right)\left(G_{3q}(q^2)\right)^2 G_{9q}(q^2)\right] \times F_{4c}$$

$$F_{6-6-3-3}\left(q^2\right) = \frac{1}{3}\left[2F_{6q}\left(q^2\right)\left(G_{3q}(q^2)\right)^2 G_{6q}(q^2) + F_{3q}\left(q^2\right) G_{3q}(q^2)\left(G_{6q}(q^2)\right)^2\right] \times F_{4c}$$

$$F_{6-6-6}\left(q^2\right) = F_{6q}\left(q^2\right)\left(G_{6q}(q^2)\right)^2 \times F_{2c}$$

$$F_{9q-6q-3q}\left(q^2\right) = \left[\frac{1}{2}F_{9q}\left(q^2\right) G_{6q}(q^2) G_{3q}(q^2) + \frac{1}{3}F_{6q}\left(q^2\right) G_{9q}(q^2)\ G_{3q}(q^2) + \frac{1}{6}F_{3q}\left(q^2\right) G_{9q}(q^2)\ G_{6q}(q^2)\right] \times F_{3c}$$

$$F_{12q-3q-3q}\left(q^2\right) = \frac{1}{3}\left[2F_{12q}\left(q^2\right)\left(G_{3q}(q^2)\right)^2 + F_{3q}\left(q^2\right) G_{3q}(q^2)\ G_{12q}(q^2)\right] \times F_{3c}$$

$$F_{9q-9q}\left(q^2\right) = F_{9q}\left(q^2\right)\ G_{9q}(q^2) \times F_{2c}$$

$$F_{12q-6q}\left(q^2\right) = \frac{1}{3}\left[2F_{12q}\left(q^2\right) G_{6q}(q^2) + F_{6q}\left(q^2\right) G_{12q}(q^2)\right] \times F_{2c}$$

$$F_{15q-3q}\left(q^2\right) = \frac{1}{6}\left[5F_{15q}\left(q^2\right) G_{3q}(q^2) + F_{3q}\left(q^2\right) G_{15q}(q^2)\right] \times F_{2c}$$

$$F_{18q}\left(q^2\right) = F_{18q}\left(q^2\right)$$

The terms F_{nc} arise from the relative coordinates of *n* clusters and is given by:

$$F_{nc}\left(q^2\right) = \left(1 + \frac{q^2}{m^2}\right)^{1-n}$$

where *m* is of the order of 1.0 GeV/c^2 = 5.0 fm^{-1} as in Namiki [9].

Results

The elastic electric charge form factor of ^{6}Li has been calculated in the HQH model with the variational Monte Carlo method mentioned earlier. The result is presented in Figure 1 up to a range of momentum transfer squared 100 fm^{-2}. The elastic charge form factor of ^{6}Li has also been calculated using the hadronic (nuclear) wave function only, i.e., without quark degrees of freedom, and it is presented in Figure 2. The experimental data are taken from Li [5] and Bergstrom [37]. In the low momentum transfer region ($q^2 \approx 20$ fm^{-2}), the hadron part dominates but as q^2 increases the quark-cluster component starts showing its dominance. In that region, $q^2 \leq 20$ fm^{-2}, the form factor of ^{6}Li can be produced quite accurately (as a system of non-relativistic nucleons interacting with each other) in agreement with the experimental data. There is sufficient experimental data beyond $q^2 \approx 20$ fm^{-2} to compare to the theoretical predictions. However, these predictions for the electric charge form factor of ^{6}Li (when quark-cluster contributions are included) show some interesting features pertaining to the complexity of charge distribution in ^{6}Li. These features, in the high momentum transfer region, are revealed by the elastic scattering of high energy electrons.

Conclusion

Quark-clustering phenomenon in nuclei is relatively a new tool in under-standing nuclear and quark physics at high energies in nuclei. The success of this approach in light nuclei has led to the calculation of the charge form factor of ^{6}Li. In these calculations, the quark-cluster contribution has been shown playing important role at the high momentum transfer region. The calculated charge form factor of 6Li is in good agreement with the experimental values of Li [5], Lapiks [38], and Bergstrom *et al.* [2]. The second minimum and third maximum in the form factor have been predicted at $q^2 \approx$ 25 fm^{-2} and $q^2 \approx 34$ fm^{-2}, respectively, thus shifting them toward higher momentum transfer region than predicted by purely hadron wave function. Also, the third maximum is raised by about two orders of magnitude above the one predicted by corresponding hadron wave function. In the absence of the experimental data in the high momentum region, this in itself is a significant contribution from the small admixture of multi-quark configurations in improving the hadronic (conventional nuclear physics) results. A more definite conclusion on the nature of multi-quark admixtures in ^{6}Li requires a more detailed experimental investigation of ^{6}Li form factor at high momentum transfer region than what is presently available.

List of Abbreviations

1. **HQH**: Hadron-Quark Hybrid
2. **EMC**: European Muon Collaboration Effect (EMC)
3. **QDF**: Quark Degrees of Freedom
4. **RHOM**: Relativistic Harmonic Oscillator

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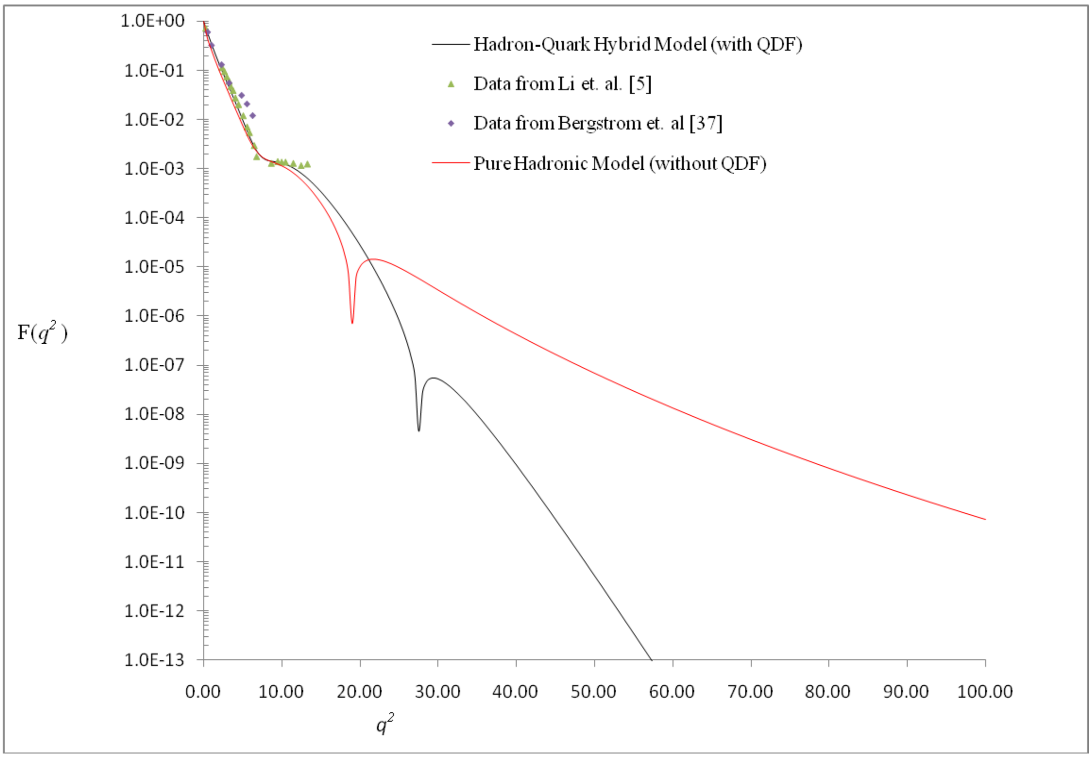

Fig. 1-Theoretical harmonic oscillator calculations of the electric charge form factor of ^{6}Li without quark degrees of freedom (red curve) and with quark degrees of freedom (black curve). Data are as indicated.

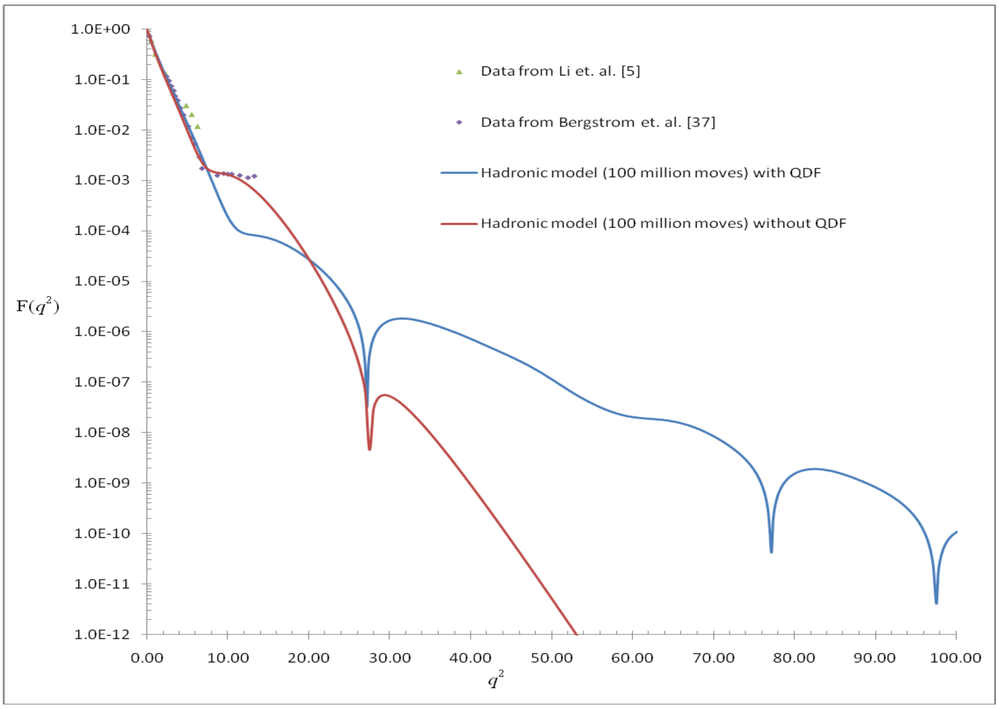

Fig. 2-Theoretical realistic wave calculations (100 million moves in the Monte Carlo simulation) of the electric charge form factor of ^{6}Li without quark degrees of freedom (red curve) and with quark degrees of freedom (blue curve). Data are as indicated.

Table 1- *The values of $\square_n$ and the parameter cM_n*

n	cM_n (GeV/c)	$\square_n$ $(GeV/c)^2$
3	1.10	0.50
6	1.20	1.41
9	1.50	2.59
12	2.00	4.00
15	2.53	5.58
18	3.02	7.33
21	3.50	9.24

Table 2: Admixture Coefficients and their values

Admixture Coefficient	Calculated value
c_1^2	0.8000
c_2^2	0.1600
c_3^2	0.0192
c_4^2	0.0192
c_5^2	7.680×10^{-4}
c_6^2	7.680×10^{-4}
c_7^2	1.600×10^{-5}
c_8^2	1.600×10^{-5}
c_9^2	1.600×10^{-5}
c_{10}^2	1.600×10^{-5}
c_{11}^2	1.020×10^{-7}