Calculation of Masses and Magnetic Moment of the Nucleon using the MIT Bag Model

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Abstract—The bag radius of the nucleon can be determined by MIT bag model based on electric and magnetic form factors of the nucleon. Also we determined the masses and magnetic moment of the nucleon with MIT bag model, using bag radius and compared with other results, suggests a suitable compatibility.

Keywords—MIT bag model, masses and magnetic moment of the nucleon, bag radius of the nucleon.

I. INTRODUCTION

The study of the electromagnetic form factors of the nucleons is of fundamental importance in understanding their electromagnetic structure. The electromagnetic form factors of the nucleon have been a longstanding subject of interest in nuclear and particle physics, and have been the subject of sustained experimental and theoretical investigations for almost 50 years [1]. The original MIT bag model was presented about three decades ago [2, 3]. This model is defined by the equation of motion and boundary condition for each field degree of freedom inside the bag and homogeneous boundary condition at the surface of the bag. Hadrons are considered as static extended objects in space. The internal structure of these objects includes quarks and varying gluon field. In MIT bag model, it is supposed that a region of space called “bag” including hadrons fields are fixed. The pressure of hadron constituents in the surface is constant and the vacuum around the bag imposes an external pressure on the surface of the bag. As this external pressure increases more than the internal one, the bag shrinks [4]. B is the only parameter of this theory. Hadrons constituent fields in the bag can carry any spin or quantum numbers. In this paper we generally supposed that the fields in the bag are massless, that is, free Lagrangian is considered for the fields without any interaction in Lagrangian. Although the fields in the bag are free in first approximation, at the next level, it is suggested that the fields couple weakly. Weak coupling is considered for the quantum numbers in the hadron. The hadron fields in the bag are colored quarks and gluons [3]. Models such as MIT bag model describe two features of QCD in the quark model [5], asymptotic in short distances and confinement in large distances. The goal of this paper is to perform the numerical analysis the masses and magnetic moment of the nucleon with MIT bag model based on the electric and magnetic form factors. Finally the obtained results are compared to the experimental and previous calculated values.

II. FORM FACTORS OF THE NUCLEON

Elastic electron scattering off the lightest nuclei, hydrogen and deuterium, yields information about the nuclear building blocks, the proton and the neutron [5].

The proton form factors $G_E$ and $G_M$, were determined by first converting the experimental elastic e-p cross section $\sigma = (E, \theta)$ to the reduced cross section $\sigma_R[6]$, as:

$$\sigma_R(Q^2, \varepsilon) = \varepsilon (1 + \varepsilon) \frac{E}{E'} \frac{\sigma(E, \theta)}{\sigma_{Mott}} = \tau'^2 G_E^2 (Q^2) + \varepsilon G_M^2 (Q^2)$$

(1)

Where $\sigma_{Mott} = \frac{a^2 \cos^2 \theta}{4E^2 \sin^2 \frac{\theta}{2}}$ are $E = E' - Q^2$.

In this portion $\varepsilon = \left(1 + 2(1 + \varepsilon)\tan^2 \frac{\theta}{2}\right)^{-1}$ is the transverse polarized of the virtual photon. By measuring the reduced cross section $\sigma_R$ at several $\varepsilon$ points for a fixed $Q^2$, and by making a linear fit to $\varepsilon$, we obtain $\tau'^2 G_E^2 (Q^2)$ from the intercept and $G_M^2 (Q^2)$ from the slope.

Quasielastic e-d spectra at each kinematic point were obtained as function of missing mass squared, $W^2 = M^2 - 2M(E - E') - Q^2$.

In this portion $\varepsilon = \left(1 + 2(1 + \tau')\tan^2 \frac{\theta}{2}\right)^{-1}$ is the longitudinal polarization of the virtual photon, with $\tau' = \frac{v^2}{Q^2}$ and $V = E - E'$. The measured e-d cross section per nucleon, $\sigma(E - E', \theta)$, were converted to reduce cross sections, defined as:

$$\sigma_R = \varepsilon (1 + \tau') \frac{\sigma(E, \theta)}{\sigma_{Mott}} \frac{\sigma_R^E}{\sigma_R^M} = \frac{E}{E'} \frac{\sigma_R}{\sigma_R^E}$$

(2)

To extract the neutron form factors, $R_L$ and $R_T$ were fitted with the model shapes for both the quasielastic and inelastic contributions. The quasielastic component was modeled with a nonrelativistic plane wave impulse approximation (PWIA) calculation [7] using par dieutron wave function [8].

In the PWL quasielastic portion of $R_L$ is proportional to $(G_E^2)^2 + (G_M^2)^2$, and that $R_T$ is proportional [9] to $(G_E^2)^2 + (G_M^2)^2$. The neutron form factors were determined by subtracting the proton form factors measured from the coefficients of the quasielastic fits [10].

III. NUCLEON BAG RADIUS

In the other hand, the nucleon form factors can be calculated in other theory models. There are many calculations.
of the nucleon electromagnetic form factors within different hadronic models. Indeed the understanding of these form factors is extremely important in any effective theory or models of strong interaction [11]. The electromagnetic form factors of proton and neutron are calculated using MIT bag model wave function and parameters [12, 13]. The MIT bag model is a conceptually very simple phenomenological model developed in 1974 at the Massachusetts Institute of Technology in Cambridge (USA) shortly after the formulation of QCD. It soon became a major tool for hadrons theorists. Technology in Cambridge (USA) shortly after the formulation of QCD. It soon became a major tool for hadrons theorists.

The remainder of the zero-point energy is:

\[ E_0 = \frac{Z_0}{R} \]  

(8)

where \( E_0 \) is the frequency defined by:

\[ \omega(m,R) = \frac{1}{2} [x^2 + (mR)^2]^\frac{3}{2} \]  

(9)

Then this term is:

\[ E_0 = N_0 \omega(m_0,R) + N_s \omega(m_s,R) \]  

(11)

(a) The quantum fluctuations contribute two terms which depend only on the radius of the nucleon. The Volume term is:

\[ E_V = \frac{4}{3} \pi B R^3 \]  

(7)

The remainder of the zero-point energy is:

\[ E_0 = -\frac{Z_0}{R} \]  

(10)

(b) The quarks contribute their rest and kinetic energies to the nucleon's mass. If \( N_n, N_s, m_n, \) and \( m_s \), the respective numbers and masses of thenonstrange and strange quarks, and if \( \omega \) is the frequency defined by:

\[ \omega(m,R) = \frac{1}{2} [x^2 + (mR)^2]^\frac{3}{2} \]  

(9)

then this term is:

\[ E_0 = N_0 \omega(m_0,R) + N_s \omega(m_s,R) \]  

(11)

(c) The gluon interaction has color magnetic exchange and color electric parts. The color magnetic exchange term will be written in the form:

\[ E_M = a_{00} M_{00} + a_{0s} M_{0s} + a_{ss} M_{ss} \]  

(12)

In Eq.(12) \( M_{00} \) is the color magnetic interaction between two nonstrange quark, \( M_{0s} \) is that between a nonstrange and strange quark and \( M_{ss} \), the interaction energy between two strange quarks. The values of \( M_{00} \), \( M_{0s} \), and \( M_{ss} \) can be read off of Fig. 1. The value \( a_{00} \) for nucleon is (-3). The color electric interaction is given by:

\[ E_E = b \epsilon \]  

(13)

Where \( \epsilon \) is the color electric interaction energy of a strange and a nonstrange quark including bothself-interaction and
exchange graphs. The coefficient b is one or zero depending upon whether the quark content of the hadron is mixed or not. Where for nucleon is zero.

The mass of hadron of radius R is then given by:
\[ M(R) = E_V + E_0 + E_Q + E_M + E_E \] (14)
Where the individual terms are given by:
\[ E_V = \frac{4}{3} \pi BR^3 \]
\[ E_0 = -\frac{Z_0}{R} \]
\[ E_Q = N_0 \alpha(m_0, R) \] (15)
Without considering the mass of quarks \( m_0 \) in above equation is zero. Then:
\[ E_Q = N_0 \frac{1}{2} \left[ x^2 + 0 \right] = \frac{N_0 \alpha}{R} = \frac{6.12}{R} \] (16)
Where due to nucleons do not have strange quark, then Eq. (11) as follow:
\[ E_M = \alpha_0 \alpha m_0 = -3M_{00} \] (17)
The value of \( M_{00} \) can be read off from Fig. 2. then:
\[ \frac{3}{8} \approx M_{00}R = 0.175 \]
\[ \alpha_c = 0.55 \]
\[ M_{00}R = 0.256 \] (18)

Next:
\[ M_N = \frac{4}{3} \pi (0.145)^4 R^3 - \frac{1.04}{R} + \frac{6.12}{R} - \frac{0.768}{R} \] (19)
Values of \( Z_0 \) and B in Eq.(19) according to Ref.[15] are
\[ Z_0 = 1 \cdot 84 \quad \text{and} \quad B^2 = 0 \cdot 145 \,(\text{Gev}). \]
Finally, mass of the nucleon is:
\[ M_N = \frac{4}{3} \pi (0 \cdot 145)^4 R^3 - \frac{1.04}{R} + \frac{6.12}{R} - \frac{0.768}{R} \] (20)
According to the calculated static radius, the numerical value of masses of the nucleons can be obtained by others. We show our results in Table 3.

V. MAGNETIC MOMENT

The magnetic moment of the proton in MIT bag model is defined as [4]:
\[ \mu_p = \oint d^3 r \int d^3 r_2 \int d^3 r_3 \psi_p \sum_i \left( \frac{\hat{\mathbf{Q}}_i \cdot \hat{\mathbf{a}}}{2} \right) \psi_p \] (21)
Here \( \psi_p \) denotes the proton wave function and \( \hat{\mathbf{Q}}_i \) is the charge operator. Since the SU(6) wave function of the proton is symmetric under permutations of the indices 1, 2, and 3, we have:
\[ i \psi_p^\dagger \left( \frac{\hat{\mathbf{Q}}_1 \cdot \hat{\mathbf{a}}}{2} \right) \psi_p d^3 r_1 d^3 r_2 d^3 r_3 = \]
\[ i \psi_p^\dagger \left( \frac{\hat{\mathbf{Q}}_2 \cdot \hat{\mathbf{a}}}{2} \right) \psi_p d^3 r_1 d^3 r_2 d^3 r_3 = \]
\[ i \psi_p^\dagger \left( \frac{\hat{\mathbf{Q}}_3 \cdot \hat{\mathbf{a}}}{2} \right) \psi_p d^3 r_1 d^3 r_2 d^3 r_3 \] (22)
We insert \( \psi_p \) in Eq. (21), then:
\[ \mu_p = \int d^3 r_1 \left| 10 u^r(1)^r \left( \frac{\hat{\mathbf{Q}}_1 \cdot \hat{\mathbf{a}}}{2} \right) u^r(1) + 2u^l(1)^l \left( \frac{\hat{\mathbf{Q}}_2 \cdot \hat{\mathbf{a}}}{2} \right) u^l(1) + 4d^l(1)^l \left( \frac{\hat{\mathbf{Q}}_3 \cdot \hat{\mathbf{a}}}{2} \right) d^l(1) \right| \]
\[ = \frac{\pi^2 N^2}{4} \int_0^\infty dr \frac{r^2}{(Er)^{\frac{7}{2}}} \int d\Omega \left( j_0(Er) x_{-1}^1 \right) \] (23)

Fig. 2 Eigen frequency x(mR) of the lowest quark mode with mass in a spherical cavity of radius R. Ref.[14]

Next we insert the quark charges and wave function of quarks obtain:
\[ \mu_p = \frac{\pi^2 N^2}{4} \int_0^\infty dr \frac{r^2}{(Er)^{\frac{7}{2}}} \int d\Omega \left( j_0(Er) x_{-1}^1 \right) \] (24)
Using commutation relations of pauli matrices, \( \sigma \), therefor :
\[ \mu_p = \frac{\pi^2 N^2}{4} \int_0^\infty dr \frac{r^2}{(Er)^{\frac{7}{2}}} \int d\Omega \left( j_0(Er) x_{-1}^1 \right) \] (25)
Now we can easily perform the \( \varphi \), \( \theta \), and \( r \) integrations:
\[ \mu_p = \frac{\pi^2 N^2}{4} \int_0^\infty dr \frac{r^2}{(Er)^{\frac{7}{2}}} \] (26)
According to the calculated static radius, the numerical value of magnetic moment of the proton can be obtained by others. With similar calculation obtained the magnetic moment of neutron. We show our results in Table 3.
VI. CONCLUSION

The electric and magnetic form factors of the proton are calculated and through using them in the MIT bag model, the bag radius can be calculated. In the limit of $Q^2 \rightarrow 0$, the static radius of the bag can be obtained and based on this, masses and magnetic moment of the nucleon can be calculated and compared with the results of others. There should be no difference between the proton and the neutron mass, because the proton and the neutron have the same quark structure.

Finally, as we have remarked, the magnetic moment of the proton is too small. This is a consequence of the fact that the magnetic moment of a quark is associated with the overlap of the small and large components of the Dirac wave function and this is rather small.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>COMPARISON OF CALCULATED MAGNETIC AND ELECTRIC FORM FACTORS WITH Ref.[15] AND RATIO OF THESE FORM FACTORS TO DIPOLE FIT. ADDITIONALLY, THE RADIUS OF THE BAG IS SHOWN</th>
</tr>
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<tbody>
<tr>
<td>$Q$ (GeV)</td>
<td>$G$</td>
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<tr>
<td>0.65</td>
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</tr>
<tr>
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<tr>
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<td>5.25</td>
<td>0.0155</td>
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<th>TABLE II</th>
<th>RESULTS FOR NEUTRON FORM FACTOR, AND THE RADIUS OF THE BAG IS SHOWN Ref.[16]</th>
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<tbody>
<tr>
<td>$Q$ (GeV)</td>
<td>$G$</td>
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<tr>
<td>1.75</td>
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<th>TABLE III</th>
<th>THE RESULTS OF OUR CALCULATIONS AND COMPARISON WITH THOSE OBTAINED BY OTHERS</th>
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<tbody>
<tr>
<td>$Q^2 (GeV/c)^2$</td>
<td>$R_{1}$ (fm)</td>
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<tr>
<td>1.011</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Ref [14]</td>
<td>0.986</td>
</tr>
<tr>
<td>Ref [17]</td>
<td>0.95</td>
</tr>
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REFERENCES