American Journal of Modern Physics
2013; 2(4): 190-194
Published online June 10, 2013 (http://www.sciencepublishinggroup.com/j/ajmp)
doi: 10.11648/j.ajmp.20130204.12

The role of pion cloud in the structure function and the EMC effect of ^{27}Al, ^{56}Fe, ^{63}Cu and, ^{107}Ag nuclei

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To cite this article:
Sara. Hatampanah, Negin. SattaryNikkhoo, Farhad. Zolfagharpour. The Role of Pion Cloud in the Structure Function and the EMC Effect of ^{27}Al, ^{56}Fe, ^{63}Cu and, ^{107}Ag nuclei. *American Journal of Modern Physics*. Vol. 2, No. 4, 2013, pp. 190-194.
doi: 10.11648/j.ajmp.20130204.12

Abstract: In this paper we have studied role of pionic contribution in the structure function and the EMC effect for^{27}Al, ^{56}Fe, ^{63}Cu and, ^{107}Ag nuclei. For extracting nuclear structure function, first we calculated contribution of the Fermi motion, and the binding energy effects and, then, we added pionic contribution to them. Also, we used the free GRV nucleon structure functions in the conventional nuclear theory. Extracted results show that using the pionic contribution in these nuclei structure function and the EMC effect give good agreement with experimental data.

Keywords: Pionic Contribution, Structure Function, the EMC Effect

1. Introduction

Deep inelastic lepton-nucleus scattering has shown that bound nucleons structure functions are different from free nucleons structure functions [1-5]. This phenomenon has been known as the EMC (European Muon Collaboration) effect [5]. This effect declared that the distribution function of quarks in the bound nucleons inside nuclei is different from free nucleons. The binding energy and the Fermi motion of nucleon inside nuclei have important role in the EMC effect in medium and large x ranges. Considering these effects could not explain bound nucleons structure functions and the EMC effect in all x ranges. There are other effects such as pion cloud, shadowing, quark exchange, Δ particle, and so on, which should be considered to explain nucleons structure functions and the EMC effect. Because quark distribution functions inside nuclei are affected by nuclear environment, bound nucleons structure are different from free nucleons structure. As a result, considering these nuclear effects could improve the extracted results. Nucleons inside nuclei are surrounded by pion cloud, so for achieving precise bound nucleons structure functions and the EMC effect, it seems that considering pionic contribution could improve theoretical results. Therefore, the probability of an incident virtual photon interacts with a nucleon is decreasing and this virtual photon is interacting with Pion cloud around nucleon inside nuclei. This interaction mainly occurs in range $x \leq 0.3$ [6-7]. In this paper, we have attempted to study of the pionic contribution in nuclei structure functions that consist of nucleons and mesons.

2. Nucleon Structure Function

The structure functions for charged lepton scattering from a nucleon are related to cross section by:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2(E')^2}{Q^4 cos^2\left(\frac{\theta}{2}\right)} \times \left[\frac{F_2(x,Q^2)}{\upsilon} + \frac{2F_1(x,Q^2)}{M} tan^2\left(\frac{\theta}{2}\right)\right] \tag{1}$$
$$Q^2 = -q^2 = -4EE'\sin^2\left(\tfrac{\theta}{2}\right) \;,\; \nu = E - E'.$$

Where $\alpha = \frac{e^2}{4\pi} \sim \frac{1}{137}$ is the fine structure constant, four--momentum transfer squared is Q^2. Initial and scattered lepton energies are $E$and E', respectively. Energy of the virtual photon is $\nu = E - E'$, and $x = \frac{Q^2}{2M\nu}$is Bjorken scaling variable. M is the nucleon rest mass. $\theta$is the detected lepton scattering angle. F_1andF_2 are the deep inelastic structure functions.

The nucleus structure function is defined by the sum of structure functions of constituted nucleons inside the nucleus [8, 9], which is defined as:

$$F_2^A(x) = \sum_{N=n,p} \sum_{nl} \int_x^\infty dz\, g_{nl}^N f^N(z)_{nl}\, F_2^N\left(\frac{x}{z}\right), \quad (2)$$

The first sum is over proton and neutron cases, and the second sum is over the quantum number of states. $g_{nl}^N$is the occupation number of energy level ε_{nl} for proton ($N = P$) and neutron ($N = n$), consideration of ε_{nl} for studied nuclei have been taken from [12]. Nucleon distribution function inside nucleus defines as:

$$f^N(z)_{nl} = \int_{|m_N(z-1)-\varepsilon_{nl}|}^\infty dp\, p\, m_N |\varphi_{nl}(p)|^2/(2\pi)^2 \quad (3)$$

Where$z = \frac{p_{nl}q}{m_N\nu}$ is for free nucleon. Effects of momentum and energy distribution of nucleon in the nucleus are included in equation 3 through $\varphi_{nl}(p)$ and ε_{nl}, respectively. Magnitude nuclear binding energy (ε_{nl}) mainly affects structure functions in the intermediate x region. Function $f^N(z)_{nl}$ describes momentum and energy distribution of nucleons inside nuclei, also satisfies the normalization rule:

$$\sum_{N=n,p} \sum_{nl} \int_0^\infty dz\, g_{nl}^N f^N(z)_{nl} = A. \quad (4)$$

If all contributions such as gluons and sea quarks are considered then the nucleon structure function satisfies sum rule:

$$\int_0^1 dx\, F_2^N(x) = 1. \quad (5)$$

Radius of each shell could be expressed by below formula:

$$\langle r^2 \rangle_{nl} = \frac{1}{\alpha^2}(2n + l + 3/2), \quad (6)$$

Where $\alpha^2 = \frac{m_n\omega}{\hbar}$, and in the natural unite we have:

$$\hbar\omega = \frac{42.2}{\langle r^2 \rangle_{nl}}(2n + l + 3/2). \quad (7)$$

$\langle r^2 \rangle^{\frac{1}{2}}and\hbar\omega$ express according to $Fermi$ and MeV unit, respectively. The calculated data for $\langle r^2 \rangle^{\frac{1}{2}}$ and $\hbar\omega$ for nuclei shell have been taken from [11, 12].

According to [8] nucleon distribution function inside nuclei is considered by below formula:

$$f^N(z)_{nl} = \frac{1}{2}\left(\frac{m_N}{\hbar\omega}\right)^{\frac{1}{2}} \frac{n!}{\Gamma\left(n + l + \frac{3}{2}\right)} \sum_{t_1=0}^{n} \sum_{t_2=0}^{n} \frac{(-1)^{t_1+t_2}}{t_1!\, t_2!} \binom{n + l + \frac{1}{2}}{n - t_1} \binom{n + l + \frac{1}{2}}{n - t_2} \times \Gamma\left[l + t_1 + t_2 + l, \frac{m_N}{\hbar\omega}\left(z - 1 - \frac{\varepsilon_{nl}}{m_N}\right)^2\right]. \quad (8)$$

The free proton and neutron structure function, $F_2^N\left(\frac{x}{z}\right)$, have been used from M. Gluck et al, [10] ,*i. e.* the free GRV nucleon structure function, and we ignored the contribution of strange quark. Therefore; the nuclear structure function is expressed by [8]:

$$\int_0^A dx\, F_2^A(x) = \int_0^\infty dx\, F_2^A(x) = A\langle z \rangle, \quad (9)$$

$$\langle z \rangle = \frac{1}{A}\int_0^A dz\, z f^A(z) = 1 + \frac{\langle \varepsilon_\lambda \rangle}{m_N}. \quad (10)$$

The $\langle \varepsilon_\lambda \rangle$ is the mean one nucleon separation energy which have been taken from [12].

The nuclear binding energy causes a violation of sum rule. This violation is proportional to the factor $\langle z \rangle$. In our calculation, we have $\langle z \rangle_{Al} = 0.9760$, $\langle z \rangle_{Fe} = 0.9747$, $\langle z \rangle_{Cu} = 0.9685$, and $\langle z \rangle_{Ag} = 0.9667$. It seems most likely that sum rule can be restored by consideration of pions appearing in nuclei as result of the nucleon-nucleon interactions. Although, their contributions may become noticeable only at small $x \leq 0.3$. They must play a role in sum rule for the nuclear structure functions. In this case, the nucleons carry only a fraction $\langle z \rangle < 1$ of the nucleus momentum. Therefore, we can recover the momentum sum rule [7, 13] like as:

$$\langle z \rangle_N + \eta_\pi = 1, \quad (11)$$

Where $\langle z \rangle_N$ could get from equation 10 and η_π is the momentum fraction which is being carried by pions:

$$\eta_\pi = \int_0^{M_\pi/m} dz\, z\, f_\pi^A(z). \quad (12)$$

We ignored contribution of virtual particles like as Δ particle and heavy mesons, so we suppose that nuclei consist of nucleons and pions. In the next section, we are going to investigate pions effects in nuclei structure function.

3. The PionicContribution and the EMC Effect

The pionic contribution is assumed to be given by [6]:

$$\delta F_2^N(x, A) = \int_x^{M_A/m} dz\, f_\pi\ (z) F_2^\pi\ (x/z), \quad (13)$$

$$f_\pi^A(z) = \frac{3g^2}{16\pi^2}\Delta\lambda z \times \left(\frac{1}{\lambda}\exp\left(-2\lambda\frac{t_0 + m_\pi^2}{m_\pi^2}\right) + \frac{1}{2}Ei(-2\lambda\frac{t_0 + m_\pi^2}{m_\pi^2})\right) \quad (14)$$

where

$$Ei(-z) = -\int_z^\infty dt\, \frac{e^{-t}}{t}. \quad (15)$$

which$g = 13.5$ is the coupling constant, $F_2^\pi(x)$ is the pion structure function, and $F_2^\pi(x)$ is the pion structure function. Pion mass is taken $m_\pi = 139.570\ Mev$. We have taken $\lambda = 0.026$for ^{27}Al, ^{56}Fe, ^{63}Cu, ^{107}Ag, and ^2H nuclei. From equation 11,$\eta_\pi = 0.0239$, $\eta_\pi = 0.0253$, $\eta_\pi = 0.0315$, $\eta_\pi = 0.0332$, and $\eta_\pi = 0.0130$, [6], are considered for ^{27}Al, ^{56}Fe, ^{63}Cu, ^{107}Ag,and ^2H nuclei, respectively. Also, $\Delta\lambda_{Al} = 0.0057$, $\Delta\lambda_{Fe} = 0.00707$, $\Delta\lambda_{Cu} = 0.752$, $\Delta\lambda_{Ag} = 0.0794$, and $\Delta\lambda_H = 0.0031$ are considered for ^{27}Al, ^{56}Fe, ^{63}Cu, ^{107}Ag, and ^2H, respectively.

For pion structure function, we used follow parameterization [7, 13]:

$$F_2^{\pi}(x) = \frac{5}{9}xV_{\pi}(x) + \frac{4}{3}xs_{\pi}(x) \quad (16)$$

$$xV_{\pi}(x) = \frac{\Gamma(\alpha+\beta+1)}{\Gamma(\alpha)\Gamma(\beta+1)}x^{\alpha}(1-x)^{\beta} \quad (17)$$

$$xS_{\pi}(x) = \frac{1}{6}A(p+1)(1-x)^{p} \quad (18)$$

$$\alpha = 0.36 - 0.074\bar{S} \quad \beta = 0.99 + 0.60\bar{S} \quad (19)$$

$$\bar{S} = ln(\frac{ln(Q^2/\Lambda^2)}{ln(Q_0^2/\Lambda^2)}) \quad (20)$$

$$Q_0^2 = 25(GeVc^{-1})^2, \ \Lambda = 0.2\ GeVc^{-1}, \ p = 8.7$$

$$A = 0.51 - 2\alpha/(\alpha+\beta+1). \quad (21)$$

The structure function in these nuclei with respecting pion cloud effect is:

$$F_2^A(x,Q^2) = \int_x^{\infty} f_{\pi}(z)F_2^{\pi}(\tfrac{x}{z},Q^2)dz + \int_x^{\infty} f_N(z)F_2^N(\tfrac{x}{z},Q^2)dz, z \geq x \quad (22)$$

First term indicates pionic contribution and the next term indicates nucleon contribution in the nucleus.

The EMC effect in these nuclei with respect the pionic contribution effect is:

$$R_{EMC}^A(x) = \frac{F_2^A(x)}{F_2^{^2H}(x)} \times \frac{2}{A}. \quad (23)$$

Which $F_2^A(x)$ have been calculated from 22 for ^{27}Al, ^{56}Fe, ^{63}Cu, ^{107}Ag, and ^{2}H nuclei.

4. Results and Discussion

Figure 1 shows pionic contribution for ^{27}Al, ^{56}Fe, ^{63}Cu, and ^{107}Ag nuclei structure functions. Nuclei structure functions with considering the Fermi motion, binding energy, and pionic contribution have been plotted in figure 2, 3, 4, 5 for mentioned nuclei, respectively. One could release from extracted data in these figures that in $x \leq 0.3$ pionic contribution is changing results up to %8.5. For example, based on our calculation in $x = 0.1$ pionic contribution in nucleus structure function is %6.2, %7.7, %0.8, and %8.5 for ^{27}Al, ^{56}Fe, ^{63}Cu, and ^{107}Ag nuclei, respectively. Considering pion cloud in nuclei structure functions improve the EMC ratios for ^{27}Al, ^{56}Fe, ^{63}Cu, and ^{107}Ag nuclei, which are plotted in figures 6, 7, 8, 9, not only in $x \leq 0.3$ region, but also in intermediate x region. This improvement causes to have better agreement with experimental results. For remaining difference, considering other nuclear effects such as quark exchange contribution [16], Δ particle [17], shadowing [18], and so on, maybe could improve the extracted results.

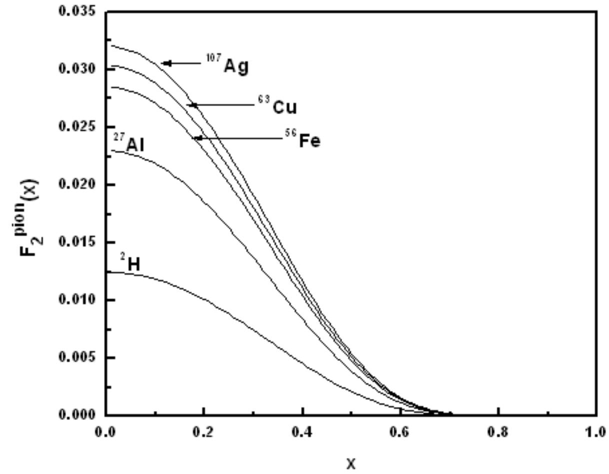

Figure 1. *The pionic contribution in the structure function for ^{27}Al, ^{56}Fe, ^{63}Cu, ^{107}Ag, and ^{2}H nuclei.*

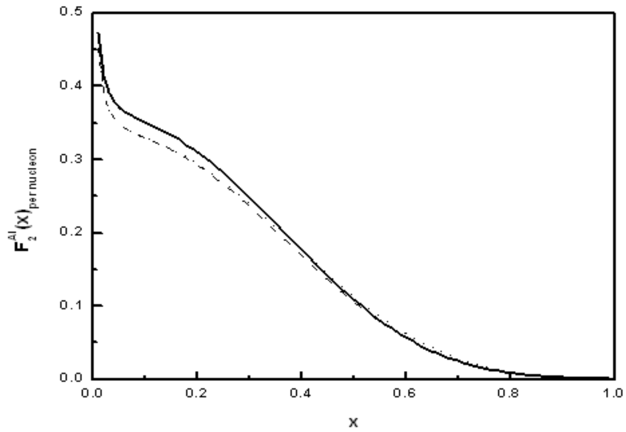

Figure 2. *^{27}Alstructure function. The full curve is plotted with considering, the Fermi motion, the binding energy, and the pionic contribution effect, the dash line is plotted with considering the Fermi motion, and the binding energy, the dotted curve with considering the Fermi motion.*

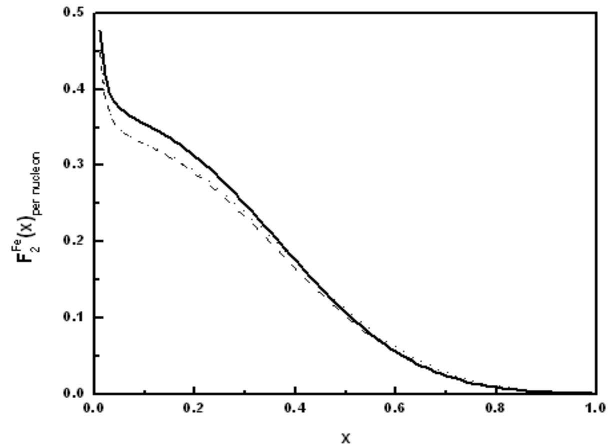

Figure 3. *^{56}Festructure function. The full curve is plotted with considering, the Fermi motion, the binding energy, and the pionic contribution effect, the dash line is plotted with considering the Fermi motion, and the binding energy, the dotted curve with considering the Fermi motion.*

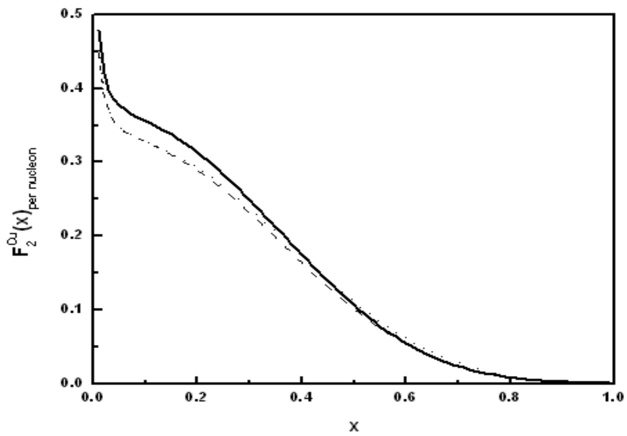

Figure 4. *^{63}Custructure function. The full curve is plotted with considering, the Fermi motion, the binding energy, and the pionic contribution effect, the dash line is plotted with considering the Fermi motion, and the binding energy, the dotted curve with considering the Fermi motion.*

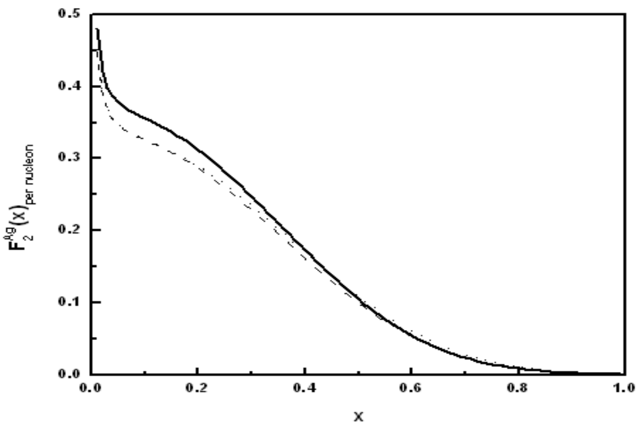

Figure 5. *^{107}Agstructure function. The full curve is plotted with considering, the Fermi motion, the binding energy, and the pionic contribution effect, the dash line is plotted with considering the Fermi motion, and the binding energy, the dotted curve with considering the Fermi motion.*

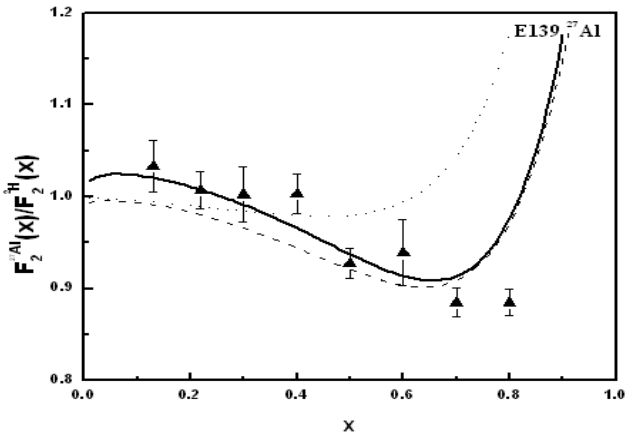

Figure 6. *The structure functions ratio for^{27}Al nucleus. The full curve is plotted with considering, the Fermi motion, the binding energy, and the pionic contribution effect, the dash line is plotted with considering the Fermi motion, and the binding energy, the dotted curve with considering the Fermi motion. Experimental data are taken from [14].*

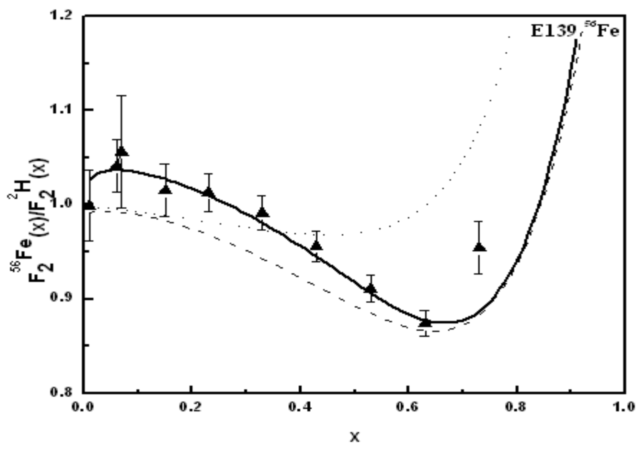

Figure 7. *The structure functions ratio 23 for ^{56}Fe nucleus. The full curve is plotted with considering, the Fermi motion, the binding energy, and the pionic contribution effect, the dash line is plotted with considering the Fermi motion, and the binding energy, the dotted curve with considering the Fermi motion. Experimental data are taken from [14].*

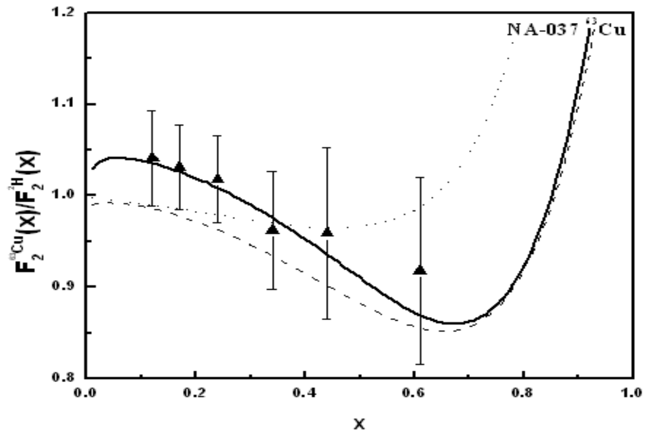

Figure 8. *The structure functions ratio for ^{63}Cu nucleus. The full curve is plotted with considering, the Fermi motion, the binding energy, and the pionic contribution effect, the dash line is plotted with considering the Fermi motion, and the binding energy, the dotted curve with considering the Fermi motion. Experimental data are taken from [15].*

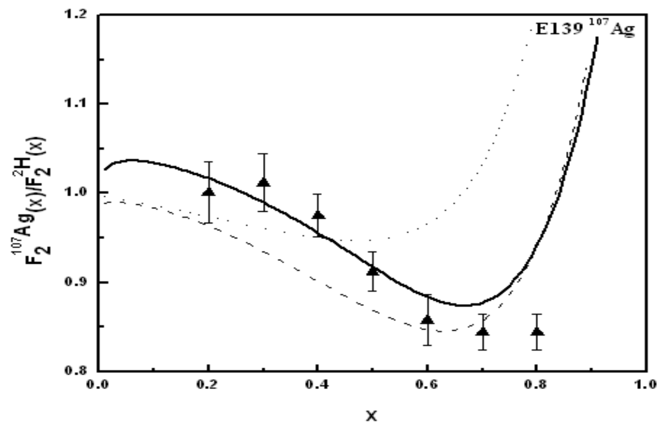

Figure 9. *The structure functions ratio for ^{107}Ag nucleus. The full curve is plotted with considering, the Fermi motion, the binding energy, and the pionic contribution effect, the dash line is plotted with considering the Fermi motion, and the binding energy, the dotted curve with considering the Fermi motion. Experimental data are taken from [14].*

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