© 2018 IJSRST | Volume 4 | Issue 8 | Print ISSN: 2395-6011 | Online ISSN: 2395-602X
Themed Section: Science and Technology

Neutron Asymmetry and Flavor Decomposition of Up and Down Quarks Using Thermodynamics Bag Model

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ABSTRACT

Neutron asymmetry A_1^n , flavor decomposition of up and down quark are evaluated as a function of Bjorken variable in the kinematic region of $0.2 \geq x \geq 0.573$ at $Q^2 = 3.67(GeV/c)^2$ with QCD correction and target mass effect using Thermodynamical Bag Model(TBM). Our results of A_1^n has zero crossing mere $x = 0.5$. We observed that the decomposition of up quark is positive distribution and the decomposition of down quark is negative distribution. Theoretical results of A_1^n and flavor decomposition are good agreement with JLab experimental data.

Keywords: DIS, Flavor decomposition, Neutron asymmetry,TBM

I. INTRODUCTION

Over two decades ago, EMC discovered [1-2] that the fraction of the proton spin is carried by constituent quark and it was insufficient determination. These results caused much excitement to investigate the spin structure of the nucleon as measured by polarized lepton-nucleon deep inelastic scattering[3-5]. But still origin of the nucleon spin has been open puzzle. In relativistic quark model, the quark spin contributes 75% of the proton spin and remaining portion 25% spin is from their orbital angular momentum and gluon spin[6-7]. The nucleon spin sum rule can be written as

$$S_Z^N = S_Z^q + L_Z^q + J_Z^g = \frac{1}{2} \quad (1)$$

Where S_z^N is nucleon total spin, S_z^q and L_z^q are the quark spin and orbital angular momentum respectively and J_z^g is the total angular momentum of gluons. According to spin sum rules, only 20-30% of the nucleon spin is carried by quark and remaining portion is carried by quark and gluon orbital angular momentum and gluon spin. The possible contribution of orbital angular momentum is under the investigation.

In the present work, we concentrate the large kinematic region $x \geq 0.2$. In this kinematic region, valence quarks more dominated over sea quarks and gluons and ratio of structure functions can be calculated based on our model calculation. An accurate knowledge of polarized Parton Distribution Functions(PDFs) on broad x values is needed to deduce the uncertainty with which the first measurement of polarized distribution and structure function can be determined. Here we fix the four momentum transfer Q^2 corresponding to the experimental data[8] to evaluate the neutron asymmetry and flavor decomposition.

Thermodynamical Bag Model:

Thermodynamical Bag Model (TBM) first developed by Ganesamurthy et.al[9-13] considering the nucleon to be in the Infinite Momentum Frame (IMF), where the quarks and gluons are treated as fermions and bosons respectively. The invariant mass(W) of the final hadron is given by

$$[\varepsilon(T)V + BV]^2 = W^2 = M^2 + 2M\nu - Q^2 \quad (2)$$

Where ε(T) is the energy density of the system at a temperature T, V is the volume of bag, B is the bag constant, W is the invariant mass of excited nucleon at T, ν is the energy transfer, Q2 is square of four momentum transfer, M is the mass of the nucleon at ground state.

The total energy density ε(T) of the bag can be written by the sum of energy densities of quarks and gluon is given by

$$\varepsilon(T) = d_q(\varepsilon_u + \varepsilon_{\bar{u}}) + d_q(\varepsilon_d + \varepsilon_{\bar{d}}) + d_g\varepsilon_g \quad (3)$$

Where d_q= 6 and d_g=16 denotes the degeneracy of quarks and gluon orderly. The pressure balance condition and energy minimization condition with respect to the nucleon volume taken into consideration. The invariant mass in TBM is obtained by considering the energy transfer to the nucleon results heating up the constituents of the nucleon. The temperature and two chemical potentials are not free parameters rather they are evaluated in accordance with x and Q2 either with fixed Q2 or with fixed x. At very low Q2, i.e. as Q2 tends to zero, temperature of the bag T also tends to zero and only the valence quarks are dominated. When $T \approx 0MeV$, the invariant mass is equal to the mass of the nucleon at rest. As Q2 increases, temperature of the bag increases and turn in more and more sea quarks and gluons are produced.

The statistical Parton Distribution Functions are expressed as

$$q_i(x,Q^2) = \left(\frac{6V}{4\pi^2}\right) M^2 Tx \ln\left\{1+\exp\left[\left(\frac{1}{T}\right)\left(\mu_i - \frac{Mx}{T}\right)\right]\right\}$$

(4)

$$\bar{q}_i(x,Q^2) = \left(\frac{6V}{4\pi^2}\right) M^2 Tx \ln\left\{1+\exp\left[\left(\frac{1}{T}\right)\left(-\mu_i - \frac{Mx}{T}\right)\right]\right\}$$

(5)

μ_i is the chemical potential of quark with the flavor 'i'.

Here 'i' denotes either u or d quark. In order to relate the PDF's with Λ_{QCD}, which is quark gluon coupling parameter, we introduce the strong quark gluon coupling constant. The experimental fit could be made by considering only with the QCD corrections. The quark and anti-quark distributions are modified by including QCD parameters as,

$$q_i'(x,Q^2) = q_i(x,Q^2)\left(1 - \frac{\alpha_s(Q^2)}{2\pi}\right)$$

(6)

$$\bar{q}_i'(x,Q^2) = \bar{q}_i(x,Q^2)\left(1 - \frac{\alpha_s(Q^2)}{2\pi}\right)$$

(7)

The strong running coupling constant (α_s) for various Q2 is evaluated using the Next to Leading Order (NLO) solution.

$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda^2)}$$

(8)

In order to account for heavy quark threshold correction and target mass effect together, a substitution of x is made with ξ .

$$\xi = \frac{2x((1+m_s^2)/Q^2)}{1+\sqrt{1+4M^2x^2/Q^2)(1+m_s^2)/Q^2)}}$$

(9)

m_s is the mass of the strange quark. Here we assume strange quark mass as 100MeV and Λ_{QCD}= 300MeV.

Theoretical evaluation of neutron asymmetry:

The structure function F_1 and F_2 are related by Callon-Gross relation[14],

$$2xF_1(x) = F_2(x) = \sum_i e_i^2 x q_i(x)$$

(10)

In this relation, structure functions depend only on x. This means that the lepton scatters on particles which do not involve any scale i.e. on point-like particles. The fact that the structure function indeed do not depend on Q2, the so called scattering discovered at SLAC [15] was the experimental validation of the parton model. The unpolarized structure function of proton and neutron are evaluated with the inclusion of up and down anti-quarks with quarks. The spin dependent structure function of proton and neutron are given by

$$g_1^p = 0.5\left[\frac{4}{9}\Delta u'(x) + \frac{1}{9}\Delta d'(x)\right] \quad (11)$$

$$g_1^n = 0.5\left[\frac{1}{9}\Delta u'(x) + \frac{4}{9}\Delta d'(x)\right] \quad (12)$$

Where $\Delta u'$, $\Delta d'$ are the spin distribution function of up and down quark with anti-quarks given by

$$\Delta u'(x) = \left[(u'(x) + \bar{u}'(x)) - \frac{2}{3}(d'(x) + \bar{d}'(x))\right]\cos 2\theta(x) \quad (13)$$

$$\Delta d'(x) = \left[-\frac{1}{3}(d'(x) + \bar{d}'(x))\right]\cos 2\theta(x) \quad (14)$$

Where

$$\cos 2\theta(x) = \frac{1}{1 + \left(\frac{H_0}{\sqrt{x}}(1-x)^2\right)} \quad (15)$$

is known as the spin dilution factor[16]. Since the spin dilution factor is derived from first principles it is adjusted to satisfy the Bjorken sum rule which is considered as the fundamental test of QCD. This enables to determine the valence quark distribution explicity. Here H_0 is a free parameter chosen as 0.09 to satisfy the Bjorken sum rule.

Neutron asymmetry is expressed by the ratio between spin dependent structure function and unpolarized structure function of neutron. Since g_1 and F_1 are evaluated at same Q2 in leading order QCD. A_1^n is expected to vary slowly with Q2.

$$A_1^n(x, Q^2) = \frac{g_1^n(x, Q^2)}{F_1^n(x, Q^2)} \quad (16)$$

Flavor decomposition:

Quark-parton model assumes that the strange quark distribution is neglected above x = 0.3 and also neglecting any Q2 dependence in the ratio structure function. The evaluation of up quark polarization $\frac{\Delta u}{u} \approx 0.979$ which is close agreement with RCQM and pQCD calculations. Our evaluation of $\frac{\Delta d}{d} = -\frac{1}{3}$ as x→1 while pQCD model predictions give $\frac{\Delta d}{d} = 1$. $\frac{\Delta d}{d}$ evaluation is good agreement with SU(6), RCQM and NNPDF experimental results. The up quark polarization is positive and down quark polarization is negative in the entire evaluated x region.

Non relativistic quark model predicted the neutron asymmetry A_1^n = 0 as x→1 on the basis of SU(6) symmetry. A_1^n is more positive at large x due to positive polarization of up and down quarks. In perturbative QCD, A_1^n is expected to unity as x→1. In this kinematic region, the contribution of both sea and gluon are small and we study the contribution of valence quarks and their orbital angular momentum to the nucleon spin. Relativistic constituent quark model also predicted A_1^n = 1 as x→1 . In the present work, the valence quarks are dominated at large x region and asymmetry of neutron is expected to unity as x→1.

Table 1. Theoretical evaluation of $\Delta u/u$, $\Delta d/d$ and A_1^n at $Q^2=4GeV^2$ are compared with several model calculations given in the following table.

	SU(6) symmetry[17]	RCQM[18]	pQCD[20]	NNPDF[21]	TBM
$\Delta u/u$	2/3	1	1	-0.07±0.05	0.979
$\Delta d/d$	-1/3	-1/3	1	-0.19±0.34	-0.304
A_1^n	0	1	1	0.41±0.31	1

II. RESULTS AND DISCUSSION

In the present work, the neutron asymmetry A_1^n and flavor decomposition of up and down quark polarization are calculated using quark distribution.

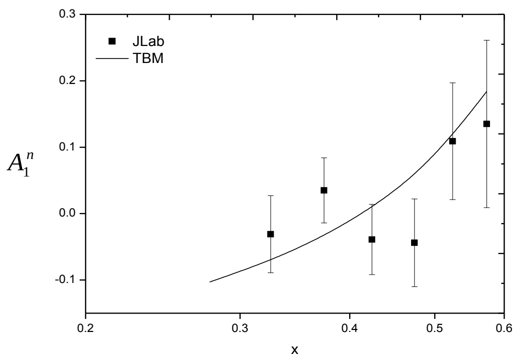

Figure 1. Asymmetry of A_1^n as a function of x at an average $Q^2=3.67(GeV/c)^2$. Present results are compared with JLab experimental data [8].

Figure 1 shows that the neutron asymmetry as a function of Bjorken variable x and squared four momentum transfer Q^2. Neutron asymmetry has negative distribution up to x = 0.495. This is due to fact that the up quark distribution is very close to the down quark distribution and more and more sea quarks and gluons are produced in that region which is the natural consequence of this model. A_1^n is zero crossing at x = 0.496 and above this x value, neutron asymmetry becomes positive distribution which is due to fact that momentum carried by the up quark is more than that of down quark. The evaluated results of A_1^n is consistent with Relativistic Constituent Quark Model(RCQM) and Perturbative Quamtum Chromo Dynamics(pQCD) models prediction which are suggest that A_1^n becomes increasingly positive at large x.

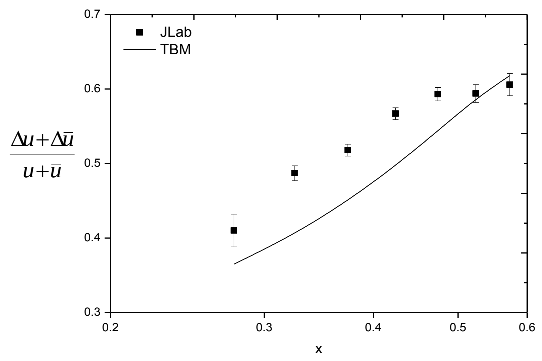

Figure 2. Decomposition of up quark polarization as a function of x at an average $Q^2=3.67(GeV/c)^2$. Present results are compared with Jlab experimental data[8].

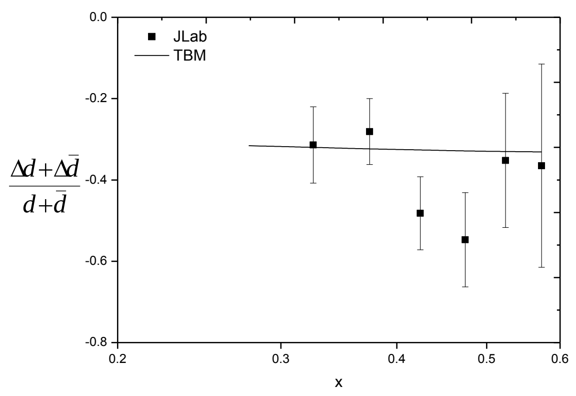

Figure 3. Decomposition of down quark polarization as a function of x at an average $Q^2=3.67(GeV/c)^2$.

Present results are compared with Jlab experimental data[8].

The flavor decomposition of up and down quark polarizations as a function of x have been studied using TBM and are shown in figure 2 and 3 respectively. The up quark decomposition polarization increases with increasing x in whole evaluated x region. Up to x = 0.523, theoretical result of up quark flavor decomposition polarization deviates with experimental data. This is due to the polarized up quark distribution is more than the unpolarized up quark distribution. Above x = 0.524, polarized up quark and unpolarized quark distribution are merely equal. The down quark decomposition polarization is decreasing with x and it is negative distribution. In inclusive deep inelastic scattering, only a fraction of the nucleon spin can be attributed to the quark spins and the strange quark sea seems to be negatively polarized. But in the case of semi-inclusive polarized deep inelastic scattering process spin contribution of quark and antiquark flavor to the total spin of the nucleon can be determined as a function of x. The evaluated results show good agreement with JLab experimental data in the moderate x region.

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