PHYSICAL REVIEW D **71,** 014019 (2005)

Magnetic moments of octet baryons and sea antiquark polarizations

Jan Bartelski

Institute of Theoretical Physics, Warsaw University, Hoa 69, 00-681 Warsaw, Poland.

Stanisław Tatur

Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Bartycka 18, 00-716 Warsaw, Poland.

(Received 12 November 2004; revised manuscript received 22 December 2004; published 19 January 2005)

Using generalized Sehgal equations for magnetic moments of baryon octet and taking into account $\Sigma^0 - \Lambda$ mixing and two particle corrections to independent quark contributions we obtain very good fit using experimental values for errors of such moments. We present sum rules for quark magnetic moments ratios and for integrated spin densities ratios. Because of the $SU(3)$ structure of our equations the results for magnetic moments of quarks and their densities depend on two additional parameters. Using information from deep inelastic scattering and baryon β-decays we discuss the dependence of antiquark polarizations on introduced parameters. For some plausible values of these parameters we show that these polarizations are small if we neglect angular momenta of quarks. Our very good fit to magnetic moments of baryon octet can still be improved by using specific model for angular momentum of quarks.

DOI: 10.1103/PhysRevD.71.014019 PACS numbers: 12.39.–x, 13.40.Em, 13.88.+e

I. INTRODUCTION

There have been several attempts [1–6] to connect precise information from octet baryon magnetic moments [7] with nucleon spin structure obtained from the analysis of polarized deep inelastic scattering (DIS) experiments (see, e.g.,[8]) and octet baryon β-decays. There is a striking similarity in description of magnetic moments and axial vector couplings in $SU(3)$ symmetrical model. In this paper we will follow phenomenological approach of Ref. [1].

We modify Sehgal equations [9] (justification for them was presented in [3]) for magnetic moments of baryons given in terms of linear independent products for u, d and s quarks of quark magnetic moments and corresponding quark densities by taking into account $\Sigma^0 - \Lambda$ mixing. We also have an additional term (we believe connected with two quark interactions) giving contribution to nucleon magnetic moments as well as to $\Sigma^0\Lambda$ transition moment. The inclusion of such term enables to satisfy Coleman-Glashow type sum rule for magnetic moments. With these phenomenological modifications we get very good fit to octet baryon magnetic moments using experimental values for errors.

Unfortunately with 4 parameters used in the fit we can not determine all six quantities, namely, magnetic moments of quarks and quark densities. We get two relations for the ratios of magnetic moments of quarks and for ratios of quark densities. One stands for the ratios of magnetic moments of quarks which are not directly measurable. Having magnetic quark densities it would be possible, by comparing this densities with spin densities (calculated from β-decays and DIS) to get antiquark sea polarizations (provided that the orbital momentum contributions are negligible). Because of the structure of our model we can only get these quantities as a functions of two introduced by us parameters ϵ and g. These new parameters are connected with the deviation of the ratio μ_u/μ_d from -2 and the difference of u and d quark densities. We get the new sum rule connecting antiquark sea contributions which do not depend on our parameters. We show how sea antiquark polarizations depend on these parameters. Assuming plausible values for these parameters suggested by $SU(2)$ isospin symmetry and by not very conclusive experimental data we calculate antiquark sea contributions. It is possible still to improve our fit to magnetic moments by adding to modified Sehgal equations term connected with orbital angular momentum proportional to the charge of the baryon. This correction makes fit much better and only slightly modifies obtained results. Our phenomenological modifications of Sehgal equations are inspired by chiral quark model [10–12] with domination of pionic exchanges.

II. FRAMEWORK

A. Formulas for magnetic moments

Let us start with the formulas for magnetic moments of $SU(3)$ octet baryons in terms of quark moments [1,4,9,13]:

$$\mu(B) = \sum_q \mu_q \delta q(B) + \ldots, \tag{1}$$

where the dots represent possible collective contributions, which will be specified later, μ_q is a dipole magnetic moment of a quark q, whereas $\delta q(B)$ stands for integrated angular momentum density (later called magnetic density) of q flavored quark in octet baryon B (beside quark spin contribution the orbital angular momentum contribution is also possible). The $SU(3)$ flavor symmetry enables us to write such densities as functions of the ones in a proton, e.g.,

$$\delta u(n) = \delta d(p), \qquad \delta d(\Sigma^+) = \delta s(p), \qquad \delta s(\Lambda) = 2\delta u(p)/3 - \delta d(p)/3 + 2\delta s(p)/3, \text{ etc.} \tag{2}$$

In the following equations we shall use short-hand notation for such densities in a proton $\delta q(p) \equiv \delta q$ (q = u, d, s):

$$\begin{aligned}
&\mu(p) = \mu_u \delta u + \mu_d \delta d + \mu_s \delta s, \qquad \mu(n) = \mu_u \delta d + \mu_d \delta u + \mu_s \delta s,\\
&\mu(\Lambda) = \frac{1}{6}(\mu_u + \mu_d)(\delta u + 4\delta d + \delta s) + \frac{1}{3}\mu_s(2\delta u - \delta d + 2\delta s), \qquad \mu(\Sigma^+) = \mu_u \delta u + \mu_d \delta s + \mu_s \delta d,\\
&\mu(\Sigma^0) = \frac{1}{2}(\mu_u + \mu_d)(\delta u + \delta s) + \mu_s \delta d, \qquad \mu(\Sigma^-) = \mu_u \delta s + \mu_d \delta u + \mu_s \delta d,\\
&\mu(\Xi^0) = \mu_u \delta d + \mu_d \delta s + \mu_s \delta u, \qquad \mu(\Xi^-) = \mu_u \delta s + \mu_d \delta d + \mu_s \delta u.\\
&\mu(\Sigma^0 \to \Lambda) = -\frac{(\mu_u - \mu_d)(\delta u - 2\delta d + \delta s)}{2\sqrt{3}}.
\end{aligned} \tag{3}$$

In the nonrelativistic quark model (NQM) with the $SU(6)$ symmetric wave function one gets for spin densities:

$$\delta u = \frac{4}{3}, \quad \delta d = -\frac{1}{3}, \delta s = 0. \tag{4}$$

Because we have postulated the $SU(3)$ symmetry the formulas for magnetic moments can be written with 4 parameters only, instead of three moments μ_u, μ_d, μ_s and three densities δu, δd and δs, namely:

$$\begin{aligned}
&\mu(p) = c_0 + 2c_8 + 2c_3, \qquad \mu(n) = c_0 + 2c_8 - 2c_3, \qquad \mu(\Lambda) = c_0 - (3r - 1)c_8,\\
&\mu(\Sigma^+) = c_0 + (3r - 1)c_8 + (1 + 1/r)c_3, \qquad \mu(\Sigma^0) = c_0 + (3r - 1)c_8,\\
&\mu(\Sigma^-) = c_0 + (3r - 1)c_8 - (1 + 1/r)c_3, \qquad \mu(\Xi^0) = c_0 - (3r + 1)c_8 - (1 - 1/r)c_3,\\
&\mu(\Xi^-) = c_0 - (3r + 1)c_8 + (1 - 1/r)c_3, \qquad \mu(\Sigma^0 \to \Lambda) = -\frac{(3 - 1/r)c_3}{\sqrt{3}},
\end{aligned} \tag{5}$$

where

$$\begin{aligned}
c_0 &= (\mu_u + \mu_d + \mu_s)(\delta u + \delta d + \delta s)/3,\\
c_3 &= (\mu_u - \mu_d)(\delta u - \delta d)/4,\\
c_8 &= (\mu_u + \mu_d - 2\mu_s)(\delta u + \delta d - 2\delta s)/12,\\
r &= \frac{\delta u - \delta d}{\delta u + \delta d - 2\delta s}.
\end{aligned} \tag{6}$$

The last parameter takes in NQM the value: $r = 5/3$.

All magnetic moments in Eq. (5) have the same scalar (c_0) contribution, differ by a hypercharge (c_8) and isovector (c_3) terms, whereas within isospin multiplet differ only by a sign of an isovector contribution.

As far we have the experimental data [7] for seven magnetic moments and for one transition moment $\mu(\Sigma^0 \to \Lambda)$ (see Table I).

B. Sum rules

Because one has seven measured magnetic moments and only four parameters we can write in our model three sum rules. One is the isovector (of Coleman-Glashow type):

$$[\mu(\Sigma^+) - \mu(\Sigma^-)] - [\mu(\Xi^0) - \mu(\Xi^-)] = \mu(p) - \mu(n). \tag{7}$$

Left hand-side of this sum rule gives 4.22 ± 0.03 n.m, whereas the right hand-side 4.71 ± 0.00 n.m. It means that it is not possible to satisfy this sum rule with our formulas with independent quark contributions only as was already mentioned before [1,3,12,14]. We can save this sum rule adding an isovector contribution to nucleon moments (such contribution can arise, e.g., when one considers charge pion exchange between different quarks [1,10–12]) and transition moment. It was stressed by Franklin [10,11] that the exchange of charged pion be-

TABLE I. Magnetic moments of octet baryons.

Magnetic Moment	Experiment (n.m)	Model A (n.m)	Model B (n.m)
$\mu(p)$	2.792847351(28)	2.793 ± 0.000	2.793 ± 0.000
$\mu(n)$	−1.91304273(45)	-1.913 ± 0.000	-1.913 ± 0.000
$\mu(\Lambda)$	-0.613 ± 0.004	-0.606 ± 0.015	-0.610 ± 0.014
$\mu(\Sigma^+)$	2.458 ± 0.010	2.465 ± 0.014	2.458 ± 0.010
$\mu(\Sigma^-)$	-1.160 ± 0.025	-1.128 ± 0.013	-1.160 ± 0.025
$\mu(\Xi^0)$	-1.250 ± 0.014	1.243 ± 0.015	1.252 ± 0.012
$\mu(\Xi^-)$	-0.6507 ± 0.0025	-0.651 ± 0.002	-0.651 ± 0.002
$\mu(\Sigma^0)$	?	0.714 ± 0.014	0.694 ± 0.019
$\mu(\Sigma \to \Lambda)$	-1.61 ± 0.08	-1.51 ± 0.01	-1.51 ± 0.02

tween different quarks gives additional correction to magnetic moment of baryon (such correction is not of one particle type contribution like the terms in Eq. (3)). This correction connected with exchange of charged pion requires the presence of u and d quarks in the baryon and gives contribution only to proton, neutron and transition moment $\Sigma \to \Lambda$. Hence, we add a new contribution to formulas in Eq. (5) (dots represent the terms already written):

$$\mu(p) = \ldots + V, \qquad \mu(n) = \ldots - V,$$
$$\mu(\Sigma^0 \to \Lambda) = \ldots - \frac{1}{\sqrt{3}}V. \tag{8}$$

In principle for $\Sigma^0 - \Lambda$ transition moment independent parameter could be introduced but we assume that it is the same V with a coefficient given by the $SU(6)$ symmetrical wave function. Hence, $\mu(\Sigma^0 - \Lambda)$ can be predicted from our fit.

The isoscalar sum rule (of Gell-Mann-Okubo type) reads:

$$3\mu(\Lambda) + [\mu(\Sigma^+) + \mu(\Sigma^-)]/2 = [\mu(p) + \mu(n)] + [\mu(\Xi^0) + \mu(\Xi^-)] \tag{9}$$

Left hand-side of this sum rule gives -1.19 ± 0.02 n.m. whereas right hand-side -1.02 ± 0.01 n.m. However, it has been pointed out [10] that $\Sigma^0 - \Lambda$ mixing should be taken into account if one considers octet baryon magnetic moments. Defining :

$$|\Lambda> = \cos\alpha|\Lambda_{SU(3)}> + \sin\alpha|\Sigma^0_{SU(3)}>,$$
$$|\Sigma^0> = -\sin\alpha|\Lambda_{SU(3)}> + \cos\alpha|\Sigma^0_{SU(3)}>. \tag{10}$$

with $\tan\alpha$ calculated from hyperon mass differences [10,15]:

$$t \equiv \tan\alpha \approx 0.014 \pm 0.004, \tag{11}$$

one gets (using the experimental numbers from Table I and Eq. (11)) for $\mu(\Lambda_{SU(3)}) = c_0 - (3r-1)c_8$:

$$\mu(\Lambda_{SU(3)}) \approx \mu(\Lambda) - 2t\mu(\Sigma^0 \to \Lambda) = -0.568 \pm 0.014 \text{ n.m.}. \tag{12}$$

Inserting this number in the left hand-side of an isoscalar formula we get -1.06 ± 0.04 n.m. for left hand-side which gives a good agreement of both sides of such sum rule. It is also possible to obtain parameter of $\Sigma^0 - \Lambda$ mixing from magnetic moments of baryons [4] reducing however number of degrees of freedom.

The third sum rule can be chosen as:

$$[\mu(\Sigma^+) + \mu(\Sigma^-)][\mu(\Sigma^+) - \mu(\Sigma^-)] - [\mu(\Xi^0) + \mu(\Xi^-)][\mu(\Xi^0) - \mu(\Xi^-)] = [\mu(p) + \mu(n)]\{[(\mu(\Sigma^+) - \mu(\Sigma^-)] - [\mu(\Xi^0) - \mu(\Xi^-)]\}. \tag{13}$$

The right hand-side gives $(1.89 \pm 0.02 \text{ n.m.})^2$, whereas the left $(1.93 \pm 0.01 \text{ n.m.})^2$ with a good agreement between them.

The fact that sum rules for magnetic moments can not be satisfied with the expressions given by generalized Sehgal equations was pointed out by several authors [1,3,14] and hence, there was a problem in getting good fit to magnetic moments (artificial errors were introduced).

III. NUMERICAL RESULTS AND DISCUSSION

A. Numerical results

In our fit we use 6 measured magnetic moments of octet baryons and $\mu(\Lambda_{SU(3)})$ from Eq. (12) with the experimental errors getting very good result for $\chi^2/d.o.f. = 1.3$. Our fitted parameters are:

$$c_0 = 0.054 \pm 0.001 \text{ n.m.}, \qquad c_3 = 1.046 \pm 0.005 \text{ n.m.},$$
$$c_8 = 0.193 \pm 0.000 \text{ n.m.}, \qquad r = 1.395 \pm 0.010,$$
$$V = 0.26 \pm 0.01 \text{ n.m.}. \tag{14}$$

The results for magnetic moments, as well as predictions for $\mu(\Sigma^0)$ and $\mu(\Sigma^0 \to \Lambda)$:

$$\mu(\Sigma^0) = c_0 + (3r-1)c_8 + 2t\frac{(3r-1)c_3 + rV}{\sqrt{3}r} + O(t^2),$$
$$\mu(\Sigma^0 \to \Lambda) = -\frac{(3r-1)}{\sqrt{3}r}c_3 - \frac{1}{\sqrt{3}}V + 2t(3r-1)c_8 + O(t^2), \tag{15}$$

are presented in Table I (Model A).

If we do not add the isovector contribution to the transition moment one gets (in Model A): $\mu(\Sigma \to \Lambda) = -1.36 \pm 0.01$. Hence, the inclusion of this correction (see Eq. (8)) improves an agreement with the experimental number.

If we use in our calculations NQM densities from Eq. (4) we get much worse fit with χ^2/d.o.f. ≈ 338 and the same is true (χ^2/d.o.f. ≈ 212) if we neglect isovector contribution (i.e., if we put $V = 0$). If we do not take into account $\Sigma^0 - \Lambda$ mixing the resulting fit gives χ^2/d.o.f. ≈ 27. In all fits the relaxation of the condition $r = 5/3$ gives (no matter if we have $V = 0$ or $V \neq 0$) for this parameter the values in a range 1.38–1.48 far from the value gotten from octet baryon β decays: 2.13 ± 0.10.

B. Parametrization of the results

In Eqs. (8) taking into account Eqs. (5) and (6) we have three magnetic moments of quarks and three magnetic quark densities and only four fitted parameters. We can not calculate magnetic moments of quarks and magnetic quark densities without additional assumptions. As the result of our model for magnetic moments we can only get relations for the ratios of magnetic moments of quarks and magnetic quark densities:

$$\frac{\mu_s}{\mu_d} = \frac{c_3 + 3rc_8}{2c_3} + \frac{c_3 - 3rc_8}{2c_3}\frac{\mu_u}{\mu_d}. \tag{16}$$

Assuming that $\mu_u/\mu_d = -2$ (one gets this result, e.g., taking Dirac magnetic moments for light quarks with equal masses) we get $\mu_s/\mu_d = 0.66 \pm 0.01$, the value which is consistent with the NQM result.

For the ratios of magnetic quark densities we get:

$$\frac{\delta u}{\delta d} = -\frac{r+1}{r-1} + \frac{2r}{r-1}\frac{\delta s}{\delta d}. \tag{17}$$

For $\delta s = 0$ (NQM assumption) we get $\delta u/\delta d = -6.1 \pm 0.1$, the number far from the naive result which is -4 (see Eq. (4)). In this case we get for the ratio $\mu_u/\mu_d = -1.83 \pm 0.01$. To verify our model one has to check whether our sum rules Eqs. (16) and (17) are satisfied.

In order to determine magnetic moments of quarks and magnetic moment densities we introduce two additional parameters. It is convenient to take them as ϵ and g:

$$\epsilon = -1 - 2\frac{\mu_d}{\mu_u}, g = \delta u - \delta d. \tag{18}$$

We have chosen parameter ϵ describing deviation from isotopic $SU(2)$ symmetry for magnetic moments (that we do not expect to be broken very strongly) and an analog of g_A for magnetic quark densities.

Using the function:

$$f(\epsilon) = \frac{(3+\epsilon)rc_0}{c_3 - 3rc_8 - \epsilon(c_3 + rc_8)}, \tag{19}$$

we can write formulas for our densities (which depend on ϵ and g) in simple form:

$$\delta u = \frac{g}{6r}[f(\epsilon) + 1 + 3r], \qquad \delta d = \frac{g}{6r}[f(\epsilon) + 1 - 3r],$$
$$\delta s = \frac{g}{6r}[f(\epsilon) - 2], \tag{20}$$

which became even simpler if we use $SU(3)$ densities (i.e., scalar, hypercharge and isovector):

$$\delta_0 \equiv \delta u + \delta d + \delta s = \frac{gf(\epsilon)}{2r}, \qquad \delta_8 \equiv \delta u + \delta d - 2\delta s = \frac{g}{r},$$
$$\delta_3 \equiv \delta u - \delta d = g. \tag{21}$$

From Eq. (21) we see that the function $f(\epsilon)$ has an interpretation of the ratio $2\delta_0/\delta_8$.

The formulas for quark magnetic moments are:

$$\mu_u = \frac{2r}{g}\left[\frac{c_0}{f(\epsilon)} + c_8 + \frac{c_3}{r}\right] = \frac{8c_3}{g(3+\epsilon)},$$
$$\mu_d = \frac{2r}{g}\left[\frac{c_0}{f(\epsilon)} + c_8 - \frac{c_3}{r}\right] = -\frac{4(1+\epsilon)c_3}{g(3+\epsilon)}, \tag{22}$$
$$\mu_s = \frac{2r}{g}\left[\frac{c_0}{f(\epsilon)} - 2c_8\right] = -\frac{2[9rc_8 - c_3 + \epsilon(c_3 + 3rc_8)]}{g(3+\epsilon)}.$$

One can see from Eqs. (20) and (22) that the differences of the quantities $\delta q - \delta q'$ and $\mu_q - \mu_{q'}$ do not depend on ϵ whereas the ratios of these quantities: $\delta q/\delta q'$ and $\mu_q/\mu_{q'}$ on parameter g. The quantities $\mu_q \delta q$ are also scale independent, i.e., does not depend on parameter g.

It is not obvious what value of parameter ϵ one should use. Because mass of the u quark is different from the d quark and/or that in some models mesonic and gluonic corrections change the values of quark magnetic moments one would expect ϵ to be slightly different from zero. In principle it is possible to get information on the μ_u/μ_d ratio from other sources, e.g., from radiative vector meson decays but unfortunately experimental data and theoretical framework are not accurate enough. Not knowing the precise value of ϵ we will present the results for two values of this parameter, namely $\epsilon = 0$ ($f(\epsilon) = 0.94 \pm 0.04$ in such case) and as an example $\epsilon = \epsilon_0 = 0.093 \pm 0.006$ ($f(\epsilon = \epsilon_0) = 2$ and $\delta s = 0$ in this case). However, the zeroth approximation will be the choice $\epsilon = 0$ and $g = g_A$.

C. Determination of sea antiquark polarizations

Now we will try to determine sea antiquark polarizations. Our magnetic densities:

$$\delta q = \Delta q_{\text{val}} + \Delta q_{\text{sea}} - \Delta\bar{q} + <\hat{L}_z^q> - <\hat{L}_z^{\bar{q}}>, \tag{23}$$

can be expressed by valence (Δq_{val}), sea quark (Δq_{sea}) and sea antiquark ($\Delta\bar{q}$) contributions [1,5,13] only if we *neglect* orbital momenta strictly speaking if we put $<\hat{L}_z^q> = <\hat{L}_z^{\bar{q}}>$ for all flavors:

$$\delta q = \Delta q_{\text{val}} + \Delta q_{\text{sea}} - \Delta\bar{q}. \tag{24}$$

The axial spin densities, used in DIS analysis, differ by a sign in an antiquark term:

$$\Delta q = \Delta q_{\text{val}} + \Delta q_{\text{sea}} + \Delta\bar{q}. \tag{25}$$

It is clear from Eqs. (24) and (25) that if we knew the axial quark densities and magnetic quark densities calculated from magnetic moments we could calculate antiquark polarizations $\Delta\bar{q}$. The quantities Δq are usually expressed by the scalar, hypercharge and isovector axial charges:

$$\Delta u = \frac{1}{3}\Delta\Sigma + \frac{1}{6}a_8 + \frac{1}{2}g_A, \quad \Delta d = \frac{1}{3}\Delta\Sigma + \frac{1}{6}a_8 - \frac{1}{2}g_A,$$
$$\Delta s = \frac{1}{3}\Delta\Sigma - \frac{1}{3}a_8. \tag{26}$$

In numerical calculations we use $g_A = 1.2695 \pm 0.0029$ [7], whereas we take a value of a_8 from our fit to the experimental data [7] on β decays of neutron and hyperons. We use the data for following β decays: $g_A \equiv g_A/g_V(n \to p)$, $g_A/g_V(\Xi^- \to \Lambda) + g_A/g_V(\Lambda \to p)$ (we use the sum of these quantities in order to get rid of eventual corrections from $\Sigma^0 - \Lambda$ mixing), $g_A/g_V(\Sigma^- \to n)$ and $g_A/g_V(\Xi^0 \to \Sigma^+)$. From such a fit, with very good $\chi^2/\mathrm{d.o.f.} = 0.27$, we get: $a_8 = 0.597 \pm 0.029$.

From Eqs. (24) and (25) we have:

$$\Delta\bar{q} = \frac{1}{2}(\Delta q - \delta q). \tag{27}$$

Our sum rule Eq. (17) can now be rewritten in terms of antiquark polarizations.

$$\Delta\bar{u} - \Delta\bar{d} - \frac{2r}{r+1}(\Delta\bar{u} - \Delta\bar{s}) = \frac{g_A - ra_8}{2(r+1)}. \tag{28}$$

That is the only result we can get in our model for antiquark polarizations without additional assumptions. One can see that we can not have in our model all $\Delta\bar{q}$ equal to zero (when $<\hat{L}_z^q> - <\hat{L}_z^{\bar{q}}> = 0$) because of the term on the right hand-side of Eq. (28) (which numerical value is 0.09 ± 0.01). If we knew the antiquark polarizations $\Delta\bar{u}$, $\Delta\bar{d}$ and $\Delta\bar{u}$ we could check whether this sum rule is satisfied in our model for magnetic moments.

It seems that data on magnetic moments are much more precise so we will work in the opposite direction and try to find out how the information on magnetic moments of baryons could be used to estimate antiquark polarizations $\Delta\bar{q}$. If we knew the values of g and ϵ we would determine the sea antiquark polarizations.

There are several results, coming from fits to the experimental data, for the value of $\Delta\Sigma$. They lie in a range between 0.2 [16] and 0.4 or even 0.45 [17]. To take into account the spread of these values we assume $\Delta\Sigma = 0.3 \pm 0.1$ (an artificial error represents our uncertainty of this quantity). Taking this value we get from Eq. (25):

$$\Delta u = 0.83 \pm 0.03, \qquad \Delta d = -0.44 \pm 0.03, \qquad \Delta s = -0.10 \pm 0.03. \tag{29}$$

Unfortunately from inclusive deep inelastic scattering of polarized particles we cannot get splitting of axial quark densities into quark and antiquark contributions. The sensitivity to each individual quark flavor can be realized in semi-inclusive deep inelastic scattering (SIDIS) in which the leading hadron is also detected.

Let us introduce the new parameter η (instead of g) defined as:

$$\eta = \frac{1}{2}(g_A - g), \tag{30}$$

which gives the difference of $\bar{u}$ and $\bar{d}$ polarizations, i.e., $\eta = \Delta\bar{u} - \Delta\bar{d}$. This quantity has been measured by the HERMES collaboration [18] in semi-inclusive DIS. The

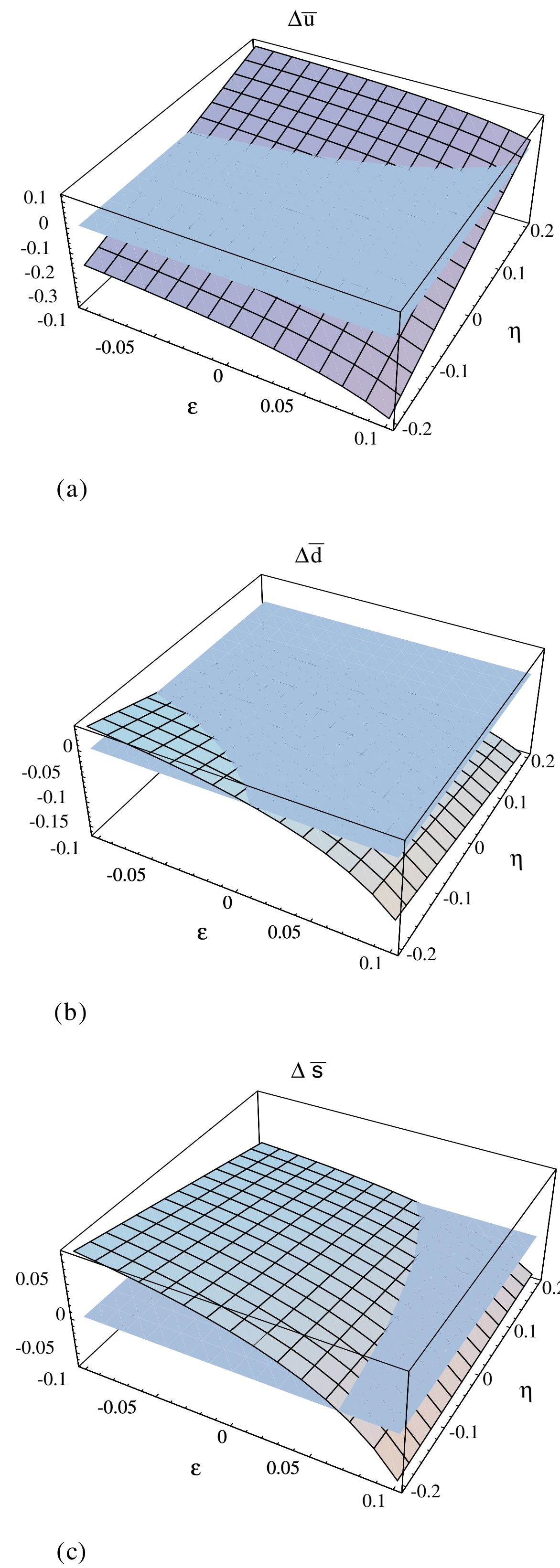

FIG. 1 (color online). The antiquark polarizations for $\bar{u}$ (a) $\bar{d}$ (b) and $\bar{s}$ (c) as a functions of parameters ϵ and η for $\Delta\Sigma = 0.3$. For comparison the plain $\Delta\bar{q} = 0$ is also shown.

result is $\Delta_H = \int_{0.023}^{0.3}[\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx = 0.05 \pm 0.07$ (an extrapolation to the whole x region, i.e., for $0 \leq x \leq 1$ with vanishing $\Delta_H(x)$ at $x = 0$ and $x = 1$ gives $\eta \approx 0.1$). The wide spectrum of theoretical models giving different values for η are presented in [19]. A new Jefferson Lab experiment [20] on spin flavor decomposition is planned and Δu_v, Δd_v and $\Delta\bar{u} - \Delta\bar{d}$ will be extracted from the measurement of the combined asymmetry $A_{1N}^{\pi^+ - \pi^-}$. One can hope that the value of η will be known with better accuracy in the near future. As was already mentioned before we do not know the precise value of μ_u/μ_d (and in consequence ϵ) or μ_s/μ_d (Eq. (16)) and how can one measure it. In principle this information is contained in radiative decays of vector into pseudoscalar mesons but the data have big errors and are not very consistent. Not knowing the precise value of parameter η (having only suggestion from Hermes experiment) and not knowing the precise value of parameter ϵ (but expecting that isotopic $SU(2)$ symmetry for u and d quarks should not be strongly broken so ϵ will be not very much different from zero) we discuss the dependence of antiquark polarizations on these parameters near the above mentioned values.

Our antiquark polarizations $\Delta\bar{q}$ depend on three variables: ϵ, η and $\Delta\Sigma$. In Fig. 1–3 we show this dependence with fixed $\Delta\Sigma = 0.3$. In Fig. 1 we present $\Delta\bar{q}$ for three flavors as a functions of both variables ϵ (in a range $-0.1 \leq \epsilon \leq 0.1$) and η ($-0.2 \leq \eta \leq 0.2$). For comparison the plain corresponding to $\Delta\bar{q} = 0$ is also shown.

The results for $\Delta\bar{q}(\eta)$ for $\epsilon = 0$ are given in Fig. 2. The changes of $\Delta\Sigma$ shift the whole diagram parallel to $\Delta\bar{q}$ axis. In the region $-0.2 \leq \eta \leq 0.2$ $\Delta\bar{d}$ and $\Delta\bar{s}$ change slowly with η and dependence of $\Delta\bar{u}$ on this variable is stronger. As is seen from Fig. 2 $\Delta\bar{u}$ and $\Delta\bar{s}$ are not very much different from zero around $\eta = 0.05$ and $\Delta\bar{d}$ is negative in order to satisfy the sum rule from Eq. (28).

The dependence of $\Delta\bar{q}$ on ϵ is shown in Fig. 3 for $\Delta\Sigma = 0.3$ and $\eta = 0.05$ (for $\eta = 0$ $\Delta\bar{d}$ is identical with $\Delta\bar{u}$). In the interesting region $-0.1 \leq \epsilon \leq 0.1$ curves for $\Delta\bar{q}$ are nearly parallel and for higher values the dependence on ϵ becomes stronger.

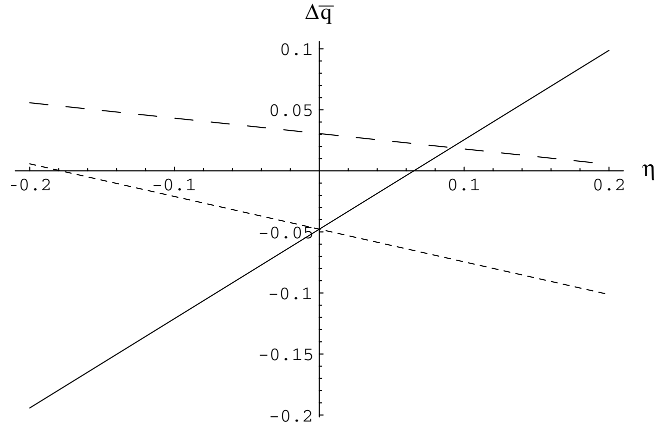

FIG. 2. The antiquark polarizations for $\bar{u}$ (solid), $\bar{d}$ (short-dashed) and for $\bar{s}$ (dashed) versus η for $\epsilon = 0$ and $\Delta\Sigma = 0.3$.

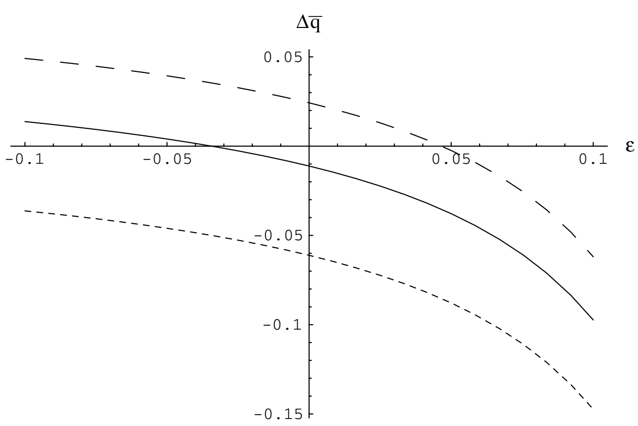

FIG. 3. The antiquark polarizations for $\bar{u}$ (solid), $\bar{d}$ (short-dashed) and for $\bar{s}$ (dashed) versus ϵ for $\eta = 0.05$ and $\Delta\Sigma = 0.3$.

If we take $\epsilon = 0$, $\eta = \Delta_H$ and $\Delta\Sigma = 0.3 \pm 0.1$ we can determine polarizations of sea antiquarks:

$$\Delta\bar{u} = -0.01 \pm 0.05, \qquad \Delta\bar{d} = -0.06 \pm 0.03, \qquad \Delta\bar{s} = 0.02 \pm 0.02. \tag{31}$$

The values of quoted errors are dominated by the contribution from the error of η. As one can see from Eq. (31) the values of $\Delta\bar{u}$ and $\Delta\bar{s}$ are consistent with zero within 1 standard deviation. The errors both in $\Delta\Sigma$ and η were taken to take into account spread of different results for these quantities so the errors in $\Delta\bar{q}$ could be treated for in the same way. From Eqs. (30) and (31) we can calculate the polarization of s sea quarks. One gets $\Delta s_{\mathrm{sea}} = -0.12 \pm 0.02$, hence $\Delta s_{\mathrm{sea}} \neq \Delta\bar{s}$ in this case. Getting the precise values of $\Delta\bar{s}$ and Δs_{sea} would be interesting for recent discussion of strangeness in the nucleon [21].

For $\epsilon = 0$ and $\eta = 0.05 \pm 0.07$ we get for quark magnetic moments

$$\mu_u = 2.39 \pm 0.29 \text{ n.m.}, \qquad \mu_d = -1.19 \pm 0.14 \text{ n.m.}, \qquad \mu_s = -0.79 \pm 0.09 \text{ n.m.}, \tag{32}$$

whereas for magnetic densities one obtains

$$\delta u = 0.86 \pm 0.10, \qquad \delta d = -0.31 \pm 0.04, \qquad \delta s = -0.15 \pm 0.02. \tag{33}$$

For such value of the parameter ϵ we have for s flavor contribution (which do not depend on η) to nucleon moments: $\mu_s \delta s = 0.116 \pm 0.004$ n.m. .

In the given formulas the possible errors connected with the value of ϵ are not included. Comparing quark densities calculated from magnetic moments with those given in Eq. (30) coming from DIS we see that with our choice of

ϵ and η the main difference is for d antiquarks. The antiquark polarizations can not be identical for all flavors because of the sum rule given in Eq. (28), but the different choice of ϵ and η can give other antiquark polarizations than in Eq. (31).

For the another considered by us as rather exotic choice of parameter $\epsilon = \epsilon_0$, i.e., such that gives $\delta s = 0$, we get the following values of an antiquark polarizations:

$$\Delta\bar{u} = -0.08 \pm 0.06, \qquad \Delta\bar{d} = -0.13 \pm 0.02, \qquad \Delta\bar{s} = -0.05 \pm 0.02. \tag{34}$$

All numbers are smaller by 0.07 than the ones given in Eq. (31) because we have $\Delta\bar{u}(\epsilon = \epsilon_0) - \Delta\bar{u}(\epsilon = 0) = g[f(\epsilon = 0) - f(\epsilon = \epsilon_0)]/12r$ (provided we do not change η and $\Delta\Sigma$). In the case when $\delta s = 0$ we get $\Delta\bar{s} = \Delta s_{\text{sea}} = -0.05$.

In [3,22] in the fit for magnetic moments $\delta q = \Delta q$ is used. The χ^2/d.o.f. is small because one uses artificial errors ($\pm$ 0.1 n.m.) instead of experimental ones. For such fit one is not able to get the values of antiquark polarizations.

D. Inclusion of orbital moments

If we include orbital moments in our analysis δq is given by Eq. (23) (see, e.g., [23])

Our sum rule (Eq. (28)) is also changed

$$\Delta\bar{u} - \Delta\bar{d} - \frac{2r}{r+1}(\Delta\bar{u} - \Delta\bar{s}) = \frac{g_A - ra_8}{2(r+1)} + \Delta L, \tag{35}$$

where

$$\Delta L = (<\hat{L}_z^u> - <\hat{L}_z^{\bar{u}}>) - (<\hat{L}_z^d> - <\hat{L}_z^{\bar{d}}>) - \frac{2r}{r+1} \times [(<\hat{L}_z^u> - <\hat{L}_z^{\bar{u}}>) - (<\hat{L}_z^s> - <\hat{L}_z^{\bar{s}}>)]. \tag{36}$$

Hence, it is not possible to determine antiquark polarizations in nucleon without any knowledge about angular momenta of quarks. In the first part of this paper we have assumed $<\hat{L}_z^q> = <\hat{L}_z^{\bar{q}}>$, now we shall try to get the results with a specific model for these angular momenta. There is a possibility to improve our fit to magnetic moment by taking into account another phenomenological contribution similar to collective orbital momenta of Casu and Seghal [22]. It could be that in such model quarks and antiquarks rotate with orbital momentum L. Our formulas for magnetic moment get an additional contributions

$$\mu(B) = \ldots + \frac{e_B}{2m_B}L. \tag{37}$$

The fit is excellent in this case and one gets χ^2/d.o.f. = 0.06 and the parameters do not change very much in comparison with the previous fit

$$c_0 = 0.042 \pm 0.007 \text{ n.m.}, \qquad c_3 = 1.037 \pm 0.007 \text{ n.m.}, \qquad c_8 = 0.179 \pm 0.009 \text{ n.m.}, \qquad r = 1.465 \pm 0.047, \qquad V = 0.24 \pm 0.02 \text{ n.m.}, \qquad L = 0.08 \pm 0.05. \tag{38}$$

The resulting values for magnetic moments of octet baryons are presented in Table I (Model B).

One can repeat the calculations done before with new parameters. The value of right hand-side in Eq. (28) of our basic sum rule changes from 0.09 to 0.08 ± 0.01. The values of antiquark polarizations (for $\epsilon = 0$, $\eta = 0.05 \pm 0.07$ and $\Delta\Sigma = 0.3 \pm 0.1$) does not change significantly in comparison to the ones presented in Eq. (31):

$$\Delta\bar{u} = 0.01 \pm 0.05, \qquad \Delta\bar{d} = -0.04 \pm 0.03, \qquad \Delta\bar{s} = 0.03 \pm 0.02. \tag{39}$$

IV. CONCLUSIONS

Summarizing, we have modified generalized Sehgal equations for magnetic moments of baryons and we get the very good fit using experimental errors. With 4 free parameters in this fit we are not able to determine 6 quantities, namely, three magnetic moments of quarks and 3 quark densities. We get sum rules for the ratios. Using information on deep inelastic scattering of polarized particles and β-decays and connecting quark densities from magnetic moments with those from spin asymmetries we can express antiquark densities as function of two parameters ϵ and η. We give antiquark polarizations calculated with the assumption that $\mu_u/\mu_d = -2$, i.e., $\epsilon = 0$ and $\eta = 0.05$ (value given in results of Hermes experiment). Taking into account errors the results are not very conclusive but because of very weak dependence on the parameters it seems that $\bar{u}$ and $\bar{s}$ are close to zero and $\bar{d}$ is small and negative. To really calculate the antiquark polarizations additional precise information on quark magnetic moments and quark densities is needed. By taking very specific corrections connected with orbital angular momentum proportional to the charge of the baryon we can get nearly perfect description of baryon octet magnetic moments. These corrections are not big and do not change conclusions from the first part of the paper.

[1] J. Bartelski and R. Rodenberg, Phys. Rev. D **41**, 2800 (1990).
[2] J. Bartelski and R. Rodenberg, Z. Phys. C **46**, 263 (1990).
[3] G. Karl, Phys. Rev. D **45**, 247 (1992).
[4] S. B. Gerasimov, Phys. Lett. B **357**, 666 (1995).
[5] T. P. Cheng and Ling-Fong Li, Phys. Lett. B **366**, 365 (1996); **381**, 487(E) (1996); T. P. Cheng and Ling-Fong Li, Phys. Rev. Lett. **80**, 2789 (1998).
[6] M. Karliner and H. J. Lipkin, Phys. Lett. B **461**, 280 (1999).
[7] Particle Data Group, S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
[8] B. W. Filippone and X. D. Ji, Adv. Nucl. Phys. **26**, 1 (2001).
[9] L. M. Sehgal, Phys. Rev. D **10**, 1663 (1974); **11**, 2016(E) (1975).
[10] J. Franklin, Phys. Rev. D **66**, 033010 (2002).
[11] J. Franklin, Phys. Rev. D **30**, 1542 (1984).
[12] S. B. Gerasimov, JINR Report No. E2-88-122 (1988); , JINR Report No. E2-89-837 (1989).
[13] C. E. Carlson and J. Milana, Phys. Rev. D **40**, 3122 (1989).
[14] J. Franklin, Phys. Rev. **182**, 1607 (1969).
[15] J. Franklin and D. B. Lichtenberg, W. Namgung, and D. Carydas, Phys. Rev. D **24**, 2910 (1981).
[16] M. Glück, E. Reya, and A. Vogt, Z. Phys. B **48**, 471 (1990); M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D **53**, 4775 (1996); Spin Muon Collaboration, B. Adeva *et al.*, Phys. Rev. D **58**, 112002 (1998); E. Leader, A. V. Sidorov, and D. B. Stamenov, Int. J. Mod. Phys. A **13**, 5573 (1998); E. Leader, A. V. Sidorov, and D. B. Stamenov, Phys. Rev. D **58**, 114028 (1998); M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D **63**, 094005 (2001); J. Bartelski and S. Tatur, Phys. Rev. D **65**, 034002 (2002); J. Bartelski and S. Tatur, Acta Phys. Polon. B **33**, 2673 (2002).
[17] J. Bartelski and S. Tatur, Acta Phys. Polon. B **34**, 2731 (2003); J. Bartelski and S. Tatur, Acta Phys. Polon. B **35**, 647 (2004).
[18] Hermes Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett. **92**, 012005 (2004).
[19] Jen-Chieh Peng, Report No. QNP2002 (2002).
[20] Xiaodong Jiang, P. Bosted, and D. Day, hep-ex/0412010.
[21] J. Ellis, hep-ph/0411369.
[22] M. Casu and L. M. Sehgal, Phys. Rev. D **55**, 2644 (1997); **56**, 3159(E) (1997); M. Casu and L. M. Sehgal, Phys. Rev. D **58**, 033002 (1998).
[23] X. Song, Int. J. Mod. Phys. A **16**, 3673 (2001).