Quark-quark correlations and baryon electroweak observables

H. Høgaasen*
Fysisk Institutt, University of Oslo, Blindern, 0316 Oslo, Norway

Kuniharu Kubodera† and Fred Myhrer‡
Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208

(Received 23 April 2002; published 3 September 2002)

The simple independent quark models have difficulties explaining simultaneously the totality of the known hyperon magnetic moments and hyperon semileptonic decay rates. We show that both the Goldstone boson loop contributions and two-quark effective exchange currents are essential in explaining these observables.

DOI: 10.1103/PhysRevD.66.057501 PACS number(s): 12.39.−x, 14.20.Jn

Chiral symmetry, one of the basic symmetries of QCD, plays an important role in hadron physics. A key point is that chiral symmetry is spontaneously broken, resulting in the generation of Goldstone bosons, and these Goldstone bosons have a strong influence on the static properties of hadrons and low-energy interactions among hadrons. These effects have been explored with much success in, e.g., chiral quark models and chiral perturbation theory. The existence of Goldstone bosons leads to a natural picture of a baryon consisting of a quark core plus a surrounding Goldstone boson cloud, with the coupling between the core and the cloud dictated by chiral symmetry. It is to be noted that loop diagrams involving the Goldstone bosons give rise to nonanalytic corrections to the hadronic observables and that these non-analytic contributions are determined model independently from chiral symmetry. This feature has recently been exploited by Thomas and co-workers [1] in a calculation of the baryon magnetic moments.

Apart from the Goldstone boson loop corrections, another important effect is expected from QCD; viz., the effective spin-dependent quark-quark interaction [denoted by V_{qq}(spin-spin)] arising from gluon exchange is expected to affect spin-dependent hadronic observables significantly. Let $\boldsymbol{J}$ represent a current that describes the response of a baryon to an external electroweak probe; $\boldsymbol{J}$ can be an electromagnetic or weak current. In general, we expect the form $\boldsymbol{J}=\Sigma_{i=1}^{3}\boldsymbol{J}_i^{(1)}+\Sigma_{ij}\boldsymbol{J}_{ij}^{(2)}$, where $\boldsymbol{J}_i^{(1)}$ is the one-body current of the ith quark, and $\boldsymbol{J}_{ij}^{(2)}$ is the two-body current involving the ith and jth quarks [2]. In the simplest impulse approximation, one assumes $\boldsymbol{J}=\Sigma_{i=1}^{3}\boldsymbol{J}_i^{(1)}$. Now, a point to be emphasized here is that the existence of V_{qq}(spin-spin) automatically engenders the corresponding two-body current, which we denote by $\hat{\boldsymbol{J}}_{ij}^{(2)}$. In most work in the literature, however, the presence of $\hat{\boldsymbol{J}}_{ij}^{(2)}$ has been overlooked [3]. The purpose of this work is to illustrate the important role $\hat{\boldsymbol{J}}_{ij}^{(2)}$ can play in describing baryonic electroweak responses.

As a first example that clearly shows the importance of the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contributions, we consider what may be called the Ξ-Λ puzzle, which is concerned with the magnetic moments of the octet baryons, Ξ^- and Λ. Experimentally, $\mu_\Lambda \simeq -0.613\pm0.004$ nm and $\mu_{\Xi^-}\simeq -0.6507\pm0.0025$ nm, and hence $R\equiv\mu_{\Xi^-}/\mu_\Lambda\simeq$ 1.062±0.005. Thus, the experiments clearly indicate $|\mu_{\Xi^-}|>|\mu_\Lambda|$. Now, suppose we adopt a naive "additive" quark model; namely, we assume that the relevant current is given by $\boldsymbol{J}=\Sigma_{i=1}^{3}\boldsymbol{J}_i^{(1)}$, and that the three quarks in the baryons are independent of each other apart from trivial spin-flavor factors. It can be shown that any additive quark model inevitably leads to

$$\mu_\Lambda=\mu_s \quad \text{and} \quad \mu_{\Xi^-}=\mu_s+\frac{1}{3}(\mu_s-\mu_d), \tag{1}$$

where μ_s and μ_d are the magnetic moments of the s and d quarks, respectively. Then, to explain the experimental fact $|\mu_{\Xi^-}|>|\mu_\Lambda|$, we must require $|\mu_d|<|\mu_s|$; recall that μ_s and μ_d are both negative numbers. In the language of the standard non-relativistic quark model, this requirement implies that the constituent mass of the d quark must be larger than that of the s quark, an obviously untenable conclusion. Meanwhile, according to [6–8], the inclusion of Goldstone boson loops only slightly changes the value of R. Cloet *et al.* [9] have very recently developed "chiral phenomenology" to refine the simplest quark model, and have reported that, partly due to the Goldstone-boson cloud, R can be increased from $R=0.8$ (the simplest quark-model value) to $R=0.99$. Yet this latest result still leaves unexplained the experimental fact, $|\mu_{\Xi^-}|>|\mu_\Lambda|$.

We now discuss the role of $\hat{\boldsymbol{J}}_{ij}^{(2)}$ in the Ξ-Λ puzzle. The origin of $\hat{\boldsymbol{J}}_{ij}^{(2)}$ is analogous to that of the nuclear exchange current due to a nucleon "Z graph," which arises from a relativistic correction to the nucleon propagator. It is well known in nuclear physics that the nucleon Z graph give significant contributions to electroweak observables of nuclei. A Z graph relevant to $\hat{\boldsymbol{J}}_{ij}^{(2)}$ involves gluon exchange and quark-antiquark excitation, as depicted in Fig. 1. We note that $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contributing to the baryon magnetic moment is essentially determined by V_{qq}(spin-spin) arising from gluon exchange, and that the strength of V_{qq}(spin-spin) can be monitored by the octet-decuplet mass splitting (e.g., the N-Δ mass difference). To show the effects of $\hat{\boldsymbol{J}}_{ij}^{(2)}$ explicitly, we use here the

*Email address: hallstein.hogasen@fys.uio.no
†Email address: kubodera@sc.edu
‡Email address: myhrer@sc.edu

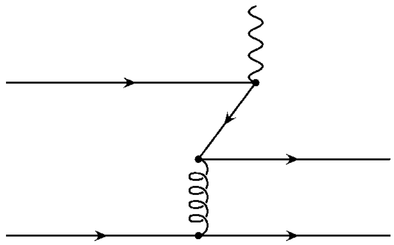

FIG. 1. Illustration of the effective two-quark spin-spin correlation mediated by an effective gluon exchange between the two quarks. The top vertex is the photon quark vertex.

results obtained in the cloudy bag or chiral bag model. According to [6,7], the inclusion of the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contribution changes μ_Λ and μ_Ξ as

$$\mu_\Lambda = \mu_s + \frac{1}{3}G \quad \text{and} \quad \mu_{\Xi^-} = \frac{4}{3}\mu_s - \frac{1}{3}\mu_d - \frac{2}{3}G, \quad (2)$$

where $G \simeq 0.2$ nm. Thus the addition of the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contributions gives a natural explanation of the inequality: $|\mu_\Lambda| < |\mu_{\Xi^-}|$.

The $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contributions affect the magnetic moments of the other baryons as well. We show here that the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contribution is also helpful to resolve the "Σ-Λ problem," a problem first pointed out by Lipkin [10] and further discussed by Thomas and Krein [1]. Consider the magnetic moment ratio R' defined by

$$R' \equiv \frac{\mu_{\Sigma^+} + 2\mu_{\Sigma^-}}{\mu_\Lambda}. \quad (3)$$

The naive "additive" quark model gives $R' = -1$, in glaring disagreement with the experimental value, $R' \simeq -0.23$ [10]. Thomas and Krein have made a detailed study of the Goldstone-boson (pion) contributions to R', using chiral perturbation theory as well as chiral quark models, and emphasized the importance of a proper treatment of the pionic contributions. The leading non-analytic expression for the pion-loop corrections was found to change R' significantly. We show here that there are additional important contributions from $\hat{\boldsymbol{J}}_{ij}^{(2)}$ and that these two effects combined lead to a dramatic reduction of $|R'|$. Here again we demonstrate our point using the results obtained in the cloudy bag model [6,7]. When the contributions from the Goldstone boson cloud and $\hat{\boldsymbol{J}}_{ij}^{(2)}$ are included, R' is given as

$$R' = \frac{\frac{4}{3}\mu_u - \frac{1}{3}\mu_s + \frac{1}{2}\delta\mu_\pi + 2\left(\frac{4}{3}\mu_d - \frac{1}{3}\mu_s - \frac{1}{2}\delta\mu_\pi - \frac{2}{3}G\right)}{\mu_s + \frac{1}{3}G} \quad (4)$$

$$\simeq (-1)\left(1 + \frac{1}{2}\frac{\delta\mu_\pi}{\mu_s} + \frac{4}{3}\frac{G}{\mu_s}\right)\left(1 - \frac{G}{3\mu_s} + \cdots\right).$$

Here $\delta\mu_\pi = 0.59$ nm [6] is the contribution from the pion-loop corrections and $G = 0.2$ nm representing the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contribution has already appeared in Eq. (2). The value of G/μ_s consistent with Eq. (1) is $G/\mu_s \simeq -1/3$. Equation (4) shows that both $\hat{\boldsymbol{J}}_{ij}^{(2)}$ and the pion-cloud contributions substantially reduce the magnitude of R', and their combined effects essentially resolve the "Σ-Λ problem."

For the nucleon magnetic moments, the pion cloud contribution is an isovector contribution and hence cannot explain the observed value $\mu_n/\mu_p \sim -2/3$. It has been demonstrated [6,7] that the inclusion of the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contributions leads to the observed value of μ_n/μ_p.

As mentioned, the effects of $\hat{\boldsymbol{J}}_{ij}^{(2)}$ can appear in weak-interation observables as well. As an example, we discuss the ratio

$$R'' \equiv \frac{g_A/g_V(\Sigma^- \to n)}{g_A/g_V(\Lambda \to p)}, \quad (5)$$

where $g_A/g_V(\Sigma^- \to n)$ and $g_A/g_V(\Lambda \to p)$ are determined from measurements of the semileptonic decays of the Σ^- and Λ particles. Experimentally, $R'' = -0.473 \pm 0.026$, whereas the additive quark model gives $R'' = -1/3$. Lipkin [10] discussed this problem in combination with the above-mentioned "R' problem," and stressed that it is impossible to simultaneously explain the observed values of R' and R''. The argument in [10], however, is based on the essential assumption that the *s*- to *u*-quark conversion can be described in the simplest "additive" quark picture. We therefore examine here to what extent the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ current changes R'' from the naive additive quark model value. According to cloudy bag calculations [6,7], the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ current changes R'' as

$$R'' = -\frac{1}{3} - 2\frac{G'}{B'} \simeq -0.47. \quad (6)$$

In the model used here, wherein the quarks are relativistic ($m_u = m_d \simeq 10$ MeV), the ratio g_A/g_V depends on the two integrals B' and G' involving the quark wave functions of the baryons; these wave function were calculated in Ref. [11]. The term with G' is the contribution of $\hat{\boldsymbol{J}}_{ij}^{(2)}$ [6]. It is found that this contribution changes R'' in the right direction and can explain the experimental value of R''. Thus, what was presented as a serious problem in Ref. [10] can be easily resolved by including the chiral corrections due to the pion cloud *and* the correction due to the $\hat{\boldsymbol{J}}_{ij}^{(2)}$ current.

We have shown in this paper the insufficiency of the naive "additive" quark models. The $\hat{\boldsymbol{J}}_{ij}^{(2)}$ current presented here gives important contributions to both the baryon magnetic moments and the hyperon beta decays. It should be noted that $\hat{\boldsymbol{J}}_{ij}^{(2)}$ also gives an important contribution to the nucleon spin content [12] and leads to the result consistent with the Bjorken sum rule. In conclusion, both the Goldstone-boson loop corrections and $\hat{\boldsymbol{J}}_{ij}^{(2)}$ contributions play a significant role in resolving the outstanding puzzles regarding baryonic electroweak observables, a feature indicating the importance of quark-quark spin-spin correlations inside baryons.

This work is supported in part by NSF Grant No. PHY-9900756.

[1] A.W. Thomas and G. Krein, Phys. Lett. B **481**, 21 (2000); E.J. Hackett-Jones, D.B. Leinweber, and A.W. Thomas, *ibid.* **489**, 143 (2000); D.B. Leinweber, D.H. Lu, and A.W. Thomas, Phys. Rev. D **60**, 034014 (1999).

[2] The three-body term is expected to be negligibly small.

[3] A notable exception is Ref. [4], which discussed the most general QCD-based parametrization of the baryon magnetic moments. See also Ref. [5].

[4] G. Dillon and G. Morpurgo, Phys. Rev. D **53**, 3754 (1996); G. Morpurgo, hep-ph/0107049.

[5] J. Arafune and M. Fukugita, Phys. Lett. **102B**, 437 (1981).

[6] H. Høgaasen and F. Myhrer, Phys. Rev. D **37**, 1950 (1988).

[7] K. Tsushima *et al.*, Nucl. Phys. **A489**, 557 (1988); Phys. Lett. B **205**, 128 (1988); T. Yamaguchi *et al.*, Nucl. Phys. **A500**, 429 (1989).

[8] F. Myhrer, Phys. Lett. **125B**, 359 (1983).

[9] I.C. Cloet, D.B. Leinweber, and A.W. Thomas, Phys. Rev. C **65**, 062201 (2002).

[10] H.J. Lipkin, hep-ph/9911261.

[11] H. Høgaasen and F. Myhrer, Z. Phys. C **48**, 295 (1990)

[12] F. Myhrer and A.W. Thomas, Phys. Rev. D **38**, 1633 (1988); H. Høgaasen and F. Myhrer, Phys. Lett. B **214**, 123 (1988); Z. Phys. C **68**, 625 (1995).