Consistency of the various methods of describing the magnetic moments of baryons

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The quark and hadron methods of calculating the magnetic moments of the baryon octet were found to systematically show a definite consistency. This consistency is retained for charmed baryons. Each method includes a prediction of the magnetic moment of Λ_c. The prediction is amenable to experimental verification.

1. Experimental values of the magnetic moments of the baryon octet, μ_B, seem to have more or less stood their ground.[1] There is therefore an increasing interest to describe them theoretically. Among the descriptions attempted so far, those approaching closest to the "first principles" appear to be the calculations based on QCD sum rules.[2–4] Other calculations which may possibly approach first principles are those of Nyman and Riska,[5] in which the effective chiral Lagrangian was used. These methods and others, which are based on a "microscopic" description of the magnetic moments, give reasonably good results, although each one has weak points.

A simple modification of the constituent quark model.[6–8] where all the baryon magnetic moments $\mu_B^{(q)}$ are expressed only in terms of the three moments of the u, d, and s quarks, gives nearly the best agreement, on the whole, with experiment. These calculations are compared with the data of Refs. 1 and 9 in Table I, where the values of μ_B for p, n, and Λ, which are seed values, are particularly noteworthy. Clearly, the

TABLE I.

B	$\mu_B^{(\mathrm{exp})}$	$\mu_B^{(q)}$	$\kappa_B^{(\mathrm{exp})}$	$\kappa_B^{(\mathrm{cloud})}$
p	2.792847	2.793	$1,793$	> 0
n	$-1,913043$	$-1,913$	-1.916	< 0
Λ	$-0,613 \pm 0,004$	$-0,613$	$-0,729 \pm 0,005$	< 0
Σ^+	$2,42 \pm 0.05$	$2,673$	$2,06 \pm 0,06$	> 0
Σ^0	– – –	0.791	$\kappa_{\Sigma^0}^{(q)} = 1,005$	> 0
Σ^-	$-1,157 \pm 0.025$	$-1,091$	$-0,47 \pm 0,03$	> 0
Ξ^0	$-1,250 \pm 0,014$	$-1,435$	$-1,75 \pm 0,02$	< 0
Ξ^-	$-0,669 \pm 0.023$	$-0,493$	$0,058 \pm 0,032$	> 0
$\Sigma^0 \to \Lambda$	$\pm(1,61 \pm 0,08)$	$-1,630$	– – –	– – –

discrepancy is greater than 15% only for Ξ^-. The agreement can be further improved by taking into account the correction factors (see Ref. 10, for example).

A similar situation arises in a related problem involving meson radiative decays of the type $V \to P\gamma$ (see Ref. 11, for example).

Many questions arise here. Some of them are of a fundamental nature and reduce to the basic question of what, in fact, are constituent quarks and what is their connection with the basic, current quarks of QCD. But there are other questions as well. Soft processes usually can be described, as we know, by various models which use only hadrons, without mentioning quarks and gluons (recall, for example, models such as the multiperipheral model). This is not surprising, since the time scales in such processes are equal to, or even greater than, the time of parton hadronization. It is surprising to find that such models cannot be applied to static supersoft characteristics, which the magnetic moment can be described as.

In the present letter we will show that the use of hadron method in the comparison with the data on μ_B identifies certain systematic features and makes it possible to make verifiable predictions. The consistency of the results of the parton and hadron methods may be yet another indication of the softness of confinement.

2. It is obvious that in the hadron method the problem reduces to the anomalous part κ_B of the magnetic moment of the baryon:

$$\mu_B = \frac{1}{2m_B}(e_B + \kappa_B), \tag{1}$$

where m_B and e_B are the mass and charge of a baryon. The calculations of κ_p and κ_n began in the Yukawa meson theories (see Ref. 12, for example). Those calculations were based on a perturbation theory (for $g^2_{\pi NN} \sim 10!$), which allows us now to view them as a curiosity. Although the previous calculations did not describe the actual values of κ_p and κ_n (or their ratios), they did give their correct signs. This can be attributed to the realization of the intuitively developed conceptual understanding of the meson cloud surrounding a nucleon. It would therefore be desirable to retain the model of the spatial structure of the baryon beyond the scope of the perturbation theory.

This goal can be achieved by viewing the baryon as a superposition of various states (single-particle, two-particle, and other states; for example, $p \to p$, $n\pi^+$, $p\pi^0$, $p\pi^+\pi^-$,...). Such a decomposition is, as we know, single-valued on the light cone or in an infinite-momentum system. We will restrict the decomposition to the states of the type $B'M$ (B' is a baryon with $J^P = 1^+/2$, and M is a pseudoscalar meson) which are reasonably close in mass to the original baryon B.

The component of the transition $B \to B'M \to B$ to κ_B is

$$\kappa_B^{(B'M)} = \frac{g^2_{B(B'M)}}{8\pi^2} \int_0^1 dz \frac{m_B(1-z)(zm_B - m_{B'})[e_{B'}(1-z) - e_M z]}{z^2 m_B^2 - z(m_B^2 + m_{B'}^2 - m_M^2) + m_{B'}^2}, \tag{2}$$

where $e_{B'}$ and e_M are the charges of the baryon and meson in the intermediate state. This expression has the same form as the component of the lower-order diagrams of the perturbation theory. Here the term $g^2_{B(B'M)}$ is not the square of the ordinary coupling constant $g_{BB'M}$, but a certain integral of the square of the corresponding wave function on the light cone. The ordinary coupling constant manifests itself in the analytic continuation of the wave function to the imaginary values of the relative momentum in the $B'M$ system.

As can be seen from (2), the contributions from various intermediate states to κ_B may have different signs. Even the sign of $\kappa_B^{(\text{cloud})}$, the total contribution of the meson clouds to κ_B, is ambiguous. The situation can be improved by assuming that for the octets B' and M the quantities $g^2_{B(B'M)}$ have the same unitarity-flavor structure as the ordinary coupling constants. Their relationship in this case is determined by a single parameter $\alpha_D = D/(D+F)$. Assuming $\alpha_D = 0.7$, which is consistent with the body of data on $g^2_{BB'M}$,[13] we find for $\kappa_B^{(\text{cloud})}$ the signs listed in the last column of Table I. A comparison of these results with the experimental values of $\kappa_B^{(\text{exp})}$ shows that they are in a remarkably good agreement. Only the case Σ^-, where the sign of $\kappa^{(\text{exp})}$ is opposite to that of $\kappa^{(\text{cloud})}$ and the case Ξ^-, where the sign of $\kappa^{(\text{exp})}$ is not solidly established, are clearly identifiable. The fact that the signs match is all the more remarkable since a numerical agreement cannot be obtained by using this simple method. In this respect, we have here the same situation as that in the previous calculations of κ_p and κ_n (Ref. 12). A numerical agreement evidently can be obtained by taking into account many intermediate states, including those that are farther removed from the mass shell. We note in this connection that for the two cases singled out above, Σ^- and Ξ^-, the values of $\kappa_B^{(\text{exp})}$ are closest to zero. This circumstance might improve their sensitivity to various corrections.

3. Since the present situation is ambiguous, it would be useful to continue to test the applicability of the quark and hadron treatments, and also their compatibility. The charmed baryons Λ_c^+ and $\Xi_c^{+,0}$ with the structure *cud* and *csq*, respectively, are the logical object of investigation (here and below $q = u, d$).

Let us first consider the hadron treatment. The transitions $\Lambda_c \to B'M$, where for M we use the pseudoscalar octet mesons and the charmed D and D_s mesons, give for $\kappa_{\Lambda_c}^{(\text{cloud})}$ the sum of contributions which are negative definite if the unitarity-flavor relations are taken into account. We thus can predict that

$$\kappa_{\Lambda_c} < 0.$$

The situation is quite different for Ξ_c. Even after the unitarity-flavor symmetry is taken into account, some contributions with opposite signs remain, so that the resultant sign of κ_{Ξ_c} can be determined by using additional dynamic relations.

In the quark treatment the situation with respect to Ξ_c is also ambiguous, this time because of the dynamic mixing of the spin configurations in the sq system (see, for example, Ref. 14 for a discussion of this problem). For Λ_c the quark calculation is much more specific. The ud system has spin 0 (with an admixture of spin 1 in the amount of 1%). Consequently,

$$\mu_{\Lambda_c} \approx \mu_c.$$

In the constituent quark model the value of μ_c can be extracted from the data for the decay $J/\psi \to \eta_c \gamma$ and from the ratio of the probability for the decays $D^{*+} \to D^+ \gamma$ and $D^{*0} \to D^0 \gamma$ (Ref. 11) (a similar treatment was suggested in Ref. 15). The present-day data[1] give the value

$$\mu_c \approx -(0,3 \div 0,7)\,\mu_c^{(\mathrm{norm})},$$

where $\mu_c^{(\mathrm{norm})}$ is the normal Dirac magnetic moment for $m_c \approx 5m_q$.

Accordingly, the hadron and quark treatments again agree with each other and predict for Λ_c an anomalous negative magnetic moment (and possibly a total magnetic moment as well), but make no definite predictions for Ξ_c. For the constituent c quark the anomalous negative moment was predicted[12] to be the result of the $c \to Dq \to c$ transitions, i.e., a manifestation of a cluster of light quarks surrounding a heavy quark.

4. Let us summarize the results. The quark and hadron methods of calculating the magnetic moments of baryons are in agreement with each other at least in the following sense. The quark treatment can satisfactorily describe the values of μ_B for the octet $1^+/2$. The hadron treatment so far has not been able to describe the numerical values of μ_B, but has systematically been able to determine correctly the sign of the anomalous magnetic moments.

The two treatments also agree with each other in application to the charmed baryons. For Λ_c an anomalous negative (and possibly the total) magnetic moment is predicted in this case.

The quark and hadron treatments do not appear to be linked with each other. Their compatibility can therefore be viewed as a manifestation of the parton-hadron duality right to the soft processes. From the point of view of quarks, a confirmation of the prediction for Λ_c would be evidence in support of the existence of a cloud of light quarks around a heavy constituent quark.

The lifetime of a charmed baryon Λ_c is only about 2×10^{-13} s and its magnetic moment cannot be measured by conventional methods. The measurement appears to be authentic, however, because of strong intratomic fields produced as a result of channeling in crystals.[16]

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