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RECOIL CORRECTIONS TO THE NUCLEON MAGNETIC MOMENT
IN THE BAG MODEL

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A B S T R A C T

It is shown that the recoil correction to the value of the nucleon magnetic moment computed in the static bag model is small and negative. This is due to an over-cancellation of the spin precession effect by the retardation effect. The latter has been ignored in previous calculations, leading to a large positive correction.

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INTRODUCTION

The magnetic moments are useful tests for our understanding of the quark structure of the hadrons. They have been used extensively in the context of the MIT bag model ¹⁾ either to confront the basic ideas against experiment ²⁾, or to test the necessary alterations to the original picture like, in particular, the restoration of chiral symmetry ³⁾⁻⁵⁾.

In the bag model, the calculation of the magnetic moments is bound to the static spherical cavity approximation (SSCA). This is the only case (in four dimensions) where the non-linear constraints ensuring energy-momentum conservation can be eliminated by an appropriate restriction of the states, at the profit of an equilibrium condition for the radius of the cavity. Poincaré invariance which is built into the classical theory is broken by the quantization step because the Hilbert space generated by the eigenmodes of the static cavity is too small to be closed under an arbitrary change of inertial frame. This brings in essentially two errors in the calculation of magnetic moments :

- i) The lack of translation invariance of the boundary introduces spurious contributions due to the motion of the field as a whole. The corresponding centre-of mass (CM) corrections have been estimated either by using the wave packet formalism ⁶⁾ which is physically reasonable but of limited application, or by using projection techniques ⁷⁾ borrowed from nuclear physics. This is more questionable because, in the bag model, there is no Hamiltonian as in the nuclear many-body problem : it must be deduced after elimination of the boundary co-ordinates, through the equations of motion. In order to obtain translation invariance, this has to be done with a boundary shape general enough so as to contain the translation mode. There have been attempts along these lines ⁸⁾ but no method for computing the intrinsic matrix element in the bag model has been proposed. In the following, we work in the limit where the CM effect can be neglected.
- ii) The equality of the velocities of the initial and final bag states used to compute non-diagonal matrix elements (as is the case for the magnetic interaction) cuts down the recoil current. The corresponding recoil corrections for the magnetic moments have been found to be large (~+30%) by two authors ^{9),10)}. However, they have only considered the spin precession current, ignoring the retardation current which in fact cancels the first one and makes the correction small and negative (~-6% of the physical value for the proton or the neutron).

Since there has been confusion about this point, I give a rigorous derivation of these recoil corrections. I shall consider only the proton case and work in the limit of equal masses for the u-d quarks. Therefore, the magnetic moment as well as the recoil correction for the neutron are $(-\frac{2}{3})$ of the same quantities for the proton. Extension to non-equal masses or to strange particles is trivial.

PRELIMINARY

Metric, Dirac matrices follow the conventions of Bjorken and Drell ¹¹⁾. Units are such that $\hbar = c = 1$. Let us start from the usual expression ¹²⁾ for the matrix element of the electromagnetic current, $\vec{V}$, between on-shell proton states of three-momentum $\vec{0}$, $\vec{k}$ and rest-frame spin projection m_σ , m'_σ . The expansion of this matrix element up to order $\vec{k}$ is :

$$\langle \vec{k}, m'_\sigma | \vec{V}(x=0) | \vec{0}, m_\sigma \rangle = e \chi_{(m'_\sigma)}^\dagger \left(\frac{\vec{k}}{2M} + i \frac{\mu_p}{\mu_N} \frac{\vec{\sigma} \times \vec{k}}{2M} \right) \chi_{(m_\sigma)} + O(k^2) \quad (1)$$

with χ a Pauli spinor, M the proton mass and $\mu_p = 2.79 \mu_N$ the proton magnetic moment ($\mu_N = e/2M$). I have chosen to work in the rest frame of the initial proton rather than in the Breit frame. This allows one to keep track of the longitudinal (orbital) current, which provides a useful consistency check of the calculation without bringing in any complication.

Due to translation invariance, the left-hand side of Eq. (1) is also

$$\langle \vec{k}, m'_\sigma | e^{i\vec{k} \cdot \vec{x}} V(0, \vec{x}) | \vec{0}, m_\sigma \rangle \quad (2)$$

and must be computed in the bag model up to terms of order $\vec{k}$. Before this, we have to get rid of the CM problem which is not considered in this paper. This means that we have to find the appropriate expression for (2) with SSCA bag states and operators, in the limit that the CM effects vanish. The clue for this is to consider the bag states as wave packets and then let the spreading of the packet go to zero ⁶⁾. This leads to the replacement of (2) by :

$$\vec{W} = \langle B(\vec{\sigma}), m'_\sigma | \int d\vec{x} e^{i\vec{k} \cdot \vec{x}} \vec{V}(0, \vec{x}) | B(\vec{0}), m_\sigma \rangle \quad (3)$$

where $|B(\vec{0}), m_0\rangle$ is the bag state for the proton in the SSCA and $\vec{V}$ is the quark current operator corresponding to the same boundary. The state $|B(\vec{V}), m'_0\rangle$ is $|B(\vec{0}), m'_0\rangle$ seen from a frame moving with velocity $-\vec{v} = -\vec{k}/M + O(k^2)$ with respect to the rest frame of the static cavity. [Details will be found in Ref. 13).]

The expansion of $\vec{W}$ to order $\vec{k}$ or $\vec{v}$ is obviously the sum of two terms :

$$\vec{W}_{(stat.)} = \langle B(\vec{0}) | \int d\vec{x} i \vec{k} \cdot \vec{x} \vec{V}(0, \vec{x}) | B(\vec{0}) \rangle \quad (4)$$

$$\vec{W}_{(recoil)} = \langle B(\vec{v}) | \int d\vec{x} \vec{V}(0, \vec{x}) | B(\vec{0}) \rangle + O(v^2) \quad (5)$$

where the $O(v^2)$ reminds us that the boosted state has to be evaluated to this order. (Unless explicitly needed, spin labels are suppressed.) Using current conservation, it is straightforward to express the static contribution in the form :

$$\vec{W}_{(stat.)} = \frac{i}{2} \langle B(\vec{0}) | \int d\vec{x} \vec{x} \times \vec{V}(0, \vec{x}) | B(\vec{0}) \rangle \times \vec{k} \quad (6)$$

and by comparison with the right-hand side of Eq. (1), one recovers the usual expression of the magnetic moment when recoil is neglected :

$$\mu_p(stat.) = \frac{1}{2} \langle B(\vec{0}), m'_p = \frac{1}{2} | \int d\vec{x} \vec{x} \times \vec{V}(0, \vec{x}) | B(\vec{0}), m_p = \frac{1}{2} \rangle \quad (7)$$

BOOST

The state $|B(\vec{0})\rangle$ and the operator $\vec{V}(0, \vec{x})$ can be written in terms of the creation and annihilation operators of the quark in the static cavity ¹⁾ : $a_{\alpha}^{\dagger}, a_{\alpha}$. (I do not distinguish particles and antiparticles so that α refers to both positive and negative energy states.) In order to compute the recoil contribution defined by Eq. (5), we have to find the unitary transformation $U(\vec{v})$ such that $|B(\vec{v})\rangle = U(\vec{v})|B(\vec{0})\rangle$. In general, it is not possible to work out this transformation because the Hilbert space generated with the static cavity is too small. However, for our purpose, we need only an expansion of $U(\vec{v})$ up to order $\vec{v}$. This allows the explicit construction of $U(\vec{v})$ in the form :

$$U(\vec{v}) a_\alpha U^\dagger(\vec{v}) = a_\alpha + \sum_{\alpha'} C_{\alpha\alpha'}(\vec{v}) a_{\alpha'} + O(v^2) \quad (8)$$

and it is sufficient to compute the recoil contribution to μ_p .

Let $\varphi_\alpha(\vec{x})$ be the set of spinor eigenfunctions of $h = -i\gamma^0\gamma\cdot\vec{\nabla}$, $h\varphi_\alpha(\vec{x}) = \omega_\alpha\varphi_\alpha(\vec{x})$ in the cavity, with the usual boundary condition : $-i\hat{x}\cdot\vec{\nabla}\varphi_\alpha(R) = \varphi_\alpha(R)$, R being the radius. Here α stands for ¹⁾ n, κ, j, m_j . (An isospin index $m_\tau = \pm\frac{1}{2}$ will be added later to distinguish between u and d quarks.) The field operator $\psi(x)$ solution of the field equation with the same boundary is expanded as follows :

$$\psi(x) = \sum_\alpha e^{-i\omega_\alpha x^0} \varphi_\alpha(\vec{x}) a_\alpha \quad (9)$$

This can be inverted :

$$a_\alpha = \int d\vec{x} e^{i\omega_\alpha x^0} \varphi_\alpha^\dagger(\vec{x}) \psi(x) \quad (10)$$

The operator a_α is the charge of the current : $e^{+i\omega_\alpha x^0} \bar{\varphi}(\vec{x}) \gamma^\mu \psi(x)$ which is conserved since both $\psi(x)$ and $e^{-i\omega_\alpha x^0} \varphi(\vec{x})$ satisfy the same Dirac equation ($i\partial_0\psi = h\psi$). Therefore, it can be evaluated at any time, and we take $x^0 = 0$. The action of $U(\vec{v})$ on a_α is :

$$U(\vec{v}) a_\alpha U^\dagger(\vec{v}) = \int d\vec{x} \varphi_\alpha^\dagger(\vec{x}) U(\vec{v}) \psi(0, \vec{x}) U^\dagger(\vec{v}) \quad (11)$$

To simplify the presentation (but without loss of generality), let us take the boost along the x^1 axis. The transformation of the field operator under the boost is deduced from the following requirement ¹¹⁾ :

$$\begin{aligned} & \langle \mid U^\dagger(\vec{v}) \psi[g(x^0+vx^1), g(x^1+vx^0), x^2, x^3] U(\vec{v}) \mid \rangle \\ & = S(\vec{v}) \langle \mid \psi(x^0, x^1, x^2, x^3) \mid \rangle \end{aligned} \quad (12)$$

with $\mid \rangle$ an arbitrary state, $g = (1-v^2)^{-\frac{1}{2}}$, and $S(\vec{v})$ the usual 4×4 boost matrix ¹¹⁾ which accounts for the spinor nature of the field :

$$S(\vec{v}) = \left(\frac{1+g}{2} \right)^{\frac{1}{2}} \left(1 + \frac{\gamma^0 \vec{\gamma} \cdot \vec{v}}{1+g^{-1}} \right) \quad (13)$$

From Eq. (12), we deduce the transformation law of the field operator which appears on the right-hand side of Eq. (11) :

$$U(\vec{v}) \Psi(0, \vec{x}) U^\dagger(\vec{v}) = S(-\vec{v}) \Psi(g^0 x^1, g^1 x^1, x^2, x^3) \quad (14)$$

To first order in $\vec{v}$, one can set $g = 1$ and the field on the right-hand side of Eq. (14) can again be expanded in terms of the original operators a_α [see Eq. (9)]. It is clear that for arbitrary velocities, the field will have to be expanded in the modes of an ellipsoid rather than a sphere. More precisely, for arbitrary velocities, one cannot apply the transformation defined by Eq. (12) to the expansion (9) because one gets a contradiction with the boundary condition of the quark field as soon as one goes beyond the term of order $\vec{v}$. For instance, the consideration of the v^2 term leads to a new boundary equation : $-i\vec{\gamma} \cdot \vec{r} \vec{\nabla} \varphi_\alpha(R) = \vec{r} \cdot \vec{\nabla} \varphi_\alpha(R)$, which is not compatible with $-i\vec{\gamma} \cdot \vec{r} \varphi_\alpha(R) = \varphi_\alpha(R)$ as can be verified by explicit calculation. This illustrates the statement that the SSCA generates a too small Hilbert space. In particular, the estimation of recoil correction for the charge radius, which requires $U(\vec{v})$ up to order v^2 is, strictly speaking, impossible if one sticks to the SSCA. If we insert Eq. (14) into Eq. (11) and use Eqs. (9) and (13), and expand to order $\vec{v}$, we easily get the expression for the matrix $C_{\alpha\alpha'}(\vec{v})$ by comparing with Eq. (8) :

$$C_{\alpha\alpha'}(\vec{v}) = \int d\vec{x} \varphi_\alpha^\dagger(\vec{x}) \left(-\gamma^0 \frac{\vec{\gamma} \cdot \vec{v}}{2} - i \omega_\alpha \vec{\gamma} \cdot \vec{x} \right) \varphi_{\alpha'}(\vec{x}) \quad (15)$$

where $v x^1$ has been replaced by $\vec{v} \cdot \vec{x}$ so as to restore the generality of the boost. One can easily verify that the corresponding transformation $U(\vec{v})$ is unitary to order $\vec{v}$. In Eq. (15), the term $[-\gamma^0(\vec{\gamma} \cdot \vec{v}/2)]$ which comes from the expansion of $S(-\vec{v})$ is the spin precession term. The term $[-i\omega_\alpha \vec{\gamma} \cdot \vec{x}]$ comes from the expansion of $e^{i\omega_\alpha \vec{v} \cdot \vec{x}}$ and is the retardation term. It arises from the fact that the $\vec{x}$ integration of the transformed field in Eq. (10) is not at constant time $x^0 = 0$ but along the hyperplane $x^0 = \vec{v} \cdot \vec{x}$.

RECOIL CORRECTIONS

The quark current is :

$$\vec{V}(x) = e \Psi_\alpha^\dagger \gamma^0 \vec{\gamma} Q \Psi(x) \quad (16)$$

with $Q = \frac{1}{6} + \tau^3/2$ the charge matrix acting on the isospin co-ordinate of the quark field which is now incorporated in the label α . The proton bag state is of the form :

$$|B(\vec{\sigma}), m_\sigma\rangle = \sum_{\alpha_1, \alpha_2, \alpha_3} B_{\alpha_1 \alpha_2 \alpha_3}^{m_\sigma} a_{\alpha_1}^\dagger a_{\alpha_2}^\dagger a_{\alpha_3}^\dagger |\Omega\rangle \quad (17)$$

with α_i ($i=1,2,3$) restricted to the lowest state $[\alpha] = [1, -1, \frac{1}{2}, m_j, m_\tau]$. $B_{\alpha_1 \alpha_2 \alpha_3}^{m_\sigma}$ are coefficients chosen so that the state is normalized and has the appropriate charge and spin projections. $|\Omega\rangle$ is the empty bag state.

The recoil contribution defined by Eq. (5) is evaluated using Eqs. (16) and (9) [define $\vec{V}_{\alpha\alpha'} = \int d\vec{x} \varphi_\alpha^\dagger(\vec{x}) \gamma^0 \vec{\gamma} Q \varphi_{\alpha'}(\vec{x})$]

$$\begin{aligned} \vec{W}(\text{recoil}) &= \langle B(\vec{\sigma}) | U^\dagger(\vec{\sigma}) \int d\vec{x} \vec{V}(\vec{\sigma}, \vec{x}) | B(\vec{\sigma}) \rangle \\ &= \sum_{\alpha\alpha'} \langle B(\vec{\sigma}) | U^\dagger(\vec{\sigma}) a_\alpha^\dagger a_{\alpha'} | B(\vec{\sigma}) \rangle \vec{V}_{\alpha\alpha'} \\ &= \sum_{\alpha\alpha'} \langle B(\vec{\sigma}) | U^\dagger(\vec{\sigma}) a_\alpha^\dagger U(\vec{\sigma}) U^\dagger(\vec{\sigma}) a_{\alpha'} | B(\vec{\sigma}) \rangle \vec{V}_{\alpha\alpha'} \end{aligned}$$

From Eq. (8), one deduces :

$$\begin{aligned} \vec{W}(\text{recoil}) &= O(v^2) + \sum_{\alpha\alpha'} \langle B(\vec{\sigma}) | a_\alpha^\dagger U^\dagger(\vec{\sigma}) a_{\alpha'} | B(\vec{\sigma}) \rangle \vec{V}_{\alpha\alpha'} \\ &\quad + \sum_{\alpha\alpha'\alpha''} \langle B(\vec{\sigma}) | a_{\alpha''}^\dagger U^\dagger(\vec{\sigma}) a_{\alpha'} | B(\vec{\sigma}) \rangle C_{\alpha\alpha''}^*(-\vec{\sigma}) \vec{V}_{\alpha\alpha'} \quad (18) \end{aligned}$$

Owing to the structure of the bag state, α and α' in the first term of Eq. (18) can only refer to the lowest state so that, by parity, $\vec{V}_{\alpha\alpha'} = 0$ and the first term does not contribute. Moreover, $C_{\alpha\alpha'}^*(-\vec{\sigma})$ is already of order $\vec{\sigma}$ [see Eq. (15)] so that we must set $U^\dagger(\vec{\sigma}) = 1$ in the second term. Using Eq. (15) and performing closure, we end with the result :

$$\begin{aligned} \vec{W}(\text{recoil}) &= \sum_{\alpha\alpha'} \langle B(\vec{\sigma}) | a_{\alpha'}^\dagger a_\alpha | B(\vec{\sigma}) \rangle \\ &\quad \int d\vec{x} \varphi_{\alpha'}^\dagger(\vec{x}) \left(\frac{\vec{\sigma} \cdot \vec{\sigma}}{2} - i \omega_{\alpha'} \vec{\sigma} \cdot \vec{x} \right) \gamma^0 \vec{\gamma} Q \varphi_\alpha(\vec{x}) \quad (19) \end{aligned}$$

After little algebra, this can be written as :

$$\vec{W}(\text{retard}) = \sum_{\alpha\alpha'} \langle B(\vec{\sigma}) | a_{\alpha'}^{\dagger} a_{\alpha} | B(\vec{\sigma}) \rangle \int d\vec{x} \psi_{\alpha'}^{\dagger}(\vec{x}) \left[\frac{\vec{k}}{2M} + i \vec{\sigma}_D \times \frac{\vec{k}}{2M} - i \omega_{\alpha'} (\vec{x} \times \vec{\gamma}^0 \vec{\gamma}) \times \frac{\vec{k}}{2M} \right] Q \psi_{\alpha}(\vec{x}) \quad (20)$$

where $\vec{\sigma}_D$ is $\gamma^5 \gamma^0 \vec{\gamma} = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$. This has to be added to the static contribution obtained from Eq. (6) :

$$\vec{W}(\text{stat.}) = \sum_{\alpha\alpha'} \langle B(\vec{\sigma}) | a_{\alpha'}^{\dagger} a_{\alpha} | B(\vec{\sigma}) \rangle \int d\vec{x} \psi_{\alpha'}^{\dagger}(\vec{x}) (i M \vec{x} \times \vec{\gamma}^0 \vec{\gamma}) Q \psi_{\alpha}(\vec{x}) \times \frac{\vec{k}}{2M} \quad (21)$$

Two comments : first, it is obvious from Eq. (20) that the longitudinal current comes out correctly. This is a good check of the derivation. Second, we see that the retardation term [proportional to $\omega_{\alpha'}$ in Eq. (20)] decreases the static contribution given by Eq. (21) and thus tends to cancel the enhancement due to the precession term [proportional to $\vec{\sigma}_D$ in Eq. (20)].

The total magnetic moment is readily obtained from the comparison of Eq. (20) and Eq. (21) with Eq. (1). Defining $\mu_p = \mu_p(\text{stat}) + \delta\mu_p(\text{retard}) + \delta\mu_p(\text{precess})$, one gets :

$$\mu_p(\text{stat}) = \mu_N \sum_{\alpha\alpha'} \langle B(\vec{\sigma}) m'_{\sigma} = \frac{1}{2} | a_{\alpha'}^{\dagger} a_{\alpha} | B(\vec{\sigma}) m_{\sigma} = \frac{1}{2} \rangle \int d\vec{x} \psi_{\alpha'}^{\dagger}(\vec{x}) M \vec{x} \times \vec{\gamma}^0 \vec{\gamma} Q \psi_{\alpha}(\vec{x}) \quad (22)$$

$$\delta\mu_p(\text{retard.}) = - \frac{\omega}{M} \mu_p(\text{stat.}) \quad (23)$$

$$\delta\mu_p(\text{precess}) = \mu_N \sum_{\alpha\alpha'} \langle B(\vec{\sigma}) m'_{\sigma} = \frac{1}{2} | a_{\alpha'}^{\dagger} a_{\alpha} | B(\vec{\sigma}) m_{\sigma} = \frac{1}{2} \rangle \int d\vec{x} \psi_{\alpha'}^{\dagger}(\vec{x}) (\sigma_D)_3 Q \psi_{\alpha}(\vec{x}) \quad (24)$$

with ω the lowest mode energy. The relevant formulae for the matrix elements already exist so I skip this point and give the result in the case of non-zero but equal quark masses ¹³⁾ :

$$\mu_p(\text{stat.}) = \frac{MR}{3} \frac{4x + 2mR - 3}{2x^2 - 2x + mR} \mu_N$$

$$\delta\mu_p(\text{retard.}) = - \frac{x}{MR} \mu_p(\text{stat.})$$

$$\delta\mu_p(\text{precess}) = \frac{1}{3} \frac{2x^2 + 4mRx - 3mR}{2x^2 - 2x + mR} \mu_N \quad (25)$$

with m the quark mass and $x = \omega R$ ($x \approx 2.04$ in the case $m = 0$). Note that $\delta\mu_p(\text{precess})$ is also $\frac{3}{5}g_A\mu_N$ with g_A the axial coupling constant of the bag. Generally, one works in the limit $m = 0$ (for the nucleon) in which case the total recoil correction is : $\delta\mu_p = (-2x+3)/6(x-1) = -0.173 \mu_N$ while keeping only the precession term leads to a large correction $\delta\mu_p(\text{precess}) = +0.654 \mu_N$. We can get an interesting check of these results by considering the limit $m \rightarrow \infty$. According to Ref. 14), this amounts to letting x and mR go to infinity with the constraint $x^2 - m^2R^2 \rightarrow \pi^2$. In this case, $M \rightarrow 3m$ so that μ_N goes to zero but this does not matter since the relevant quantity is the gyromagnetic ratio. One finds

$$\mu_p(\text{stat.}) = 3 \mu_N, \quad \delta\mu_p(\text{precess}) = - \delta\mu_p(\text{retard.}) = \mu_N \quad (26)$$

The gyromagnetic ratio takes its well-known value ¹⁵⁾ and, as expected from obvious physical considerations, there is no recoil correction at all. Keeping only the precession term would lead to an absurd increase of about 30% and the retardation term comes nicely to cancel it.

CONCLUSION

The recoil correction to the magnetic moment of the proton can be computed exactly in the SSCA insofar as the centre-of-mass effect can be neglected. In a forthcoming paper ¹³⁾, I shall treat both effects simultaneously but it is already clear that the recoil correction is small and negative. Therefore it cannot be invoked to remove the discrepancy between the bag prediction and experiment.

The cancellation between the precession and the retardation effect is of general nature but, of course, the absolute value of the remaining correction depends upon the particular case under study. One correction goes like g_A and the other like $\mu(\text{stat})$. Therefore one can expect that when the static magnetic moment is small and when one or more quarks are massive (this enhances g_A) the cancellation may be less severe than for the proton or the neutron. This has to be verified explicitly by a straightforward extension of the present calculation.

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