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LIMITS ON THE SCALING OF NUCLEON MAGNETIC MOMENTS IN NUCLEI^{*)}

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A B S T R A C T

In view of the suggestion that nucleon magnetic moments inside nuclei may be modified due to a rescaling of the nucleon size, we investigate empirically how large such an effect can be. The method is based on a nearly model-independent scaling relation between the axial vector matrix element and the main part of the corresponding magnetic dipole matrix element supplemented by a small and well understood contribution from the one-pion exchange current. Taking the mass $A = 3$ and 12 systems as examples the upper limit for such a change of the nucleon magnetic moment inside nuclei is found to be about (1-2)%, considerably smaller than previous estimates in the literature.

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1. **Introduction.** This letter is concerned with the long-standing problem whether the magnetic moment of a nucleon inside of a nucleus is modified as compared to its free value in the presence of other nucleons [1]. This issue has been brought back into focus recently by the EMC-effect, which has shown that the nucleon structure functions have to be changed in nuclei [2]. Quasi-elastic electron scattering from nuclei should also be sensitive to changes in the nucleon properties. In particular Noble [3] and Shakin [4] have pointed out that the missing strength problem in the longitudinal response may reflect a swelling of the nucleon size. The swelling of nucleons in the nuclear environment has also been proposed as a possible interpretation of the high energy experiments [2]. Various mechanisms for this effect have been suggested ranging from quark deconfinement to the modification of the pion cloud in traditional nuclear physics approaches (see e.g. [5] and refs. therein).

These observations made at high energy raise the issue whether a possible swelling can be observed in experiments at low and medium energy. The change in charge radius has been explored using quasi-elastic scattering and y-scaling, so far with negative results [6]. On the theoretical side, M. Ericson and Rosa-Clot [7] have suggested that pionic effects like those responsible for quasi-deuteron photoabsorption will increase the apparent nuclear charge radius.

We address ourselves here to the complementary problem of the nucleon magnetic moment inside nuclei. Karl et al. [8] have presented evidence that these moments appear to be larger than in free space. For the $A=3$ system they advocate on the basis of a six-quark bag model that the observed 10% increase in magnetic moment should be associated with a change in length scale for the nucleon inside nuclei.

The conclusions of this model calculation have, however, later been questioned [9]. Mulders [10] has derived from quasi-elastic electron scattering on ^{12}C that the magnetic moment of nucleons in nuclei is increased by about 15%. Evidence for an enhanced nuclear magneton in heavy nuclei has also been put forward by Yamazaki [10] who found through a careful reanalysis of the orbital g-factors an $(8 \pm 3)\%$ larger effective nuclear magneton in the $A=208$ region than the value for a free nucleon.

An interesting suggestion to study the change of the free magnetic moment μ into an effective magnetic moment $\mu^* \equiv \mu(1 + \epsilon)$ has been proposed by Close [11]. The argument is based on a modification of the Morpurgo-rule [12], that the ratio of isoscalar to isovector M1-transition rates in selfconjugate nuclei is approximately proportional to

$$\left[\frac{\mu_p + \mu_n - \frac{1}{2}}{\mu_p - \mu_n} \right]^2 = 0.65 \cdot 10^{-2}. \quad (1)$$

If $\mu_{p,n}$ are replaced by $\mu_{p,n}^*$ this ratio is multiplied by the factor $\simeq (1 + 1.3\epsilon)^2$. Although this argument at first looks quite attractive it has several flaws. Theoretically it rests on the isoscalar moment which has a strong numerical cancellation as compared to the individual nucleonic magnetic moment values. It is therefore strongly exposed to basically small corrections. Experimentally it is known that such isoscalar M1-transitions in selfconjugate nuclei are strongly isospin mixed with isovector transitions. The classical case is ^{12}C , where the isospin $\Delta T = 0$ transition from the 0^+ g.s. into the 1^+ state at 12.71 MeV is strongly isospin mixed with the $\Delta T = 1$ transition into the 1^+ state at 15.11 MeV [13-15]. This isospin mixing leads to an enhancement of the isoscalar M1-transition strength by about a factor of three. Since ϵ is expected to be small ($\epsilon < 0.1 - 0.2$) the method based on eq.(1)

is impractical.

We propose here another method to investigate the effective nucleon magnetic moment in nuclei. The method which is explained in detail in the next section is based on a nearly model independent approach using the scaling between isovector magnetic moments and the corresponding axial matrix element from beta decay. By this procedure the dependence on nuclear wave functions is nearly entirely eliminated on the nucleonic level as well as part of the pionic exchange currents. We then apply the method to the mass $A=3$ and $A=12$ systems for which sufficiently accurate data exist.

2. Method and applications. Let us first assume that the magnetic and axial vector operators $\vec{\mu}^V$ and $\vec{A}^\pm$ are described completely in terms of pointlike nucleons. The corresponding matrix elements have the following spin-isospin structure:

$$\vec{\mu}^V = \frac{\mu_p - \mu_n}{2} \sum_{i=1}^A \sigma_{iz} \tau_i^3 \quad (2)$$

$$\vec{A}^\pm = g_A \sum_{i=1}^A \vec{\sigma}_i \tau_i^\pm \quad (3)$$

Here $\vec{\sigma}_i$ and $\vec{\tau}_i$ denote spin and isospin operators with their components in standard notation and $g_A = 1.254 \pm 0.006$ is the axial vector coupling constant of the nucleon [16]. The magnetic moments μ_p and μ_n are given in units of nuclear magnetons [n.m.] so that the difference $\frac{\mu_p - \mu_n}{2} = 2.353 \text{ n.m.}$. Within a given isospin multiplet and under the assumption of isospin conservation we thus have the following scaling relation

$$\vec{\mu}^V = \frac{\mu_p - \mu_n}{2g_A} \vec{A}^\pm \quad (4)$$

with $\frac{\mu_p - \mu_n}{2g_A} \simeq 1.875 n.m..$ In the absence of meson exchange corrections deviations from this relation would indicate a renormalization in the magnetic moments and/or the axial vector coupling constant.

Let us now discuss relation (4) more realistically. First, the nucleus cannot be considered a simple collection of inert nucleons: the operators (2) and (3) have additional contributions from meson exchange currents even in traditional nuclear physics. For the axial vector operator (3) the main additional terms involve the Δ -isobar. Since the Born terms for the axial and magnetic excitation of the Δ obey the scaling relation (4) on the nucleon level, the corresponding corrections are automatically included in the relation (4) for nuclei (diagram (c) in fig.1). On the other hand, the pion exchange current contributes to the magnetic operator, but not to the axial one (diagrams (a) and (b) in fig.1). This distinction is important to the later discussion. Second, it should be realized that both $\frac{\mu_p - \mu_n}{2}$ and g_A will be renormalized in nuclei by purely **nucleonic** interactions (as well as by Δ -mechanisms). This effect does not change the relation (4) and is outside the present discussion (although covered by a considerable literature [18]). Here we address ourselves specifically to renormalizations of the nucleon magnetic moment, associated for instance with the magnetic length scale $\frac{e}{2M}$ as distinct from a change in the axial coupling strength g_A . In this respect we adhere to the spirit of the issues raised by Karl et al. [8] and by Close [11].

In order to apply eq.(4) to actual data we proceed in two ways. First, we look at the $A=3$ system for which the isovector magnetic moment $\frac{\mu(^3He) - \mu(^3H)}{2} =$

$-2.553n.m.$ and the ${}^3H - {}^3He$ beta decay are known. Second, the case ${}^{12}N - {}^{12}C - {}^{12}B$ is inspected where an isovector M1-transition is compared with the corresponding beta decays.

A=3: The A=3 system is predominantly in a symmetric S-state, but tensor forces give a substantial D-state component. In addition there is a small probability for the mixed symmetry S' -state. Typical probabilities [19] are $P_S \simeq 90.5\%$, $P_D \simeq 8\%$ and $P_{S'} \simeq 1.5\%$. The experimental values for the isovector magnetic moment and the allowed β -decay matrix elements can be expressed in terms of these nucleonic probabilities and discrepancies $\delta\mu^V$ and Δ_A as

$$|\mu^V(A=3)| = \frac{\mu_p - \mu_n}{2} (P_S - \frac{1}{3}P_{S'} + \frac{1}{3}P_D) - \frac{1}{6}P_D + \delta\mu^V = 2.553n.m. \quad (5)$$

$$\frac{M_A}{\sqrt{3}} = g_A(P_S - \frac{1}{3}P_{S'} + \frac{1}{3}P_D) + \Delta_A = 1.211 \pm 0.002. \quad (6)$$

Here μ^V and $\frac{M_A}{\sqrt{3}}$ are the respective matrix elements to be compared as required by eq.(4).

Using the typical values for P_D and $P_{S'}$ given above $\delta\mu^V$ and Δ_A have the empirical values 0.39 ± 0.03 and 0.05 ± 0.01 , respectively, where the error assignments reflect estimated theoretical uncertainties in S' - and D-state probabilities. Using the relation between the isovector magnetic moment and the axial vector matrix element of eq.(4) we find correcting for the small term $\frac{1}{6}P_D$ from orbital motion:

$$|\mu^V(A=3)| - \frac{\mu_p - \mu_n}{2g_A} \frac{M_A}{\sqrt{3}} + \frac{1}{6}P_D = 0.28n.m. + 0.01n.m. = 0.29n.m. \quad (7)$$

This 11% number is the model independent discrepancy resulting from the scaling law (4), and should be considered as a candidate for the contribution from a rescaling of the magnetic moments. However, the pionic exchange current is well defined and can be calculated straightforwardly. It has been separately evaluated by Hadjimichael et al. to be -0.24 n.m.. In other evaluations [19] it is given together with model dependent contributions from the πNN -formfactor and ρ -exchange, so that a clean cross-check on this evaluation is not available. We therefore ascribe a $\pm 20\%$ (i.e. $\pm 0.05 n.m.$) theoretical uncertainty to this contribution.

The possible change of the nucleon magnetic moment in the mass $A=3$ nuclei is thus

$$\epsilon(A=3) \leq 2\%. \quad (8)$$

We do not consider it possible to ignore the 10% correction for the pion exchange current. This contribution is on the two-body level associated with the $^1S_0(T=1) \leftrightarrow [^3S_1(T=0) + ^3D_1(T=0)]$ transition of exactly the same nature as in the wellknown $np(^1S_0; T=1) \rightarrow d(^3S_1 + ^3D_1; T=0)$ M1-transition. In the deuteron case it is the dominant contribution [21] to the $5 \pm 1\%$ discrepancy in the rate, and this matrix element dominates the well investigated deuteron electrodisintegration at momentum transfers $q^2 \leq 15 fm^2$. It is known to have its main contributions from distances larger than 1 fm [22].

A=12: In this system we are dealing with the transition magnetic moment. The isovector M1-decay of the $J^\pi; T = 1^+; 1$ at $E_x=15.11$ MeV to the $0^+; 0$ ground state is linked to the β^- and β^+ decay of ^{12}B and ^{12}N , respectively. In order to compare the M1-transition, which is predominantly a spin-flip transition, with the

β -decay in a transparent way, we express the relation given in eq.(4) by the formula [23]

$$\frac{\mu_p - \mu_n}{2g_A}(1 + \epsilon) = \frac{M}{E_\gamma} \left(\frac{3}{4\alpha} \frac{\Gamma_\gamma}{E_\gamma} \frac{(ft)}{(ft)_{14O}} \right)^{1/2}. \quad (9)$$

Here ϵ describes the empirical discrepancy of the universal ratio (4), E_γ is the photon energy, M the nucleon mass, Γ_γ the M1-transition width, and $\alpha \simeq \frac{1}{137}$ the fine structure constant. The β -decay is described by its measured ft -value, while $(ft)_{14O} \simeq (3084.4 \pm 1.1)s$ refers to the superallowed $0^+ \rightarrow 0^+$ β -transition in ^{14}O [24].

We apply this expression to the $A=12$ system for which $\Gamma_\gamma = (35.7 \pm 0.9)eV$ [15] and the ft -values for the β^- -decay of ^{12}B and for the β^+ -decay of ^{12}N to the ^{12}C ground state are $(11789 \pm 51)s$ and $(13151 \pm 82)s$, respectively. These ft -values differ by 10% due to remaining Coulomb effects, modifications of the wavefunctions in ^{12}B and ^{12}N due to different binding energies etc. (see e.g.[26]). Since we are not interested in such effects we eliminate the bulk of them by the single expedient of using the average $(ft)_{av} = (12470 \pm 68)s$. The uncertainty in the final ratio (9) from this source should then be very substantially below the 2.5% value corresponding to the difference of the average value of the individual ft -values. The experimental value for ϵ is then

$$\epsilon = (3.8 \pm 1.3)\%, \quad (10)$$

where we have neglected in the error the residual theoretical uncertainties from the ft -values [21]. A more sophisticated analysis must include a small correction from

the tensor formfactor in the β -transitions which appears due to the finite energy release. In this case the empirical values for the magnetic and axial matrix elements of Guichon and Samour [28] (corrected to $\Gamma_\gamma = (35.7 \pm 0.9)eV$) give

$$\epsilon = (5.8 \pm 1.2)\% \quad (11)$$

consistent with our result (10).

Like in the $A=3$ system the present procedure has eliminated the dependence on nuclear wavefunctions and part of the meson exchange current effects. The contributions of the pion exchange currents to the transition magnetic moment have been evaluated [28] to be 6.9%. Thus there is little room for rescaling of the nucleon magnetic moment beyond the effect from the pion exchange current. However, if we allow an uncertainty of the latter on the few percent level we get that a possible change of the nucleon magnetic moment in the $A=12$ system must be

$$\epsilon(A=12) \leq 2\%. \quad (12)$$

Conclusion. We conclude that an almost model independent analysis of the $A=3$ and $A=12$ systems permits very strict limits on the possible modifications of nucleon magnetic moments in nuclei. After the well understood pion meson exchange currents have been accounted for further modifications amount to less than a few percent. This is much smaller than the (10-20)% effects which have been advocated as a possibility inside of QCD inspired approaches [8,12]. Such large renormalizations are untenable by such mechanisms. On the other hand the pion

exchange current gives (7-10)% corrections. They are not small, but have the same sign and origin as the corresponding correction in the $np \rightarrow \gamma d$ radiative capture and in the deuteron electrodisintegration, both of which are well understood. This shows therefore that the magnetic moment renormalization must be looked at in the traditional light of pion physics whether described by QCD or not. In fact, in nuclear matter Delorme [29] has estimated the change of the isovector magnetic moment to be about +13% from this origin.

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Figure Caption

Fig. 1 The main meson exchange current corrections: The pion pair term (a) and the pion current term (b) contribute to the magnetic moment operator only. The Δ -isobar term (c) contributes both to the magnetic moment and to the axial current operator and obeys the scaling relation (4) given in the main text. The electromagnetic and axial current operators are denoted by V_λ and A_λ , respectively.

Fig. 1