

Neutrino magnetic moments and photo-disintegration of deuterium

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Abstract

Neutrinos with non-zero magnetic moments can dissociate deuterium nuclei by a photon exchange, in addition to the weak neutral current process. We calculate the neutrino-magnetic moment induced photo-dissociation cross section of deuterium using the equivalent photon method. This process would contribute extra events to the neutral current reaction which is observed with high precision in the salt-phase of SNO experiment. Using the SNO data and the recent laboratory measurements of the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction which give a more precise value of the solar ${}^8\text{B}$ flux we find that the neutrino effective magnetic moment is $\mu_{eff}^2 = (-2.76 \pm 1.46) \times 10^{-16} \mu_B^2$ which can be interpreted as an upper bound $|\mu_{eff}| < 3.71 \times 10^{-9} \mu_B$ (at 95%CL) on the neutrino magnetic moments.

Enormous progress in neutrino physics has resulted in recent years from the experiments in Super-Kamiokande, SNO, KamLAND, and other experimental sites. We now know beyond any reasonable doubt, for instance, that neutrinos oscillate which implies a non-vanishing neutrino mass spectrum [1]. The wealth of new experimental input should provide also new ways of probing and nailing down neutrino properties other than masses. Electromagnetic static properties and, in particular, transition magnetic moments are obvious quantities to be subject to close scrutiny (precisely because non-zero neutrino masses naturally allow for helicity flip transitions) [2]. In this paper we use the SNO data [3] and the recent laboratory measurements of the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction [4] to put restrictions on neutrino magnetic moments.

The theoretical calculation of the deuteron break-up cross section induced by electromagnetic static quantities of the neutrino has been carried out in [5]. However, we follow here another approach which is simpler and is specially suited for the magnetic moment case (left-right transition amplitudes do not interfere with Z-exchange). Indeed, we shall use the equivalent photon approximation. Of course, although the method gives only approximate results, they are entirely satisfactory for our purposes, as we have explicitly checked by comparing to the calculation in [5].

The photon-exchange amplitude of the reaction $\nu_i(k) + d(p) \rightarrow \nu_j(k') + n(p'_n) + p(p'_p)$ can be written as

$$\mathcal{M} = \frac{l^\mu J_\mu}{q^2} \quad (1)$$

where J^μ is the hadronic current, $q = k - k'$ the momentum of the exchanged photon and l^μ the neutrino current given explicitly by

$$l^\mu = \mu_{ij} \frac{e}{2m_e} \bar{u}_i(k') \sigma^{\mu\nu} u_j(k) q_\nu \quad (2)$$

where μ_{ij} is the transition magnetic moment (in units of Bohr-magneton $\mu_B = e/(2m_e)$) of the neutrino mass eigenstates involved in the scattering process. The differential cross section can be written as

$$d\sigma_{mag} = \frac{\mu_{eff}^2}{4I} \frac{e^2}{4m_e^2} \frac{1}{(q^2)^2} \frac{d^3 k'}{(2\pi)^3 2k'_0} \int (l^{\mu\dagger} l^\nu J_\mu^\dagger J_\nu)_{avg} (2\pi)^4 \delta^4(k + p - k' - p'_n - p'_p) d\Pi' \quad (3)$$

$$d\Pi' \equiv \frac{d^3 p'_n}{(2\pi)^3 2p'_{0n}} \frac{d^3 p'_p}{(2\pi)^3 2p'_{0p}} \quad (4)$$

where μ_{eff}^2 will be defined later, see (27). In (3), $I \simeq k \cdot p$ is the incident flux and we have neglected the neutrino mass in the kinematics. The subscript *avg* in (3) refers to spin-average. The spin-averaged neutrino current tensor can be explicitly evaluated and turns out to be

$$N^{\mu\nu} \equiv (l^{\mu\dagger} l^\nu)_{avg} = q^2 (q^\mu q^\nu + 2(k'^\mu k^\nu + k'^\nu k^\mu)) \quad (5)$$

The hadronic current tensor can be written in the general form

$$D_{\mu\nu} \equiv (J_\mu^\dagger J_\nu)_{avg} = a \left(\frac{-q^2}{p \cdot q} p_\mu p_\nu - p \cdot q g_{\mu\nu} + p_\mu q_\nu + p_\nu q_\mu \right) + b (q^2 g_{\mu\nu} - q_\mu q_\nu) \quad (6)$$

where we have used current conservation

$$q^\mu D_{\mu\nu} = q^\nu D_{\mu\nu} = 0 \quad (7)$$

and where a and b are in general functions of the invariants q^2, p^2 and $p \cdot q$. Contracting the spin averaged currents $N^{\mu\nu}$ and $D_{\mu\nu}$ we get

$$N^{\mu\nu} D_{\mu\nu} = 4(q^2)^2 \frac{(p \cdot k)^2}{p \cdot q} \left[a \left(-1 + \frac{p \cdot q}{p \cdot k} \right) - b \frac{1}{4} \frac{p \cdot q}{(p \cdot k)^2} q^2 \right] \quad (8)$$

Using the kinematic relations $p = (M_d, \vec{0}), k = (E_\nu, \vec{k}), k' = (E'_\nu, \vec{k}'), q^2 = -2E_\nu E'_\nu (1 - \cos\theta_{\nu\nu'})$ we find that the coefficient of the b term in (8) is

$$\frac{(E_\nu - E'_\nu)}{M_d} \sin^2 \frac{\theta_{\nu\nu'}}{2} \quad (9)$$

times the coefficient of the a term. Since we are dealing with neutrinos in the energy range of (5 – 20) MeV which is much smaller than the deuterium mass, we can drop the b term in (8). Substituting in (3) we find that

$$d\sigma_{mag} = \mu_{eff}^2 \frac{e^2}{4m_e^2} \frac{d^3 k'}{(2\pi)^3 2k'_0} \int \frac{p \cdot k}{p \cdot q} a \left(-1 + \frac{p \cdot q}{p \cdot k} \right) (2\pi)^4 \delta^4(k + p - k' - p'_n - p'_p) d\Pi' \quad (10)$$

The amplitude for the photo-dissociation process $\gamma(q) + d(p) \rightarrow n(p'_n) + p(p'_p)$ is

$$\mathcal{M} = \epsilon^\mu J_\mu(q^2 = 0) \quad (11)$$

and the deuterium photo-dissociation cross section can be written as

$$\sigma_\gamma = \frac{1}{4p \cdot q} \int \frac{-1}{2} g^{\mu\nu} (J_\mu^\dagger(0) J_\nu(0))_{avg} (2\pi)^4 \delta^4(q + p - p'_n - p'_p) d\Pi' \quad (12)$$

where again *avg* stands for spin average. Using the fact that $g^{\mu\nu} D_{\mu\nu}(q^2 = 0) = -2a p \cdot q$ we have

$$\sigma_\gamma = \frac{1}{4} \int a(q^2 = 0) (2\pi)^4 \delta^4(q + p - p'_n - p'_p) d\Pi' \quad (13)$$

Comparing the neutrino cross section (10) with the photo-dissociation cross section (13) we see that we have the relation

$$\sigma_{mag} = \frac{e^2 \mu_{eff}^2}{m_e^2} \int \frac{d^3 k'}{(2\pi)^3 2E'_\nu} \left(\frac{k \cdot p}{q \cdot p} - 1 \right) \sigma_\gamma(q_0 = E_\nu - E'_\nu) \quad (14)$$

if we assume that in the hadronic current $a \simeq a|_{q^2=0}$. This is totally justified since the transferred momenta are much smaller than the typical hadronic energies that set the scale about and beyond which form factors cease to have a point-like behavior [6]. Using the relations $k'_0 = |\vec{k}'| = E'_\nu$ and using the fact that

$$\frac{k \cdot p}{p \cdot p} - 1 = \frac{E'_\nu}{E_\nu - E'_\nu} \quad (15)$$

is independent of $\theta_{\nu\nu'}$ we can reduce the integral $d^3k'/k'_0 = 4\pi E'_\nu dE'_\nu$. The limits of the integration of the variable E'_ν are $(0, E_\nu - \epsilon_b)$ where $\epsilon_b = 2.224$ MeV is the binding energy of deuterium. Defining the dimensionless variable $x \equiv (E_\nu - E'_\nu)/E_\nu$ the expression (14) for the neutrino magnetic moment induced deuterium disintegration reduces to the form

$$\sigma_{mag} = \mu_{eff}^2 \frac{\alpha}{\pi} \left(\frac{E_\nu}{m_e}\right)^2 \int_{\epsilon_b/E_\nu}^1 dx \frac{(1-x)^2}{x} \sigma_\gamma(E_\gamma = xE_\nu) \quad (16)$$

For the photo-dissociation cross section we use the expression ¹

$$\sigma_\gamma(E1) = \sigma_0 \left[\frac{\epsilon_b(E_\gamma - \epsilon_b)}{E_\gamma^2} \right]^{3/2} \quad (17)$$

where the energy dependent factor shown in the square bracket is the theoretical prediction appropriate for the electric dipole transition of deuterium [7]. We have determined the pre-factor $\sigma_0 = 19.4$ mb by doing a least square fit of the energy dependent function shown in (17) with the experimental results [8] for the photo-disintegration of deuterium in the energy range $E_\gamma \simeq (5 - 10)$ MeV appropriate for the 8B neutrinos observed at SNO.

The neutrino flux from 8B in the Sun which is observed at SNO can be represented by

$$\phi_B(E_\nu) = \Phi_{SSM} \xi(E_\nu) \quad (18)$$

where $\Phi_{SSM} = (5.87 \pm 0.44) \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1}$ is the new predicted value of the 8B neutrino flux in the standard solar model [9] after taking into account the recent laboratory measurements of the ${}^7Be(p\gamma){}^8B$ cross section [4, 10]. The spectral shape of the 8B neutrino flux can be parameterized by the analytical expression [11]

$$\xi(E_\nu) = 8.52 \times 10^{-6} (15.1 - E_\nu)^{2.75} E_\nu^2 \quad (19)$$

where the neutrino energy E_ν is in units of MeV. The total events of deuterium dissociation observed at SNO is the sum of the standard neutral current events plus those due to neutrino magnetic moments ²

$$N^{exp} = N_d T \Phi_{SSM} \int dE_\nu \xi(E_\nu) (\sigma_{NC}(E_\nu) + \sigma_{mag}(E_\nu)) \quad (20)$$

¹Adding the small M1 component of the cross section does not modify our results appreciably.

²The sum is incoherent because the magnetic transition amplitude and the weak amplitude do not interfere.

where N_d is the total number of deuterium atoms in the fiducial volume and T is the exposure time. The neutral current flux reported by SNO [3] assumes that the total dissociation events arise from the standard neutral currents,

$$\Phi_{NC}^{SNO} \equiv \frac{N^{exp}}{N_d T \int dE_\nu \xi(E_\nu) \sigma_{NC}(E_\nu)} \quad (21)$$

Combining (20) and (21) we see that the experimental "NC" flux reported by SNO can be related to the magnetic moment cross section as

$$\Phi_{NC}^{SNO} = \Phi_{SSM} \left(1 + \frac{\int dE_\nu \xi \sigma_{mag}}{\int dE_\nu \xi \sigma_{NC}} \right) \quad (22)$$

Factoring out the unknown μ_{eff}^2 from (16), we can evaluate the numerical factor in the second term of (22) by evaluating the integrals over E_ν in the range (5.5 – 15.1) MeV. We should add, returning to the comment we made at the beginning of this paper, that in this energy range our cross section σ_{mag} is smaller than the corresponding cross section in [5]. In the higher part of that energy range, where σ_{mag} dominates the integral in (22), the difference is about a factor of 2 and thus the bound on μ_{eff} we shall obtain below may be considered a conservative limit by roughly a factor of $\sqrt{2}$. We use the numerical tables of $\sigma_{NC}(E_\nu)$ given by Nakamura *et al.* [12] to evaluate the denominator of the second term of (16). We find that the relation between the experimentally observed flux Φ_{NC}^{SNO} and the SSM prediction Φ_{SSM} is given by

$$\Phi_{NC}^{SNO} = \Phi_{SSM} (1 + 6.06 \times 10^{14} \mu_{eff}^2) \quad (23)$$

The experimental value for the total neutrino flux assuming the spectral shape of the 8B neutrinos from the Sun from the recent SNO observations [3] is

$$\Phi_{NC}^{SNO} = (4.90 \pm 0.37) \times 10^6 \text{cm}^{-2} \text{sec}^{-1} \quad (24)$$

The fact that the central value of the observed flux is smaller than the new SSM prediction $\Phi_{SSM} = (5.87 \pm 0.44) \times 10^6 \text{cm}^{-2} \text{sec}^{-1}$ leaves room open for the possibility of sterile neutrinos [13] but it tightens the constraint on neutrino magnetic moments. Using the numbers quoted above we find from equation (23) that μ_{eff}^2 is numerically

$$\mu_{eff}^2 = (-2.76 \pm 1.46) \times 10^{-16} \quad (25)$$

where we have added the errors in Φ_{SSM} and Φ_{NC}^{SNO} in quadrature. This can be interpreted as an upper bound on $|\mu_{eff}|$ at 95% C.L. (1.96σ) given by

$$|\mu_{eff}| < 3.71 \times 10^{-9} \mu_B \quad (95\% C.L.) \quad (26)$$

Earlier bounds on μ_{eff} [14, 15] were based on the extra electron scattering events that can be accommodated by the SuperK spectrum ($|\mu_{eff}| < 1.5 \times 10^{-10}$ at 90% C.L.) [14] and by a combination of all experimental rates ($|\mu_{eff}| < 2.0 \times 10^{-9}$ at 90% C.L.) [15]. Notice that in the case of elastic scattering of electrons, since the cross section of $\nu_e e^-$ scattering is different from that of $\nu_{\mu,\tau} e^-$, the extra events due to magnetic moment scattering were adjusted by the uncertainties in δm^2 and (mainly) $\sin^2 \theta_{12}$. In our case, since in the deuterium dissociation neutral current process the cross sections for all three neutrino flavours are identical, the event rate is independent of the oscillation parameters and therefore the extra events due to possible neutrino magnetic moments cannot be accommodated by shifting the values of the mass squared difference and the mixing angle. The only extra parameter with which the magnetic moment can be adjusted is the theoretical uncertainty in the total 8B flux.

For the case of the MSW solution of the solar neutrino problem which has been selected by Kamland [16], the 8B neutrinos undergo resonant adiabatic conversion. The matter mixing angle in the Sun is $\theta_m = \pi/2$. The neutrino mass eigenstate at production is $\nu_e = \nu_2$. As the evolution is adiabatic, at the Earth the neutrinos are still in the ν_2 mass eigenstate [14]. The effective magnetic moment for the solar 8B neutrinos is therefore

$$\mu_{eff}^2 = \mu_{21}^2 + \mu_{22}^2 + \mu_{23}^2 \quad (27)$$

Our bound on the components of the neutrino magnetic moment tensor can thus be written as

$$(\mu_{21}^2 + \mu_{22}^2 + \mu_{23}^2)^{1/2} < 3.71 \times 10^{-9} \mu_B \quad (95\% \text{ C.L.}) \quad (28)$$

At this point a qualification is in order. In fact, in the present state of affairs one cannot exclude a small contamination of ν_1 in the neutrinos arriving from the Sun that would depend on the neutrino energy (see for example [17]). We should emphasize that our bound on μ_{eff} would still be valid, but a different interpretation than (27) would follow. In the future, with more data at hand, it may be worth to reconsider the interpretation of μ_{eff} for solar neutrinos.

Sure enough, our bound here is not much different from other laboratory limits [18] obtained elsewhere and in fact it is definitely worse than the one obtained from the plasma emission argument in globular cluster stars [11]. However, two facts have to be considered when ascribing it its actual relevance. First, as we just mentioned the best limit is derived from energy-loss constraints in stars and hence does rely exclusively on stellar evolution theory. Second, since neutrinos oscillate and as a consequence different flavors mix differently in different settings, reactor, accelerator, solar, and astrophysical data cannot be compared directly when obtaining the bounds on magnetic moments [14, 15]. It is the analysis of the

various pieces of information coming from a variety of experimental sources that will eventually lead to a separate restriction on each and every μ_{ij} . The SNO data used in this paper, and the better data which will hopefully follow in the future on neutrino initiated deuteron break-up, is just one source of information among other sources that one can use to reach this goal.

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