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The effect of a neutrino magnetic moment on nuclear excitation processes

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Abstract

It is shown that MeV-range neutrinos with a magnetic moment of $\simeq 10^{-11}$ Bohr magnetons would excite nuclei, like ^{12}C , with cross sections comparable to those obtained in the Standard Model. This implies the possibility of improving the present experimental bounds on the magnetic moment of any flavour of neutrinos by one order of magnitude. Such a magnetic moment would also enhance the coherent neutrino-nuclear scattering in low-temperature detectors, enabling them to set comparable limits.

(February 1991)

1 Introduction

The possibility that neutrinos might have a magnetic moment $\mu_\nu \geq 10^{-11} \mu_B$ ($\mu_B = e/2m_e$ being the Bohr magneton), which exceeds by far the Standard Model (S.M.) value $\mu_\nu \simeq 10^{-19} (m_\nu/1\text{eV}) \mu_B$, has received renewed attention as an interesting way to solve the solar neutrino puzzle, in view of the apparent anticorrelation between the neutrino flux and the sun-spot activity [1]. The suggestion of Voloshin *et al.* [2], according to which the left-handed electron neutrinos produced in the core of the sun are flipped into sterile right-handed ones (also other flavours) via a magnetic moment interaction with the sun's magnetic field, requires μ_ν to be at least $\sim 10^{-11} \mu_B$.

A large neutrino magnetic moment would also indicate the existence of physics beyond the Standard Model, like left-right symmetry, supersymmetry, compositeness, or some of the more recent models where a large μ_ν can exist even for a very light neutrino as a consequence, for example, of some extra "custodial" symmetry [3].

The present experimental limits come from neutrino-electron elastic scattering, using beam-dump neutrino sources, which constrains the values of μ_{ν_e} and μ_{ν_μ} to be less than $1.08 \cdot 10^{-9} \mu_B$ and $7.4 \cdot 10^{-10} \mu_B$, respectively [4]. From a reactor $\bar{\nu}_e - e$ scattering experiment a limit of $\mu_{\bar{\nu}_e} \leq 4 \cdot 10^{-10} \mu_B$ has been obtained [5]. Astrophysical considerations, in general, yield more stringent limits. In particular, from the study of the cooling of the supernova SN1987a, a limit of $\mu_\nu \leq 10^{-13} \mu_B$ has been derived, which however seems to be still controversial [6]; on the other hand, the limit obtained from the cooling of red giants, $\mu_\nu \leq 0.8 \cdot 10^{-11} \mu_B$, is generally considered more reliable [7].

The KARMEN experiment [8] is presently looking for the neutrino induced ^{12}C transition to the 1^+ ($E^*=15.1$ MeV) level, for which the S.M. predicts a cross section of $\simeq 5 \cdot 10^{-42} \text{cm}^2$ for beam dump neutrinos with an average energy $\langle E_\nu \rangle \simeq 30$ MeV [9].

In this paper we show that a neutrino magnetic moment (either Dirac or Majorana) equal to the best laboratory bound will induce the above nuclear transition, but with a cross section larger than the Standard Model one. For neutrinos whose masses are much smaller than their energies, the S.M. interactions (which in such a limit conserve helicity) do not interfere with the magnetic moment interaction. Therefore, any neutrino magnetic moment will enhance the event rate of these nuclear transitions, allowing the KARMEN experiment (as well as other experiments of this type) to set limits on μ_ν .

2 ^{12}C (15.1 MeV) excitation via a neutrino magnetic moment.

The matrix element for the 15.1 MeV M1-transition of ^{12}C via a neutrino magnetic moment can be written as:

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

where:

$$J_{lep}^\mu = \mu_\nu \bar{u}_\nu(k_2, s_2) i\sigma^{\mu\lambda} q_\lambda u_\nu(k_1, s_1) \quad (2)$$

is the neutrino current. The most general form of the nuclear current for a $0^+ \rightarrow 1^+$ transition in the elementary particle (EPT) treatment is given by [10]:

$$J_\mu^{nucl} = F \epsilon_{\mu\nu\rho\sigma} \xi^\nu p_1^\rho p_2^\sigma, \quad (3)$$

where p_1 and p_2 are the initial and the final nuclear momenta, ξ is the polarization vector of the excited nucleus and $q = k_1 - k_2$ the four-momentum transfer. We parametrize the nuclear magnetic moment F , as the magnetic form factor F_M (which has been determined from electron scattering) times the nuclear magneton $\mu_N = e/2m_p$. For F_M we use the low- q^2 parametrization given by Mintz and Pourkaviani [9]¹:

$$F_M(q^2) = \frac{4.04 \cos^2(-q^2/3.12m_\pi^2)}{(1 - q^2/2.86m_\pi^2)^2}, \quad \text{for } |q^2| \leq 3.7 m_\pi^2. \quad (4)$$

The square of the matrix element in the rest-frame of the initial nucleus, after summation of the polarization states of $^{12}\text{C}^*$ and some algebra becomes:

$$|\mathcal{M}|^2 = \frac{2}{t} (\mu_\nu F M_1)^2 \left\{ (M_1 + \nu) [(2E_\nu - \nu)(t + 4M_1 E_\nu - \Delta) + t(M_1 + \nu)] \right. \\ \left. - \frac{1}{4}(t + \Delta)^2 - 2M_2^2 t - M_2^2 (2E_\nu - \nu)^2 + (\Delta - 2M_1 E_\nu)(t + 2M_1 E_\nu) \right\} \quad (5)$$

where $\nu = E_\nu - E'_\nu$ is the energy transfer, $t = q^2$, M_1 and M_2 are the ^{12}C and $^{12}\text{C}^*$ masses, $\Delta = M_2^2 - M_1^2$, and the neutrino mass has been neglected with respect to its energy. This leads to the following differential cross section:

$$\frac{d\sigma}{d|t|} = \frac{\kappa_\nu^2 \mu_B^2 \mu_N^2 F_M^2(t)}{32\pi E_\nu^2} \left[M_2^2 + 4E_\nu^2 - 2\Delta \frac{E_\nu}{M_1} - |t| \left(1 + \frac{2E_\nu}{M_1} \right) \right], \quad (6)$$

where we have taken into account that t is negative and have set $\mu_\nu = \kappa_\nu \mu_B$.

Note that for magnetic dipole-dipole interaction (elastic or inelastic), the $1/|t|$ singularity is absent. We obtain the $|t|$ -independent and the $|t|$ -proportional terms

¹The scale of the nuclear magnetic interaction is given by the nucleon size.

which are also present in the elastic interaction of a neutrino dipole moment with the dipole moment of a spin 1/2 fermion, but not any terms proportional to t^2 as reported by Vogel *et al.* [5]. For neutrino energies much below a few GeV the cross section is dominated by $(M_2/E_\nu)^2$, becoming constant for energies above a few GeV. As expected, there cannot be any mass threshold in the matrix element, since it is the same as for the time-reversed process, *i.e.*, the de-excitation of the nucleus. The phase space dependence on the threshold can be seen explicitly in the neutrino angular distribution:

$$\frac{d\sigma}{d\Omega_\nu} = \frac{|\mathcal{M}|^2}{64\pi^2 M_1^2} \left[1 - \frac{(E^* + E_{rec})}{E_\nu} \right], \quad (7)$$

where E_{rec} is the nuclear recoil energy and $E^* = M_2 - M_1 = 15.1$ MeV is the excitation energy.

The total cross section is obtained by numerically integrating eq.(6) from a maximum value $q_{max}^2 = 3.7 m_\pi^2$ to a minimum value q_{min}^2 of the order of the inverse screening radius squared, which can be set equal to zero, due to the lack of sensitivity of the cross section to q_{min}^2 . Our results can be presented in the following compact form:

$$\sigma = \sigma_0(1 + \epsilon), \quad (8)$$

where

$$\sigma_0 = 11.23 \frac{\pi \alpha^2}{32 m_e^2} \kappa_\nu^2 A^2 \left(\frac{m_\pi}{E_\nu} \right)^2, \quad (9)$$

$$\epsilon = 4 \frac{E_\nu^2}{M_2^2} \left(1 - \frac{E^*}{E_\nu} \right) - \left(\frac{7.15}{11.23} \right)^2 \left(\frac{m_\pi}{Am_p} \right)^2 \left(1 + \frac{2E_\nu}{M_1} \right), \quad (10)$$

and A , m_π and m_p are the atomic mass number, and the pion and proton masses, respectively. Since we are considering neutrino sources with $E_\nu \leq 53$ MeV, the ϵ term can be neglected and

$$\sigma \simeq \frac{\kappa_\nu^2}{E_\nu^2 (\text{MeV}^2)} (2.58 \cdot 10^{-19} \text{ cm}^2). \quad (11)$$

For a neutrino with a magnetic moment equal to the present experimental limit ($\kappa_\nu \simeq 10^{-10}$) and energy close to the threshold E^* , the cross section for exciting the carbon nucleus is of the order of 10^{-41} cm^2 , which is larger than the Standard Model cross section [9].

In Table 1 we present our results choosing $\kappa_\nu = 10^{-10}$, also showing the Standard Model predictions [9] (σ_{SM}) for the ν_e, ν_μ and $\bar{\nu}_\mu$ interactions with the ^{12}C nucleus. Notice that the magnetic moment-induced process, in contrast with the Standard

Model one, yields the same cross section for any neutrino flavour. Our cross section is larger than the Standard Model prediction for neutrino energies up to ~ 30 MeV.

This makes the beam dump neutrino sources useful for neutrino magnetic moment searches. Using the known shape of the ν_e, ν_μ and $\bar{\nu}_\mu$ energy spectra from pion decays at rest, given by:

$$\Phi(E_{\nu_e}) = N \frac{12E_{\nu_e}^2}{E_m^4} (E_m - E_{\nu_e}), \quad (12)$$

$$\Phi(E_{\bar{\nu}_\mu}) = N \frac{2E_{\bar{\nu}_\mu}^2}{E_m^4} (3E_m - 2E_{\bar{\nu}_\mu}), \quad (13)$$

where $E_m = 52.8$ MeV is the end-point energy, we calculate the averaged cross sections:

$$\langle \sigma \rangle = \frac{\int_{E^*}^{E_m} dE \sigma(E) \Phi(E)}{\int_{E^*}^{E_m} dE \Phi(E)}. \quad (14)$$

The numerical values, in units of $\kappa_\nu^2 \cdot 10^{-22} \text{ cm}^2$ are 3.05 for the ν_e 's and 2.36 for the $\bar{\nu}_\mu$'s. The muon-neutrino spectrum is monochromatic with an energy of 29.8 MeV, giving a cross section of 3.07 in the same units.

In the KARMEN experiment a reasonable expectation for the experimental sensitivity (*i.e.*, the error on the cross section measurement) is 20% of the sum of the $\bar{\nu}_\mu$ and the ν_e averaged Standard Model cross sections, namely, $2 \cdot 10^{-42} \text{ cm}^2$. This would set an upper limit (at 90 % C.L) of 10^{-10} on both κ_{ν_e} and $\kappa_{\bar{\nu}_\mu}$. Assuming a similar experimental sensitivity for the 29.8 MeV muon neutrino induced cross section, one expects (at 90 % C.L) a limit of $\kappa_{\nu_\mu} \leq 5 \cdot 10^{-11}$ ². A similar experiment, using beam dump neutrinos, is under construction at Los Alamos [11] (LSND) which has an estimated sensitivity of 10% for one year's running. For such large experiments, which are not limited by statistics, the main uncertainties come from the nuclear inelastic form factor and the neutrino flux. However, since the same form factor is used in the calculation of the charged current process (which leads to the isobaric analogue state of the 15.1 MeV state in carbon) these uncertainties (as well as the neutrino flux) cancel in the ratio between neutral and charged current event rates. It is thus conceivable that a sensitivity of a few percent can be reached, which would result in setting limits on μ_ν down to $\sim 10^{-11} \mu_B$.

²The experimental limits at 90% confidence level (C.L) for the neutrino magnetic moments have been obtained from the formula: $\sigma < 1.6\Delta\sigma$, where $\Delta\sigma$ is the experimental sensitivity.

3 Coherent neutrino-nucleus elastic scattering

As is well known, neutrino elastic cross sections in the S.M. scale as E_ν^2 , while the corresponding neutrino magnetic moment induced interactions are to first approximation energy independent [14], and can dominate in the low-energy limit. This fact has been used in neutrino-electron elastic scattering to set the current limits on the neutrino magnetic moment. Here we explore an analogous possibility for low-temperature detectors which are designed to look for low-energy neutrino fluxes from astrophysical sources via their coherent interaction with nuclei [12]. In interactions where the nucleus remains intact, the momentum transfer being small compared with the inverse nuclear size, the relative phase factors of the waves scattered from the individual nucleons are small and the waves add coherently. This results in an enhancement of the cross section, which in the electromagnetic case is proportional to Z^2 (the square of the nuclear charge), while in the neutral-current case it is approximately equal to N^2 (the number of neutrons squared).

In fact, the coherent neutral-current differential cross section for low-energy neutrinos, is given by [13]:

$$\frac{d\sigma}{d|t|} \simeq \frac{G_F^2}{8\pi} \left[Z(1 - 4 \sin^2 \theta_W) - N \right]^2 \left(1 - \frac{|t|}{4E_\nu^2} \right) F_{el}(t)^2, \quad (15)$$

where F_{el} is the nuclear elastic form factor. Non-zero spin nuclei get also small contributions from axial-vector currents, which have been neglected here. The corresponding coherent cross section induced by the neutrino magnetic moment is [14]:

$$\frac{d\sigma}{d|t|} \simeq \frac{2\pi\alpha^2 Z^2 \kappa_\nu^2}{m_e^2 |t|} \left(1 + \frac{|t|}{4E_\nu^2} \right) F_{el}(t)^2. \quad (16)$$

For neutrino energies of a few MeV the maximum momentum transfer squared ($|t|_{max} = 4E_\nu^2$) is still small compared to $1/R^2$, where R , the nuclear radius, is approximately $(30 - 100)^{-1} \text{ MeV}^{-1}$. As a consequence, the elastic form factor can be set equal to one, and the integrated cross sections to first order reduce to:

$$\sigma_{SM} \simeq \frac{G_F^2}{4\pi} N^2 E_\nu^2 \simeq 0.4 \cdot 10^{-44} N^2 E_\nu^2 \text{ cm}^2, \quad (17)$$

where E_ν is given in MeV, and:

$$\sigma_{mag} \simeq \frac{2\pi\alpha^2 Z^2 \kappa_\nu^2}{m_e^2} \ln \left(\frac{t_{max}}{t_{min}} \right) \simeq 10^{-23} Z^2 \kappa^2 \text{ cm}^2, \quad (18)$$

respectively.

It is interesting at this point to compare the inelastic cross section (equ. 11) for neutrino-nucleus scattering via a neutrino magnetic moment to the elastic one (equ. 18). Their ratio is given by:

$$\frac{\sigma_{in}}{\sigma_{el}} \simeq \left(\frac{A}{Z}\right)^2 \left(\frac{13}{E_\nu}\right)^2, \quad (19)$$

where E_ν , which is given in MeV, has to be larger than the excitation energy of the nucleus. For a 30 MeV neutrino on ^{12}C , for example, the two cross sections are comparable.

From eqs.(17-18) one can see that a 1 MeV neutrino with $\mu_\nu = 10^{-10}\mu_B$ scattered on protons and medium-size nuclei gives a cross section twenty-five times larger than expected from the Standard Model. Such low-energy (anti-)neutrinos are provided by many radioactive sources and nuclear reactors.

To give an idea of the sensitivity which could be reached for a one year exposure to a typical reactor neutrino flux, ($\simeq 10^{13}\text{cm}^{-2}\text{s}^{-1}$ at $E_\nu \simeq 1$ MeV), consider a gas proportional counter containing 1 kg of hydrogen, which should be able to detect 1 keV proton recoils. For $\mu_\nu = 10^{-10}\mu_B$, some 10^4 events are expected from magnetic moment scattering compared to only 2-3 events from the Standard Model. Therefore a limit of $\mu_\nu \simeq 10^{-11}\mu_B$ could be obtained.

For heavier nuclei, dark matter type detectors would have to be used, because the target recoil energy scales as: $1/A$. For a 1 kg detector of, say, germanium, the detector energy threshold might be 0.1 keV. Therefore, higher energy neutrinos, say, 5 MeV, would be needed, for which the reactor flux is $\simeq 5 \cdot 10^{11}\text{cm}^{-2}\text{s}^{-1}$. For a one year exposure, the Standard Model in this case, already predicts some 10^4 events. For a neutrino magnetic moment as before, an additional 10^4 events are expected. This would probably allow a dark matter detector to set a limit of $10^{-11}\mu_B$, as well. This is comparable to the limit that could be obtained by low-energy neutrino-electron scattering, as proposed by Vogel and Engel [5].

4 Conclusions

In the present paper we have studied nuclear excitation processes induced by a magnetic dipole-dipole interaction with the neutrino. Taking the ^{12}C (15 MeV) transition as an example, and choosing a neutrino magnetic moment equal to $10^{-10}\mu_B$, which is the present experimental limit, we find a cross section in the range $10^{-41} - 10^{-42} \text{ cm}^2$ for neutrino energies up to 50 MeV, which, interestingly, exceeds the Standard Model prediction by up to a factor of 20. Our results imply that current and planned experiments with beam dump neutrino sources, which

could reach a sensitivity of a few percent, would be able to push the limit on the neutrino magnetic moments down to $10^{-11} \mu_B$. The same limit could also be reached in the near future with low-temperature detectors exposed to reactor neutrino fluxes.

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$E_\nu(\text{MeV})$	σ_{mag}^ν *	σ_{SM}^ν †	σ_{SM}^p †
18	7.96	0.11	0.10
20	6.45	0.31	0.29
22	5.33	0.61	0.56
24	4.48	1.02	0.92
26	3.82	1.52	1.36
28	3.29	2.11	1.87
30	2.87	2.79	2.45
35	2.11	4.85	4.14
40	1.61	7.33	6.09
45	1.27	10.1	8.20
50	1.03	13.1	10.4

Table 1: Cross sections for the reaction $\nu + {}^{12}\text{C} \rightarrow \nu + {}^{12}\text{C}^*$ (15.1 MeV) in units of 10^{-42}cm^2 .

* For a neutrino magnetic moment of $10^{-10}\mu_B$.

† Ref. 9.