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New limits on nucleon decay modes to neutrinos

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Abstract: New limits on neutron decay to 3 and 5 neutrinos based on Kamioka data [1] are derived by evaluating the bremsstrahlung photon emission probability during decay. One finds that $\tau(n \rightarrow 3\nu)/\text{BR} > 2.3 \cdot 10^{27} \text{yrs}$ (90% CL) and $\tau(n \rightarrow 5\nu)/\text{BR} > 1.7 \cdot 10^{27} \text{yrs}$ (90% CL)

1 Introduction

Limits on invisible decay modes of the nucleon have been reported in recent papers [2,3]. Decays such as

$$n \rightarrow \nu\nu\nu$$

where ν can be any one of ν_e , ν_μ , ν_τ or the corresponding antineutrinos are especially hard to constrain experimentally. Decays with neutrinos in the final state have been predicted in some grand-unified models: nucleon decay into 3 leptons [5], into 5 and more leptons [6], dinucleon decay into 2 leptons [7]. Two basic ideas have been tried to put limits on those modes. The simplest upper limit comes from the flux of neutrinos with energy less than 1 GeV measured in underground detectors. The main part of the flux comes from atmospheric neutrinos but a fraction of the neutrinos might be induced by nucleon decays inside the Earth [2,4]. Alternatively, in experiments with water Cerenkov detectors, neutron decay would leave the daughter ^{15}O nucleus in an excited state [3]. The non-observation of the gamma rays from

the desexcitation of a specific nuclear level of the ^{15}O nucleus gives an upper limit on the neutron decay rate.

In this letter, a completely different method is used to constrain the invisible decay modes of the nucleon. Only single nucleon decays will be investigated: di- and tri-nucleon decays are more complicated and will be studied in a subsequent paper.

2 Photon emission induced by a neutron decay into neutrinos

The idea is to take advantage of the initial state radiation of the neutron. When a free neutron decays to N neutrinos, the total magnetic moment of the system drops from

$$\mu = a\mu_n = -1.91\mu_n = -1.91(e\hbar/2m_p)$$

to essentially 0, since neutrinos have a negligible or zero magnetic moment [13]. According to classical electrodynamics [8], the sudden acceleration or time variation of a magnetic moment results in the emission of radiation.

In the classical electrodynamics limit, the number of photons emitted with momentum p by a decaying neutron is given by: [8]:

$$dn(p) = (\alpha/2\pi)a^2(p/m_p)^2 F(p)^2 dp$$

where $F(p)$ is the neutron magnetic form factor. In the small photon momentum limit, the photon spectrum is linear in momentum except for the form factor $F(p)$. For all numerical applications, $F(p)$ is approximated by the dipole formula

$$F(p) = \frac{1}{(1 + p^2/Q^2)^2}$$

with $Q^2 = .71\text{GeV}^2$ [10]

When the neutron is bound in a nucleus, its magnetic moment is in general different from μ . The value of the magnetic moment μ_{SM} for a neutron in a (l,j) shell is given by the nuclear shell model [9] :

$$\begin{aligned}\mu_{SM} &= \mu \text{ for } j = l + 1/2 \\ \mu_{SM} &= -\mu(j/j + 1) \text{ for } j = l - 1/2\end{aligned}$$

In the case of the ^{16}O nucleus, the average value for μ_{SM}^2 is $.78 \mu^2$.

Proton decay detectors such as Frejus or Kamiokande had a threshold for photon detection of typically a few hundred MeV. They were thus sensitive to the high energy part of the photon spectrum, while the linearity of the spectrum is valid only in the low energy part. The probability for photon emission is expected to tend to 0 at high energy due to phase space limitations. The exact shape of the spectrum is also dependent a priori on the type of interaction responsible for the neutron decay into neutrinos.

Before studying the decay into 3 neutrinos in more details, it is interesting to give an order of magnitude calculation of the probability for photon emission. For this purpose, only the influence of phase space is taken into account: the matrix element of the interaction responsible for decay is assumed to be constant over phase space. This assumption will be further discussed in the case of the decay into 3 neutrinos. The decay is assumed to take place in an ^{16}O nucleus.

One can show that phase space factor for the decay of a neutron into N neutrinos is:

$$\Phi = (1 - 2p/m_n)^{N-2}$$

The photon spectrum in the N neutrino decay is thus:

$$\frac{dn(p)}{dp} = (\alpha/2\pi).78 a^2 \left(\frac{p}{m_p^2}\right) F(p)^2 (1 - 2p/m_n)^{N-2}$$

The probability P for photon emission above a typical threshold of 100 MeV is obtained by integrating numerically $\frac{dn(p)}{dp}$. This gives $P \sim .8 \cdot 10^{-4}$ for the 3 neutrino decay, and $P \sim 2.4 \cdot 10^{-5}$ for the 5 neutrino decay.

It is also interesting to have an approximate formula for any number N of neutrinos. To achieve this, we replace the slowly varying $F(p)$ term by an average value $F(m_n/4)$. The integration over p gives:

$$\begin{aligned} P &\sim (\alpha/8\pi) \left(\frac{m_n}{m_p}\right)^2 .78 a^2 F(m_n/4)^2 / (N(N-1)) \\ &= .78 \cdot 10^{-3} F(m_n/4)^2 / (N(N-1)) \end{aligned}$$

A bremsstrahlung photon is thus emitted in a small ($< 10^{-4}$) fraction of the neutron decays to neutrinos. Since no other particle is visible, this small fraction of events should appear as one prong electromagnetic showers ("contained e-like events") in underground detectors. The upper limit to the neutron decay rate into N neutrinos is thus given by the number of observed 1-prong e-like events with an energy of less than $m_n/2$ divided by the probability for photon emission. The limit obtained is independent of neutrino flavor.

3 Neutron decay into 3 neutrinos

The calculation of the previous section was only taking into account the effect of phase space. It is interesting to compare with the result obtained with the extra assumption that $n \rightarrow \nu\nu\nu$ is similar to the β decay $\mu \rightarrow e\nu_\mu\bar{\nu}_e$ or the corresponding decay modes for the τ . The published results on the emission of bremsstrahlung photons in the muon [11] or tau [12] decay cannot be used directly since most of the radiation is due to the acceleration of the charged particles. Still, the effect on photon spectrum of an abnormal magnetic moment a of the tau was computed in

reference [12]. The result can be taken over to the neutron case by considering only the part of the spectrum which is proportional to a^2 . By integrating formula 8 of reference [12] over electron energy and angle, and multiplying the result by a form factor, one finds the photon spectrum:

$$\frac{dn(p)}{dp} = (\alpha/2\pi) \cdot 78 \cdot a^2 \left(\frac{p}{m_p^2} \right) F(p)^2 (1 - 2p/m_n)^2 (1 - p/m_n)$$

This spectrum is linear in p in the low momentum limit, as expected from classical electrodynamics, but shows an extra suppression compared to the pure phase space calculation at high p ^{*}. By integrating over p above a threshold of 100 MeV, the probability for photon radiation is found to be $P = 3.3 \cdot 10^{-5}$. The comparison with the value of P found in section 2 shows that P is relatively insensitive (at the factor of 2 level) to the underlying interaction responsible for neutron decay.

Since the photon spectrum peaks at relatively low values, we use Kamiokande data [1] to derive the limit. Kamiokande had a total of 248 e-like 1-prong events (with momentum $100 < p_e < 1330$ MeV/c) for an exposure of 7.7 kiloton.years of data. This was in agreement with the expectation from cosmic ray neutrino interactions which is 243 ± 15 (syst) events [1]. The lower limit for the partial decay mode of the neutron into 3 neutrinos (with unknown branching ratio BR) is computed from:

$$\tau(n \rightarrow 3\nu)/\text{BR} = \frac{7.7AP}{S}$$

We assume a 100 % efficiency for detection and identification of the photon in the Kamiokande detector over the whole energy range. $A = 3 \cdot 10^{32}$ is the number of neutrons in 1 kton of the Kamiokande detector. $P = 3.3 \cdot 10^{-5}$ is the probability for photon emission into the $100 \text{ MeV} - \frac{m_n}{2}$ range assuming a β decay-like

^{*} The photon spectrum was derived with a V-A current-current interaction, but remains valid for a general current-current interaction

interaction for $n \rightarrow 3\nu$. The number of (background subtracted) candidates S is found by taking all single ring e-like candidates in the energy range 100 – 1330 MeV. Kamiokande has an excess of $5 \pm 16(\text{stat}) \pm 15(\text{syst})$ over the Monte-Carlo expectation[1], corresponding to:

$$S \leq 33 \text{ (90\% CL)}$$

This gives

$$\tau(n \rightarrow 3\nu)/\text{BR} \geq 2.3 \cdot 10^{27} \text{ years (90\% CL)}$$

which is an order of magnitude better than the published limits [3,2]. As already noted, this limit applies to neutrinos of any flavor.

4 Neutron decay into more than 3 neutrinos

The method used above can be extended to give limits on neutron decay into more than 3 neutrinos. Let us consider the decay into 5 neutrinos as an example. We use the classical formula supplemented with phase space suppression at high photon momentum. Under this assumption, the probability $P = 2.4 \cdot 10^{-5}$ given in section 2 leads to a partial lifetime limit of

$$\tau(n \rightarrow 5\nu)/\text{BR} > 1.7 \cdot 10^{27} \text{ yrs (90\% CL)}$$

5 Conclusion

A new method based on initial state radiation of the nucleon has been shown to improve the lower limits on the nucleon decay modes into neutrinos by an order of magnitude. Those limits are independent of neutrino (or antineutrino) flavor. Since they rely on the limited statistics of the Kamiokande experiment, they will likely be further improved at SuperKamiokande.

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