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WHY SEARCH FOR DOUBLE BETA DECAY? *

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Abstract

Searching for neutrinoless double beta decay is the only known practical method for trying to determine whether neutrinos are their own antiparticles. The theoretical motivation for supposing that they may indeed be their own antiparticles is described. The reason that it is so difficult to ascertain experimentally whether they are or not is explained, as is the special sensitivity of neutrinoless double beta decay. The potential implications of the observation of this reaction for neutrino mass and for the physics of neutrinos is discussed.

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Why search for double beta decay? For that matter, what is double beta decay? Perhaps the most interesting variety of this nuclear process is the neutrinoless variety $(A, Z) \rightarrow (A, Z+2) + 2e^-$, in which a nucleus with A nucleons and Z protons decays into another nucleus with two additional protons by emitting two electrons but nothing else. This decay is very interesting because its observation would imply that neutrinos are their own antiparticles and that they have mass.

Why should we expect that neutrinos may have nonzero masses? One reason is that from the standpoint of the grand unified theories which unify the strong, electromagnetic, and weak forces, it is more natural for neutrinos to be massive than to be massless. This is for a trivial reason. In any grand unified theory, one places a given neutrino in a family (a multiplet of some group) together with a charged lepton and with quarks of various charges. Now, it is known experimentally that, apart from the neutrino, every particle in such a family has a nonzero mass. Thus, the neutrino would have to be exceptional to be massless.

Let us assume that neutrinos do have mass. Then we must understand why they are so light compared to the other fundamental fermions–the charged leptons and quarks. The most popular explanation of this fact suggests that neutrinos are their own antiparticles. This possibility is not open to the other fundamental fermions because they are all electrically charged. Thus, neutrinos may differ in a basic way from the charged leptons and quarks, and perhaps this difference is the origin of their relative lightness.

A neutrino which is its own antiparticle is referred to as a Majorana neutrino, and one which is not as a Dirac neutrino. Since the world is presumably CPT–invariant, but definitely not C–invariant, one must define a Majorana neutrino in terms of its behavior under CPT. A Majorana neutrino at rest goes into itself under CPT, apart from a spin reversal caused by the time–reversal operator T. Such a neutrino has just two states: spin up and spin down. By contrast, a Dirac neutrino has four states: two spin states for the neutrino, and an additional two for the antineutrino.

In the popular explanation[1] of the relative lightness of neutrinos, a four–state Dirac neutrino ν^D is split into a pair of two–state Majorana neutrinos, ν^M and N^M. One of these Majorana neutrinos, ν^M, is light, and is identified as one of the familiar neutrinos. The other, N^M, is heavy, with a mass which is generally pictured as being above 10 GeV.

In this scheme, it is natural for the masses M_ν and M_N of ν^M and N^M to satisfy the so–called "see–saw relation"

$$M_\nu M_N \approx M^2_{l\ or\ q}, \tag{1}$$

in which $M_{l\ or\ q}$ is a typical charged lepton or quark mass. If we assume that M_N is indeed large, then this relation explains why M_ν is so small.

When we say that some neutrino ν differs from its antiparticle $\bar{\nu}$, what we mean is that ν and $\bar{\nu}$ interact differently with matter. To determine whether a given neutrino ν is of Dirac or of Majorana character, we must find out whether the interactions of the antiparticle $\bar{\nu}$ differ from those of ν or not. In practice, this is very difficult to do. The reason is that the experimentally available neutrinos are always polarized, and, in particular, the "neutrinos" are polarized oppositely from the "antineutrinos". The particles we call "neutrinos" are always left–handed, while those we refer to as "antineutrinos" are always right–handed. Now, it is well–known that the left–handed neutrinos interact very differently from the right–handed antineutrinos. However, there is no way of knowing whether this difference is due to a real distinction between neutrinos and antineutrinos, or simply to the difference in polarization in the two cases.

Let us examine this situation more closely. The neutral lepton emitted in the decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$, which by convention we call a neutrino rather than an antineutrino, is always left–handed. That is, it has negative helicity, and we shall indicate this fact by labelling it $\nu_\mu(-)$. By contrast, the neutral lepton emitted in the decay $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$, which by convention we call an antineutrino, is always right–handed. We shall indicate this fact by labelling it $\overline{\nu_\mu}(+)$. Now, it is observed that when a $\nu_\mu(-)$ strikes a nucleon N, the reaction $\nu_\mu(-) + N \rightarrow \mu^- + X$ may occur, but the reaction $\nu_\mu(-) + N \rightarrow \mu^+ + X$ will not. By contrast, when $\overline{\nu_\mu}(+)$ strikes a nucleon, the reaction $\overline{\nu_\mu}(+) + N \rightarrow \mu^+ + X$ may occur, but $\overline{\nu_\mu}(+) + N \rightarrow \mu^- + X$ will not. Unfortunately, there are two possible explanations of this difference in interaction patterns: (1) The difference may be due simply to the fact that $\nu_\mu(-)$ and $\overline{\nu_\mu}(+)$ have different polarizations. (2) It may be that ν_μ and μ^- are leptons, while $\overline{\nu_\mu}$ and μ^+ are antileptons, and lepton number is conserved.

To settle the issue of whether ν_μ and $\overline{\nu_\mu}$ differ, we must find out how the interactions of a ν_μ and a $\overline{\nu_\mu}$ of the <u>same</u> helicity compare. Suppose, for example, that we could somehow reverse the helicity of a $\overline{\nu_\mu}(+)$ created in π^- decay. We could then ask whether the resultant left-handed particle, $\overline{\nu_\mu}(-)$, interacts with nucleons in the same manner as the left-handed $\nu_\mu(-)$ born in π^+ decay. If the answer is yes, then $\overline{\nu_\mu}(+)$ and $\nu_\mu(-)$ differ only in helicity; that is, ν_μ is a Majorana neutrino. If the answer is no, then ν_μ is a Dirac neutrino. Unfortunately, reversing neutrino helicity is very difficult and has not been done.

When $M_\nu = 0$, the distinction between Majorana and Dirac character disappears, unless there are right-handed currents. The reason is that when $M_\nu = 0$, it is impossible to flip neutrino helicity,[2] and consequently meaningless to ask how a particle such as $\overline{\nu_\mu}(-)$ behaves. Furthermore, the approach to the $M_\nu = 0$ limit is a smooth one, so that even if, as we suspect, neutrinos have nonzero masses, it is nevertheless very difficult to tell whether they are Majorana or Dirac particles because their masses are so small compared to their energies and other mass scales.[3] The existence of this difficulty has been referred to as the "practical Dirac-Majorana confusion theorem".[4]

In spite of this difficulty, there is one reaction-neutrinoless double beta decay ($\beta\beta_{o\nu}$) - which could provide evidence that neutrinos are Majorana particles even if their masses are of order 1 eV or less. This reaction can arise from the diagram in Fig. 1. In this diagram, two neutrons in the parent nucleus emit a pair of W bosons, and then the W bosons exchange a neutrino mass eigenstate ν_m. The amplitude is a sum over the contributions from all the ν_m that exist.

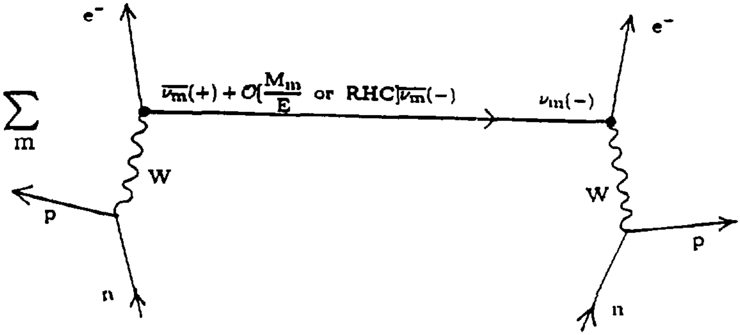

Fig. 1. Neutrinoless double beta decay. In the figure, E denotes the energy of the exchanged neutrino, and "RHC" stands for right-handed current.

At the vertex where it is emitted, the exchanged ν_m in Fig. 1 is created together with an e^-. Thus, should there be a difference between leptons and antileptons and lepton number be conserved, this "ν_m" would have to be a $\overline{\nu_m}$, as indicated. However, at the vertex where it is absorbed, this same particle creates a second e^-, so it must be a ν_m. Thus, the diagram in Fig. 1 vanishes unless $\overline{\nu_m} = \nu_m$; that is, unless ν_m is a Majorana particle. Even then, it is suppressed by a helicity-mismatch at the two lepton vertices. At the vertex where the exchanged ν_m is emitted, this particle is behaving like an antineutrino. Thus, if the leptonic current is purely left-handed, it will be emitted in a predominantly right-handed state. However, where it is absorbed, it is behaving like a neutrino, so the current prefers to absorb it from a left-handed state.

If ν_m has a mass M_m, then, as indicated in Fig. 1, there is an amplitude of order M_m/[Energy of ν_m] for it to be emitted left-handed. If it is a Majorana particle, it can then be reabsorbed without further suppression. Thus, in effect, in $\beta\beta_{o\nu}$ we actually carry out the type of gedanken experiment described earlier for neutrinos from pion decay. That is, we produce a particle (here ν_m) which is identified as an antineutrino by the production process, but which is left-handed. We then find out whether this particle interacts as would a left-handed neutrino.

If the leptonic weak current contains a small right-handed piece, then, like the ν_m mass, this piece will lead to emission of a virtual $\overline{\nu_m}(-)$ in $\beta\beta_{o\nu}$. As before, if $\overline{\nu_m}(-) = \nu_m(-)$, this particle can then be reabsorbed without suppression.

Why is $\beta\beta_{o\nu}$ able to provide evidence that neutrinos are Majorana particles even if their masses are much smaller than those required by any other process that has been considered? The primary reason is that the decays which can in principle compete with $\beta\beta_{o\nu}$ are highly-suppressed. One will always choose a parent nucleus which is stable against single beta decay, so that this competing mode is totally absent. Of course, $\beta\beta_{o\nu}$ must always compete with decay by emission of two electrons and two antineutrinos, a mode which can occur even if neutrinos are not Majorana particles. However, the latter mode is phase-space suppressed, typically by six orders of magnitude, relative to $\beta\beta_{o\nu}$. An additional advantage of $\beta\beta_{o\nu}$ is that in this reaction, the energy of the exchanged neutrino is of order 10 MeV, which is much smaller than the neutrino energies encountered in elementary particle processes. Hence, effects which distinguish between a Majorana neutrino and a Dirac one and are of order [neutrino mass]/[neutrino energy] are larger.

The amplitude $A[\beta\beta_{o\nu}]$ for $\beta\beta_{o\nu}$ can be written in the form

$$A[\beta\beta_{o\nu}] = M_{eff}N, \tag{2}$$

where N is a very nontrivial nuclear matrix element,[5] and M_{eff}, the effective neutrino mass for neutrinoless double beta decay, contains the particle physics of the process. If there are no right–handed currents, and all neutrino masses are small compared to 10 MeV, the typical momentum transfer in $\beta\beta_{o\nu}$, then the effective mass is given by[6]

$$M_{eff} = \sum_m \omega_{em} \left|U_{em}\right|^2 M_m. \tag{3}$$

In this sum over neutrino–exchange contributions, the contribution of ν_m is proportional to it mass, M_m, because the required emission of ν_m in a state with disfavored helicity has an amplitude proportional to M_m. The quantity U_{em} in Eq. (3) is an element of a unitary mixing matrix describing the coupling of neutrinos to charged leptons, and ω_{em} is a phase factor which is essentially U_{em}/U_{em}^*.

Suppose that $\beta\beta_{o\nu}$ should actually be observed. From the observed decay rate, and a calculated value for the nuclear matrix element N, one could then infer an experimental value for M_{eff}. Since $\sum\limits_m |U_{em}|^2 = 1$, it follows from Eq. (3) that this experimental value could not exceed the largest of the actual neutrino masses M_m. That is, the observation of $\beta\beta_{o\nu}$ would imply a lower bound on neutrino mass: at least one neutrino would have to have a mass no smaller than the measured M_{eff}. On the other hand, the observed absence of $\beta\beta_{o\nu}$ at a given level would not imply an upper bound on the masses of any neutrinos. Such an absence would merely limit M_{eff}, and M_{eff} can be very small compared to the physical neutrino masses, or even zero, due to the possible cancellations in Eq. (3).

Cancellations among the various contributions to M_{eff} can occur even if CP is conserved. In the CP–conserving case,[6]

$$\frac{\omega_{em}}{\omega_{em'}} = \frac{\tilde{\eta}(\nu_m)}{\tilde{\eta}(\nu_{m'})}, \tag{4}$$

where $\tilde{\eta}(\nu_m)$ is the intrinsic CP–parity of ν_m. Thus, $\omega_{em}/\omega_{em'}$ can be -1 as well as $+1$. If CP is violated, then $\omega_{em}/\omega_{em'}$ can be complex, and $|M_{eff}|$ can differ from what is allowed for given neutrino masses and mixing angles when CP is conserved. Interestingly enough, CP–violating values of $|M_{eff}|$ can already occur when there are only two generations of leptons, since Eq. (3) need only contain two terms for $|M_{eff}|$ to be sensitive to complex phase factors. This situation is in striking contrast to that encountered in the case of quarks, where there can be no CP-violating effects unless there are at least three generations. Indeed, if neutrinos are Majorana particles, then, for any given number of generations, there can be more CP–violating phases in the leptonic sector than in the quark sector.[7] The reason[8] is that when neutrinos are Majorana particles, the amplitudes for certain leptonic processes involve interferences with no analogues in the quark sector. Some of these new interferences are sensitive to phase factors in the leptonic mixing matrix U that would be physically irrelevant if U were mixing quarks. The interference which occurs in Eq. (3) when there are only two neutrinos, and which can lead to a CP–violating value of $|M_{eff}|$ through its sensitivity to $\omega_{e1}/\omega_{e2}(= U_{e1}U^*_{e2}/U^*_{e1}U_{e2})$, is an example of this phenomenon.[9]

In the presence of right–handed currents and/or additional W bosons beyond the familiar one, the ν_m–exchange contribution to $\beta\beta_{o\nu}$ can become quite complicated, and M_{eff} is no longer given by Eq. (3). In particular, the individual ν_m contribution need no longer vanish with M_m. However, in any gauge theory which does not contain doubly–charged gauge bosons, it remains true that the <u>sum</u> of the ν_m contributions yields a vanishing M_{eff} (hence a vanishing $\beta\beta_{o\nu}$ amplitude) unless at least one ν_m has a nonzero mass.[10] Indeed, a simple argument shows that even if $\beta\beta_{o\nu}$ is not engendered primarily by neutrino exchange but by some more exotic mechanism, the observation of this reaction would still imply nonzero neutrino mass.[11]

Recently, it has been shown[10] that for a broad class of gauge theories, the observation of $\beta\beta_{o\nu}$ would imply an experimentally interesting lower bound on neutrino mass. This bound would be related to the observed $\beta\beta_{o\nu}$ lifetime. If, for example, ^{76}Ge should be seen to undergo neutrinoless double beta decay with a lifetime τ_{Ge}, this observation would imply that at least one neutrino must have a mass M satisfying

$$M \gtrsim 1 eV \left[\frac{10^{24} yr}{\tau_{Ge}}\right]^{1/2} . \tag{5}$$

Now, the present lower bound on τ_{Ge} is approximately 10^{24} yr.[12] Thus, if ^{76}Ge should be found to undergo $\beta\beta_{o\nu}$ with a lifetime close to the present limit, at least one neutrino must have a mass exceeding $\sim 1eV$. A mass of order $1eV$ is large enough to be sought in neutrino oscillation experiments, and possibly also in future tritium beta decay experiments.

As noted earlier, the amplitude for $\beta\beta_{o\nu}$ depends on a nontrivial nuclear matrix element. Thus, the interpretation of $\beta\beta_{o\nu}$ experiments relies on our ability to calculate this matrix element. The experimental observation[13] of the reaction $^{82}Se \rightarrow ^{82}Kr + 2e^- + 2\bar{\nu}$ has provided us with a test of the accuracy of nuclear calculations for the two-neutrino mode of double beta decay. It is not clear how much such a test tells us about the calculations for the neutrinoless mode.[5]

There has been recent discussion[14] of the possible occurrence of a reaction closely-related to $\beta\beta_{o\nu}$; namely, the process $(A, Z) \rightarrow (A, Z+2) + 2e^- + \mathcal{M}$, where $\mathcal{M}$ is a massless, spinless, neutral particle known as the Majoron.[15] The Majoron, somewhat akin to a Higgs particle, occurs in several versions of a particular theoretical scheme for generating neutrino masses. This scheme is a very attractive and simple one. However, it is one of numerous possibilities, and one cannot argue that gauge theories of the weak interaction require the existence of a Majoron as they do that of a Higgs particle. If the Majoron does exist, its coupling to neutrinos would lead to $(A, Z) \rightarrow (A, Z+2) + 2e^- + \mathcal{M}$ through a diagram like that in Fig. 1, but with an $\mathcal{M}$ emitted from the neutrino line.

In summary, the search for neutrinoless double beta decay is the only known feasible way of trying to determine whether neutrinos are their own antiparticles. In addition, under quite general circumstances, the observation of $\beta\beta_{o\nu}$ would imply neutrino mass which is not only nonzero, but is large enough to be confirmed through other types of experiments. From the theoretical standpoint, it is natural to suppose that neutrinos do have mass and are their own antiparticles. Thus, the search for neutrinoless double beta decay may prove very fruitful.

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