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Can one ever prove that neutrinos are Dirac particles?

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A B S T R A C T

According to the "Black Box" theorem the experimental confirmation of neutrinoless double beta decay ($0\nu2\beta$) would imply that at least one of the neutrinos is a Majorana particle. However, a null $0\nu2\beta$ signal cannot decide the nature of neutrinos, as it can be suppressed even for Majorana neutrinos. In this letter we argue that if the null $0\nu2\beta$ decay signal is accompanied by a $0\nu4\beta$ quadruple beta decay signal, then at least one neutrino should be a Dirac particle. This argument holds irrespective of the underlying processes leading to such decays.

Ever since the early days of neutrino physics [1–4] there has been a debate about the nature of neutrinos i.e. whether they are Dirac or Majorana fermions. The debate has origins in the fact that, although most of the known fermions (except neutrinos, whose nature is yet to be ascertained) are Dirac particles and hence four-component spinors, the fundamental irreducible spinorial representations of the Poincaré group are actually two-component. However, the Poincaré group describes just the kinematics, and does not represent the full unbroken symmetry of nature.

Apart from spacetime symmetry, particle theories also have "internal symmetries" for example "gauge symmetries", such as the $SU(3)_C \otimes SU(2)_L \otimes U(1)$ of our cherished Standard Model (SM). According to the gauge paradigm, these symmetries dictate the dynamics of all fundamental processes amongst elementary particles. The SM gauge group is spontaneously broken by the celebrated Brout–Englert–Higgs mechanism, but not completely. As far as we know from experiments, an $SU(3)_C \otimes U(1)_{EM}$ gauge symmetry remains unbroken. This symmetry then dictates the dynamics of fundamental processes at energies below the electroweak symmetry breaking scale. Thus at energy or temperature scales well below the electroweak breaking scale, one must not only take into account the invariance under the Poincaré group, but also under the unbroken $SU(3)_C \otimes U(1)_{EM}$ gauge group. Thus, any fermion carrying a non-zero color or electric charge cannot have a Majorana mass term, since such term would necessarily break the $SU(3)_C \otimes U(1)_{EM}$ gauge symmetry. This implies that, although two-component spinors are indeed fundamental, the requirement that color and electromagnetic charges remain conserved, forces all the quarks and charged leptons to be Dirac particles. On the basis of this argument it has been argued in [5] that, thanks to their complete charge neutrality, only neutrinos can be — and should be — Majorana fermions. However, nature need not follow our theoretical prejudices, so that only experiments can settle whether neutrinos are Dirac or Majorana particles.

Thanks to the small neutrino mass m_ν and the V–A nature of the weak interaction, discerning the nature of neutrinos from experiments is a formidable task. A basic difference between Dirac and Majorana fermions resides in the CP phases present in their mixing matrices [5]. Indeed, due to helicity suppression, the sensitivity to the physical Majorana phases present in neutrino to anti-neutrino oscillations [6] is well below any conceivable test. Likewise, electromagnetic properties of neutrinos [7–9] have a hidden dependence on m_ν. Indeed, in a V–A theory like the Standard Model all observables sensitive to the Majorana nature of neutrinos end up being suppressed by a power of m_ν.[1] The small scale of the active neutrino masses makes such differences very tiny.

However, there is a potentially feasible process which may settle the issue, namely the neutrinoless double beta decay, which has long been hailed as the ultimate test concerning the nature of neutrinos.[2] Indeed, if $0\nu2\beta$ decay is ever observed, its amplitude can always be "dressed" so as to induce a Majorana mass, ensur-

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[1] In a general phenomenological form for the weak interaction this statement does not hold, see, e.g. [10]. However, to a good approximation, nature follows a V–A gauge theory structure.

[2] In SM extensions there may be feasible complementary probes of lepton number violation at collider energies [11–15].

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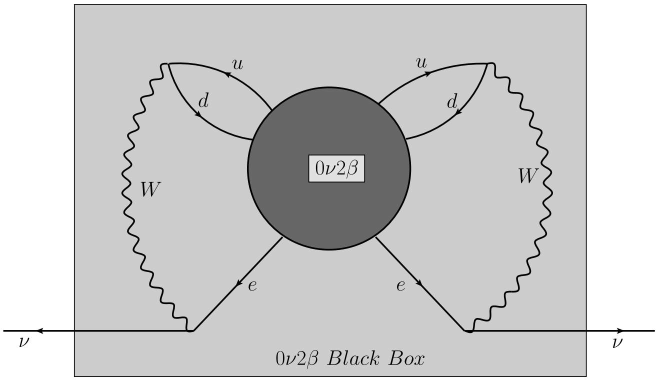

Fig. 1. The "Black Box" theorem states that a $0\nu 2\beta$ signal ensures that at least one neutrino is Majorana in nature [16].

ing that at least one of the neutrinos is of Majorana type [16], as illustrated in Fig. 1. See Ref. [17,18] for recent discussions.

However, the non-observation of $0\nu 2\beta$ decay so far [19–22] has raised the intriguing possibility that neutrinos might well be Dirac particles. Several well motivated high-energy completions of the SM do lead to naturally light Dirac-type neutrinos [23–26]. Note however that, given current laboratory and cosmological observations, the absence of a $0\nu 2\beta$ signal is certainly consistent with the Majorana nature of neutrinos. Moreover, the decay amplitude may be suppressed as a result of a destructive interference amongst the three active neutrinos, even if they are Majorana type [27,28]. Thus, although the observation of $0\nu 2\beta$ decay would necessarily imply that at least one neutrino species is Majorana in nature, the converse is not true: a negative $0\nu 2\beta$ decay signal does not tell us anything about the nature of neutrinos.

This prompts us to search for processes beyond the simplest $0\nu 2\beta$ decay which can also shed light upon the nature of neutrinos.[3] We will specifically focus on the two lowest $0\nu 2n\beta$ processes characterized by $n = 1, 2$, namely, the neutrinoless double beta decay $0\nu 2\beta$ and the neutrinoless quadruple beta decay.

An experimental search for the $0\nu 4\beta$ process has been recently performed by the NEMO-3 collaboration, using ^{150}Nd [29]. The possible existence of $0\nu 4\beta$ decays has been first suggested in [30], and it is expected to arise in a number of models with family symmetries leading to Dirac neutrinos [31–33]. Here we argue that the combination of the $0\nu 2\beta$ and $0\nu 4\beta$ processes may be enough to settle the nature of neutrinos within a very broad class of models.

In order to proceed let us first look at the $0\nu 2\beta$ process and the neutrino mass generation from the symmetry point of view. In the Standard Model the neutrinos are massless and there is an accidental global "classically conserved" $U(1)_L$ symmetry in the lepton sector associated to Lepton number for all the leptons in SM.[4] By just adding right handed neutrinos ν_{iR} sequentially to the SM particle content one can give mass to neutrinos without breaking the lepton number symmetry. In such a case neutrinos will necessarily be Dirac particles and the $0\nu 2n\beta$; $n \geq 1$ decays will all be absent.

We now turn to the cases when this lepton number is broken down to a discrete Z_m subgroup ($m \geq 2$) which remains conserved. Notice that a $U(1)$ symmetry only admits Z_m subgroups, where Z_m is a cyclic group of m elements, characterized by the property that if x is a non-identity group element, then $x^{m+1} \equiv x$. The Z_m groups only admit one-dimensional irreducible representations, conveniently represented by using the n-th roots of unity, $\omega = e^{\frac{2\pi I}{m}}$, where $\omega^m = 1$. If lepton number is broken to a Z_m subgroup (with neutrinos transforming non-trivially under Z_m) by the new physics responsible for neutrino mass generation, then we have two possible cases:

$$
\begin{aligned}
U(1)_L &\rightarrow Z_m \equiv Z_{2n+1} \text{ where } n \geq 1 \text{ is a positive integer} \\
&\quad \Rightarrow \text{Neutrinos are Dirac particles} \\
U(1)_L &\rightarrow Z_m \equiv Z_{2n} \text{ where } n \geq 1 \text{ is a positive integer} \\
&\quad \Rightarrow \text{Neutrinos can be Dirac or Majorana}
\end{aligned} \tag{1}
$$

If the $U(1)_L$ is broken to a Z_{2n} subgroup, then one can make a further broad classification

$$\nu \sim \omega^n \text{ under } Z_{2n} \Rightarrow \text{Majorana neutrinos} \tag{2}$$

$$\nu \nsim \omega^n \text{ under } Z_{2n} \Rightarrow \text{Dirac neutrinos} \tag{3}$$

depending on the charges of neutrinos under the unbroken Z_{2n} symmetry. For neutrinos transforming non-trivially under any unbroken Z_{2n+1} symmetry, they must be Dirac particles. For neutrinos transforming non-trivially under the Z_{2n} symmetry, they can be Majorana if and only if $\nu \sim \omega^n$. For any other transformation neutrinos will be Dirac particles. Thus, from a symmetry point of view, in contrast to popular belief, the Majorana neutrinos are the special ones, emerging only for certain transformation properties under the unbroken residual Z_{2n} symmetry.

The simplest Z_m group to which the $U(1)_L$ can break is Z_2. This case is special, as it only offers two possibilities for neutrino transformation i.e. $\nu \sim +1$ or -1, both of which satisfy Eq. (2) and only allows for Majorana neutrinos. Breaking $U(1)_L$ to Z_2 is quite simple, through a Majorana mass term $\nu\nu$ arising effectively from new physics, as is the case of Weinberg's dimension 5 operator $\bar{L}^c \Phi \Phi L$ [34]. Most popular in the literature, this case covers a big chunk of model setups, which typically involve breaking of lepton number to a residual Z_2 symmetry. This also induces a nonzero $0\nu 2\beta$ decay amplitude, as this decay is now allowed by the symmetry. The converse is also true, namely, if the $0\nu 2\beta$ decay process is allowed, it always implies that lepton number is broken and the associated new physics is bound to generate Majorana mass terms.[5] Notice that, since the higher $0\nu 2n\beta$ beta process are also allowed by the residual Z_2 symmetry, they all will also occur through 'multiples of n" $0\nu 2\beta$ amplitudes as illustrated in Fig. 2, for the simplest case of $n = 2$. These higher processes can be intuitively thought of as "multiples" of the basic $0\nu 2\beta$ process, $0\nu 2n\beta \equiv n(0\nu 2\beta)$ and thus we have $\Gamma_{0\nu 2n\beta} \ll \Gamma_{0\nu 2\beta}$.

We now turn to the case of $U(1)_L$ broken to higher symmetries, with neutrinos transforming non-trivially under the residual Z_m symmetry. Clearly if $U(1)_L$ breaks to an Z_{2n+1} symmetry, the lowest possible allowed neutrinoless beta decay process will be $0\nu(2n+1)\beta$, where n is a positive integer. But such processes are forbidden, as can be easily seen. Consider, for simplicity $0\nu 3\beta$. This process would require us to write down a 9-fermion operator, which is of course not possible.[6] Hence in such cases no neutrinoless beta decay of any order below $0\nu 2(2n+1)\beta$ are possible and neutrinos can only be Dirac particles [35,36].

[3] Observation of a non-zero mass in KATRIN, together with non-observation of $0\nu 2\beta$ decay would also favor Dirac neutrinos.

[4] There is an additional accidental global $U(1)_B$ symmetry associated to conserved Baryon number. While B and L are separately anomalous at the quantum level, there are anomaly free combinations, such as $U(1)_{B-L}$. For simplicity here we discuss only $U(1)_L$, though our argument remains valid for $U(1)_{B-L}$.

[5] Notice that the Majorana mass term might be generated at the loop level, and need not be the dominant source of $0\nu 2\beta$ decay.

[6] Notice that although the lowest $0\nu(2n+1)\beta$ is forbidden, the higher dimensional $0\nu a(2n+1)\beta$ processes (a is a even integer and $a \geq 2$) are still allowed by Z_{2n+1} symmetry.