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Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than $3\frac{1}{2}$ printed pages and must be accompanied by an abstract.*

Feasibility of detecting neutrinoless double-beta decay between pairs of single-beta emitters

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New experiments are suggested to search for neutrinoless double-beta decay between pairs of single-beta emitters. This addresses the Majorana mass of the neutrino. The electron capture decay mode for single-beta emitters is much easier to investigate than the previously considered beta-decay modes. The experimental problems introduced by the bremsstrahlung background are examined. Actual implementation of these experiments appears somewhat beyond current technical means.

Observation of neutrinoless double-beta decay would imply, for instance, that the electron neutrino is a massive Majorana particle. Most of the numerous investigations of double-beta decay[1] have been concerned with decays occurring within a single nucleus. Recently, however, Pacheco[2] introduced a new mechanism: neutrinoless double-beta decay between separated pairs of single-beta emitters. That is, one nucleus in a sample of element X weakly decays, emitting one virtual neutrino which propagates to *another nucleus* in the sample, where a second weak vertex occurs, giving double-beta decay,

$$\begin{array}{l} {}^{A}_{Z}\mathrm{X}\to{}^{A}_{Z+1}\mathrm{Y}+\beta^{-}+\bar{\nu}_{\mathrm{e}} \\ \downarrow \\ \nu_{\mathrm{e}}+{}^{A}_{Z}\mathrm{X}'\to{}^{A}_{Z+1}\mathrm{Y}'+\beta^{-} . \end{array} \tag{1}$$

Notice that this requires $\bar{\nu}_e=\nu_e$, the Majorana property, and it may also require $m_\nu\neq 0$ since the neutrino must flip its helicity to initiate the second reaction in Eq. (1). Conversely, this last requirement can also be met (with or without $m_\nu=0$) if right-handed currents contribute to the weak interaction. These properties exactly parallel those required for ordinary neutrinoless double-beta decay within a single nucleus. In that case, the virtual neutrino propagates between two nucleons contained in one nucleus. One experimental advantage[2] of double-beta decay between pairs of single-beta emitters is the lack of the interfering, double-beta decay with two neutrinos present in ordinary double-beta decay.

Subsequent to Pacheco's article,[2] a comment on his idea appeared in the literature.[3] The focus of the comment is on the feasibility of experiments to search for double-beta decay from single-beta emitters, a topic originally discussed briefly by Pacheco.[2] Both papers[2,3] correctly point out that (1) the required mass of source would be very large and, hence, the numerous electrons from the single-beta decays could present substantial noise problems; and (2) a positron in the final state of the double-beta decay would give a clean signal, a pair of annihilation gamma rays, that could perhaps be separated from the background noise. The positron is generated by requiring the Q value for the single-beta decay to be in the range $m_e<Q_\beta<2m_e$. The bremsstrahlung from these beta particles is below the 1.022 MeV threshold for e^+-e^- pair production, in contrast to the double-beta decay beta particles which could create pairs.

Regrettably, a quite technical, but important point was missed in both papers.[2,3] The external bremsstrahlung photons from the single-beta decay beta particles would completely mask the desired signal of the positrons—the 511 keV annihilation gamma rays. For this reason alone, experimental searches for the double-beta decay shown in Eq. (1) are almost certainly doomed to failure.

That is not to say that the essence of Pacheco's original idea, double-beta decay between pairs of single-beta emitters, is necessarily beyond experimental investigation, as alluded to in Ref. 3. There are much more promising reactions than those shown in Eq. (1). For example, consider an electron capture (EC) decay,

$$e^{-}+{}^{A}_{Z}\mathrm{X}\to{}^{A}_{Z-1}\mathrm{Y}+\nu_{\mathrm{e}} . \tag{2a}$$

Again, if the neutrino is a massive Majorana particle, it can propagate to another nucleus in the sample and initiate the reaction,

$$\bar{\nu}_{\mathrm{e}}+{}^{A}_{Z}\mathrm{X}'\to{}^{A}_{Z-1}\mathrm{Y}'+\beta^{+} . \tag{2b}$$

If the Q value for the reaction shown in Eq. (2a) is in the range $m_e<Q_{\mathrm{EC}}<2m_e$, then the reaction shown in Eq.

(2b) will satisfy energetics. This range of Q values also prohibits (through energy conservation) positron emission by the single-beta decay. Hence, double-beta decay is the only way to get a positron in the final state.

Unfortunately, internal bremsstrahlung[4] appears with electron capture decays, albeit at a much lower photon yield than external bremsstrahlung in beta decay. Consideration of the internal bremsstrahlung photon energy spectra[4] leads one to suggest candidates for double-beta decay experiments that have Q_{EC} just above 511 keV and low Z. Three appropriate decays that could be used in such an experiment exist in nature [see Table I (Ref. 5)]. X rays from the single beta decays also present a possible background problem. For any choice of source, the appropriate shielding with its K absorption edge just above the x-ray energies can reduce the x-ray effect to a negligible level. Therefore, somewhat arbitrarily, the decay of ${}^{49}\mathrm{V}$ will be used as a specific example for the experimental discussion that follows.

TABLE I. Allowed electron capture decays, with no positron emission, $Q > m_e$, and accompanying nuclear gamma rays restricted to a maximum energy of 100 keV (Ref. 5). Of all forbidden beta decays, only two isotopes (${}^{53}\mathrm{Mn}$, ${}^{137}\mathrm{La}$) satisfy all of the above constraints (Ref. 5).

Isotope	Half-life	Q_{EC} (keV)[a]	logft	Nuclear gamma rays
${}^{37}\mathrm{Ar}$	35.0 d	814	5.1	
${}^{49}\mathrm{V}$	330 d	602	6.2	
${}^{119}\mathrm{Sb}$	38.0 h	584	5.1	23.9 keV γ's 100%

[a] Ground state to ground state.

The detection of the double-beta decay of a pair of ${}^{49}\mathrm{V}$ nuclei,

$$\begin{tikzcd}
e^- + {}^{49}\mathrm{V} \rightarrow {}^{49}\mathrm{Ti} + \nu_e \arrow[d] \\
\bar{\nu}_e + {}^{49}\mathrm{V} \rightarrow {}^{49}\mathrm{Ti} + \beta^+ \arrow[d] \\
2\gamma\ ,
\end{tikzcd} \qquad (3)$$

presents several formidable experimental problems. First, an extremely intense source (many Ci) would certainly be required by rate considerations. This source will have the problems of production, purification, handling, and contamination from normal β^+ emitters (e.g., ${}^{48}\mathrm{V}$). Next, the detection of the two antiparallel 511 keV annihilation gamma rays would be greatly hindered by the background of the internal bremsstrahlung photons,[4] as pointed out earlier. A reasonable way to reject the bremsstrahlung background is to use many Ge solid state photon detectors, which have extremely good energy resolution (≈ 1 keV), to distinguish the 511 keV lines from the continuous bremsstrahlung background. Also, the coincidence resolving time for two 511 keV photon events in two Ge detectors is roughly 5 ns. The coincident timing and the antiparallel geometry can be used to further suppress the bremsstrahlung background.

The largest conceivable size for the source in this experiment is limited by the attenuation of the 511 keV photons in the source material. For a spherical ${}^{49}\mathrm{V}$ source, the maximum radius is about 1 cm, giving a mass of 25 g. Estimates indicate that 1–2 yr of running, using an intense source (≈ 200 kCi if pure ${}^{49}\mathrm{V}$) surrounded by an extensive 4π Ge detector array ($\approx 3\times10^6$ crystals), will be sensitive to an initial double-beta decay event rate of one per day. These figures give a value of $10^{-21}\ \mathrm{yr}^{-1}$ for the parameter Λ/N used in Ref. 3, which is just inside the range they consider of current interest. Prospects are not promising for producing the source or obtaining the required detector array and associated electronics, both are clearly beyond the bounds of technical feasibility at the present time. However, the experimental limitations and major sources of background that would be encountered in this experiment have been identified. Straightforward procedures could be implemented to deal with these problems which, unfortunately, lead to technical nonfeasibility. Backgrounds due to cosmic muons, neutrinos, and ambient radioactivity appear to be negligible. A pilot experiment to test these ideas is being planned.

In conclusion, the authors of Ref. 3 are extremely pessimistic on the feasibility of experiments to search for neutrinoless double-beta decay between pairs of single-beta emitters. In the final analysis, this conclusion may be correct for technical reasons, but their study is incomplete, which is the point of this Brief Report. At this time, the feasibility of experiments to demonstrate double-beta decay between single-beta emitters should remain an open question. Hopefully, Pacheco's interesting idea will be the subject of further investigations.

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