Allowed Neutrinoless Double Beta Decay: $0\nu\beta^{\pm}\beta^{\mp}$

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Abstract

We consider the process $(N,Z)^* \rightarrow (N,Z) + e^+ + e^-$ via virtual neutrino exchange, an allowed double beta decay process in the Standard Model. We an estimate of the lifetime of ^{178m2}Hf and consider the value of an experiment to measure the lifetime.

Neutrinoless double beta decay, $0\nu\beta^\pm\beta^\pm$, presents the best and perhaps the only, way to detect Majorana neutrinos. Fig. 1 shows the process and the experimentally required nuclear level scheme for the transition $(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$. The $V-A$ structure of the weak interaction selects the Majorana mass term from the Majorana propagator since [1],

$$\frac{1}{2}(1-\gamma_5)\left(\not{p}+m\right)\frac{1}{2}(1-\gamma_5) = \frac{1}{2}(1-\gamma_5)\,m$$

resulting in an expression for the lifetime that depends on the Majorana neutrino mass m,[2]

$$\lambda = \ln 2 G \left|M\right|^2 m^2.$$

The nuclear matrix element M presents a major calculational obstacle to interpreting $0\nu\beta^\pm\beta^\pm$ experimental limits and G is a phase space factor that only depends on the transition energy. Another decay is also possible, $0\nu\beta^\pm\beta^\mp$, that is allowed in the Standard Model.

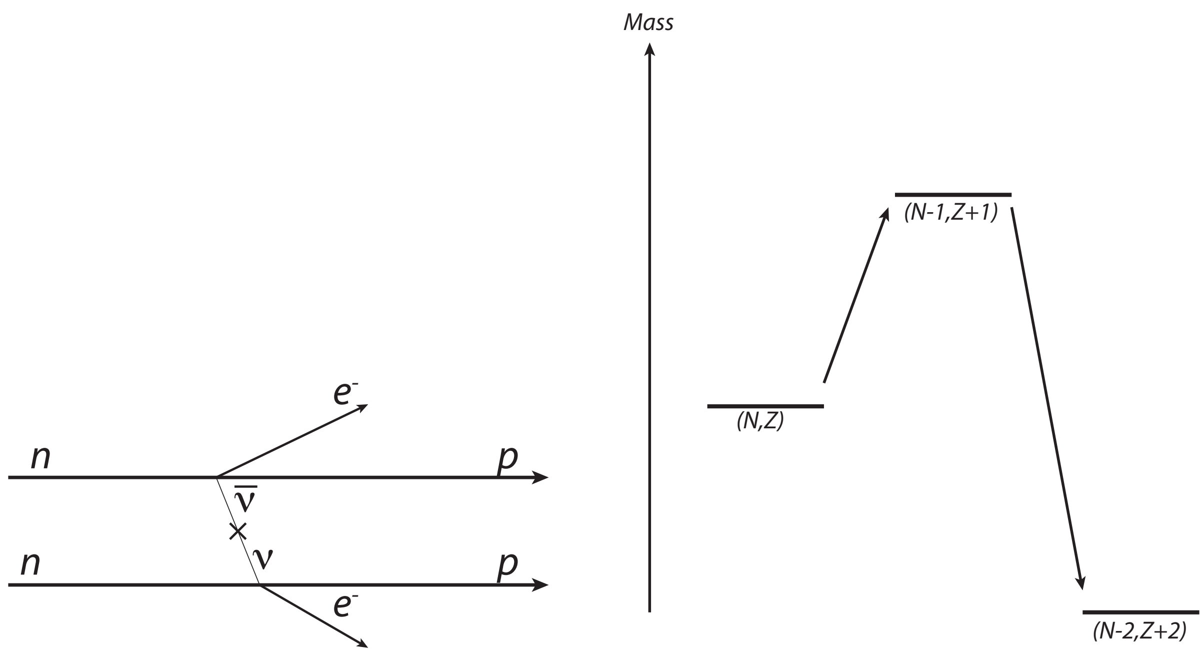

FIG. 1. Left: Feynman diagram for the $0\nu\beta^\pm\beta^\pm$, Right: nuclear level scheme for $0\nu\beta^\pm\beta^\pm$ candidate isotopes.

Fig. 2 shows $(N,Z)^* \rightarrow (N,Z) + e^+ + e^-$. In this process, the virtual neutrino may be either Majorana or Dirac and the $V-A$ structure of the decay selects the momentum piece of the propagator since,

$$\frac{1}{2}(1-\gamma_5)\left(\not{p}+m\right)\frac{1}{2}(1+\gamma_5) = \frac{1}{2}(1-\gamma_5)\,\not{p}.$$

The only kinematic requirement for the decay to take place is that there must be an excited state with energy larger than $2m_e$ above the ground state. As a practical matter, one would want a long lived, say 10^7 s, metastable state and the neighboring nuclear ground states to be have a higher mass that the excited initial state to prevent sequential β decay from reaching the ground state. Exactly one state meets these requirements, the ^{178m2}Hf state, Fig. 3, which lies 2,446 keV above the ground state, leaving 1,424 keV kinetic energy for the outgoing leptons. The approximate decay rate is then,

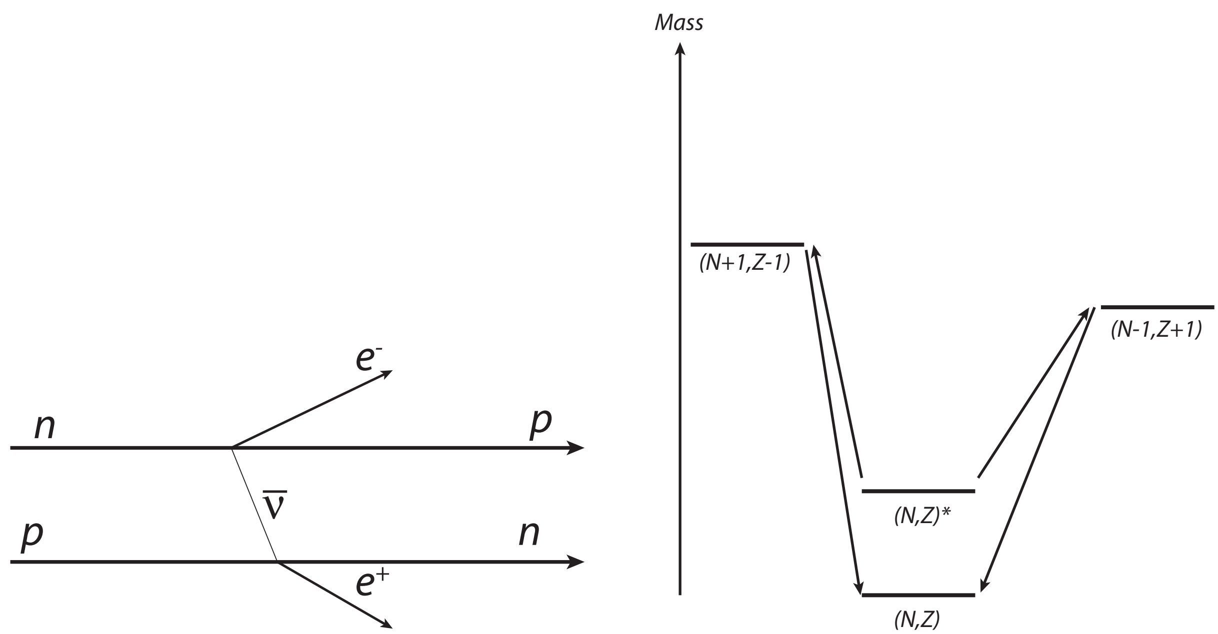

FIG. 2. Left: Feynman diagram for the $0\nu\beta^{\pm}\beta^{\mp}$, Right: nuclear level scheme for $0\nu\beta^{\pm}\beta^{\mp}$ candidate isotopes. The transition may take place either through the $(N+1, Z-1)$ or $(N-1, Z+1)$ nucleus.

$$\lambda \sim \ln 2 G' \left|M'\right|^2 \langle p \rangle^2 ,$$

where $\langle p \rangle \sim 10$ MeV is the typical momentum of the virtual neutrino and $G' \sim 5 \times 10^{-26} \mathrm{y}^{-1}$, computed from the transition energy. We estimate the nuclear matrix element in the following way: most $0\nu\beta^{\pm}\beta^{\pm}$ matrix elements have values of around a few eV^{-2} for $0^+ \to 0^+$ transitions. For $0\nu\beta^{\pm}\beta^{\mp}$ in $^{178\mathrm{m}2}$Hf, the $16^+ \to 0^+$ transition brings a large suppression factor of $(pr/\hbar c)^{16} \sim 10^{-8}$, where r is the nuclear radius. Putting this all together gives a half-life estimate of 10^{25} y. The small neutrino mass suppressed the decay rate in $0\nu\beta^{\pm}\beta^{\pm}$ while the highly forbidden nuclear transition suppresses the decay rate in $0\nu\beta^{\pm}\beta^{\mp}$.

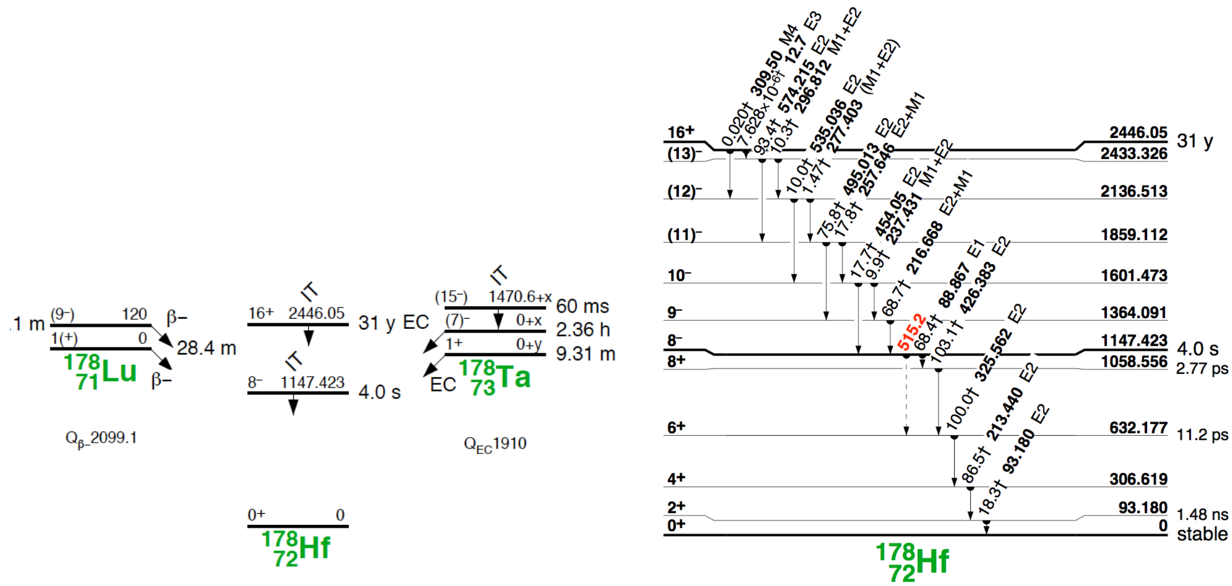

FIG. 3. Left: ^{178}Hf and neighboring isotopes, Right: nuclear level scheme for^{178}Hf.

Measuring the $0\nu\beta^{\pm}\beta^{\mp}$ decay rate would require tens of kilograms of $^{178\mathrm{m}2}$Hf, which could be produce using $^{176}\mathrm{Yb}(\alpha, 2n)^{178\mathrm{m}2}$ Hf, followed by the appropriate chemistry[3]. As hafnium is a metal, a TPC-like detector as was used for the Irvine experiment [4] that first observed $2\nu\beta^{\pm}\beta^{\pm}$ in ^{82}Se would be a good starting point. However, there is really no reason the measure this decay – one learns nothing about the Standard Model or new physics. This process does, however, add to the list [5–7] of notorious aspects of this nuclear level.

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