Neutrino Mass, Neutrinoless Double Electron Capture and Rare Beta Decays

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Abstract. We present results of our theoretical calculations on three nuclei of interest from the neutrino-physics point of view: Firstly, we present the second-forbidden decay branch of $^{115}$In with the ultra-low $Q$ value and theoretical open questions related to such decays. Secondly, we have calculated estimates for the half-lives of the single-beta decay channels of $^{96}$Zr and concluded that the possible contamination from those to the geochemical measurements of $^{96}$Zr double-beta-decay half-life is rather small. Thirdly, we have taken a look at the neutrinoless resonance double-electron-capture decay of $^{112}$Sn in the light of recent JYFLTRAP $Q$ value measurements and discovered that the badly fulfilled resonance condition renders the decay unobservable.

1. The ultra-low-$Q$-value decay of $^{115}$In
The decay of $^{115}$In to the first excited state of $^{115}$Sn was first experimentally discovered and recognized to possibly have the lowest observed beta-decay $Q$ value by Cattadori et al [1]. This discovery raised hopes to use this decay as a sensitive neutrino-mass detector. The same decay was recently studied in more detail as a joint effort of one theoretical and two experimental groups [2]: First, a half-life measurement was conducted at the HADES underground laboratory to confirm the first observation and to reduce the uncertainties in both the partial half-life and the branching ratio. Second, the mass difference of the mother and daughter isotopes was measured in the JYFLTRAP Penning trap to evaluate the $Q$ value previously known to be 2(4) keV. Third, we calculated theoretically the decay half-life using our model (the proton-neutron microscopic quasiparticle-phonon model, pnMQPM) that had previous success [3] in describing the ground-state-to-ground-state decay of the same nucleus.

The JYFLTRAP measurement revealed the $Q$ value to be record-setting low 0.35(17) keV, which is an order of magnitude smaller than 2.469(4) keV, the $Q$ value of $^{187}$Re beta decay [4]. The HADES measurements for the half-life and branching ratio, $4.1(6) \times 10^{20}$ y and $1.07(17) \times 10^{-6}$, were in perfect agreement with the results of Cattadori et al [1], $3.7(10) \times 10^{20}$ y and $1.2(3) \times 10^{-6}$, respectively. From the theoretical point of view this decay is second-forbidden unique, which simplifies the calculation remarkably: The dependence of the decay on nuclear structure is contained in the square of a single nuclear matrix element. However, the difference between the calculated rate and the experimental rate (with one-sigma uncertainties) was roughly two orders of magnitude when using the experimentally derived $Q$ value in the calculations.
Table 1. Theoretical half-lives based on experimental $Q$ values for yet unobserved $^{96}$Zr single-beta decay channels.

| $J_f$       | Forbiddensess       | $Q$ value (keV) | $T_{1/2}$ [a] |
|------------|---------------------|-----------------|---------------|
| $6^+$      | 6th non-unique      | 161             | $4.9 \times 10^{29}$ |
| $5^+$      | 4th unique          | 117             | $2.6 \times 10^{20}$ |
| $4^+$      | 4th non-unique      | 15              | $2.3 \times 10^{23}$ |
| Total      |                     |                 | $2.6 \times 10^{20}$ |

The initial and final state can both be explained as simple one-quasiparticle states, and taking the small three-quasiparticle contributions into account using the pnMQPM has only a small effect on the nuclear matrix element. We find it therefore very unlikely that the discrepancy could be explained solely by inaccuracies in our nuclear matrix element. However, bearing in mind that we have crossed to the previously unexplored $Q$ value regime, we have realized that there are several atomic effects that are usually neglected but possibly have a dramatic consequences for the decays with such ultra-low $Q$ values. These effects are electron screening, atomic overlap effects, exchange effects and final-state interactions.

None of these effects have been estimated for $Q$ values with order of magnitude this low, but it is known that they are generally the more important the lower the $Q$ value is. The electron screening has been only studied for allowed decays [5]. The existing formulas (Rose prescription [6] and the fully relativistic formula by Lopez and Durand [7]) for taking the screening into account break down for ultra-low $Q$ values. The work on exchange effects [8, 9] has yielded contradictory results. The final-state interactions have only been studied in tritium decay [10]. There is hence a vast gap in our theoretical understanding of nuclear beta decay when we move past the traditional low-$Q$-value regime.

2. The beta-decay channels of $^{96}$Zr

The three single-beta-decay channels of $^{96}$Zr are highly forbidden and have low $Q$ values (see Table 1 for details). Due to these two reasons the single beta decays are hindered so strongly that the double beta decay actually has higher transition rate than this first-order weak process. Our first calculation for these single beta decays was published in Ref. [11]. The values of Table 1 have been updated to use more recent experimental data as input parameters. The conclusions remain the same: The total single-beta-decay rate, dominated by the 4th-forbidden unique channel, is much slower than the double beta decay. Therefore the contamination from the single beta decay to geochemical double-beta-decay experiments [12, 13] is well within the experimental uncertainties.

3. The neutrinoless double-EC decay of $^{112}$Sn

The neutrinoless double electron-capture ($0\nu$ECEC) decay with a resonance condition has attracted attention recently [14, 15]. The resonance condition - close degeneracy of the initial and final (excited) atomic states - can enhance the decay rate by a factor as large as $10^6$. Fulfillment of the resonance condition [14] depends on the so-called degeneracy parameter $D = Q - E$, where $E$ is the excitation energy of the final atomic state and $Q$ is the difference between the initial and final atomic masses. Possible candidates for the resonant decays are many [14, 15], among them the decay $^{112}$Sn $\rightarrow$ $^{112}$Cd($0^+$), depicted in Fig. 1. For a long time this $0\nu$ECEC decay of the $^{112}$Sn ground state to the fourth $0^+$ state in $^{112}$Cd was considered to be the flagship of neutrinoless double electron capture.

In [16] the degeneracy parameter was determined by using the JYFLTRAP Penning trap.
Figure 1. The resonance double-electron-capture decay of $^{112}$Sn.

The results $D = -4.5$ keV for KK capture, $D = 18.2$ keV for KL capture and $D = 40.9$ keV for LL capture were derived. This yield for the decay half-life the estimate

$$T_{1/2} > \frac{5.9 \times 10^{29}}{(m_{\nu}[eV])^2} \text{years }.$$  \hspace{1cm} (1)

This result indicates that experimental sensitivities of $T_{1/2} > 10^{30}$ years are required to detect the $^{112}$Sn decay. This is impossible in the foreseeable future.

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