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Ultralow Q values for neutrino mass measurements

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We investigate weak nuclear decays with extremely small kinetic energy release (Q value) and thus extremely good sensitivity to the absolute neutrino mass scale. In particular, we consider decays into excited daughter states, and we show that partial ionization of the parent atom can help to tune Q values to $\ll$1 keV. We discuss several candidate isotopes undergoing $\beta^{\pm}$, bound state β, or electron capture decay and come to the conclusion that a neutrino mass measurement using low-Q decays might only be feasible if no ionization is required and if future improvements in isotope production technology, nuclear mass spectroscopy, and atomic structure calculations are possible. Experiments using ions, however, are extremely challenging because of the large number of ions that must be stored. New precision data on nuclear excitation levels could help to identify further isotopes with low-Q decay modes and possibly less challenging requirements.

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I. INTRODUCTION

One of the big unknowns in astroparticle physics today is the absolute neutrino mass scale m_ν. While indirect probes such as cosmology [1] and neutrinoless double β decay [2] achieve sub-eV sensitivity to m_ν, it is desirable to complement these measurements with model-independent direct bounds. The most advanced efforts in this direction have been the kinematical studies of the β spectrum in tritium decay by the Mainz [3] and Troitsk [4] Collaborations, yielding the limit $m_\nu \lesssim 2$ eV. In the near future, the sensitivity will be improved to $m_\nu \lesssim 0.2$ eV by the KATRIN experiment [5]. However, Mainz, Troitsk, and KATRIN are limited by the accuracy to which the spectrum of decay electrons can be measured a few eV below the kinematical endpoint, where the impact of $m_\nu > 0$ is largest. Since the kinetic energy release (Q value) of tritium decay is 18.6 keV, only a very small fraction of decays falls into that region so that large statistics, very good background suppression, and an excellent energy resolution are required. If KATRIN should not see a positive signal, new experimental techniques would be required to push the sensitivity to even smaller m_ν. For example, it has been proposed to study nuclear recoils in bound-state β decay of tritium [6], to reconstruct the electron and nuclear kinematics in tritium decay [7], or to measure the electron flux near the tritium endpoint in a storage ring [8]. However, all of these proposals are limited by the large Q value of tritium, which makes the neutrino mass a small effect. The decay ^{187}Re → ^{187}Os offers a lower Q value of only 2.657 keV and thus better sensitivity to m_ν, but since it is a unique first forbidden decay, the small decay rate makes it difficult to accumulate sufficient statistics [9].

In this paper, we investigate weak decays with even smaller Q values. In particular, we consider continuum β (cβ), bound state β (bβ), and electron capture (EC) decays. The key ideas are to consider decays to *excited* nuclear daughter states and to use *ions* instead of neutral atoms if necessary. As illustrated in Fig. 1, an appropriate choice of the ionization level allows for some tuning of the Q value since every spectator electron contributes to Q with its energy gain or loss from the change of the nuclear charge during the decay. For bβ decay [10,11], ionization can also have the direct effect of opening up new decay modes. Our aim is to find decays that have sufficiently small Q values to depend appreciably on m_ν, but at the same time still have an absolute rate large enough to allow for a good signal-to-noise ratio.

For bβ and EC decay, the observable sensitive to m_ν is the decay rate, which could be measured by detecting γ and x-ray photons accompanying the decay. In the case of cβ decay, the sensitivity can be increased by guiding the decay electrons into a spectrometer similar to the ones used in Mainz, Troitsk, and KATRIN to also measure the β spectrum near the endpoint. For those decays where ionization is required to achieve sufficiently low Q, we propose to store the parent ions in a trap or in a storage ring. We discuss the feasibility of these ideas in the following.

II. NUCLEAR DECAYS WITH ULTRA-LOW Q VALUES

Nuclear decays with an ultrasmall kinetic energy release $Q \ll 1$ keV can occur only if the daughter nucleus has a state with excitation energy $E^* \geqslant 0$ fulfilling

$$\begin{array}{ll} \beta^-: & Q_0 - (B_{Z+1,Z} - B_{Z,Z}) \lesssim E^* \lesssim Q_0 + B_{Z,1} - B_{Z+1,2}, \\ \beta^+: & Q_0 - 2m_e \lesssim E^* \lesssim Q_0 - 2m_e + B_{Z,Z} - B_{Z-1,Z}, \\ \text{EC:} & Q_0 - B_{Z,1} \lesssim E^* \lesssim Q_0. \end{array}$$

Here, we have neglected contributions from the order eV binding energies of outer shell electrons. Q_0 refers to the atomic mass difference of the parent and daughter nuclei[1] and $B_{Z,n}$ is the modulus of the total electron binding energy in an atom or ion with nuclear charge Z and n orbital electrons.

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[1] Note that, in most reference tables, the atomic mass difference is simply called Q, whereas we reserve that notation for the actual kinetic energy release in a decay, which is the quantity that determines the sensitivity to m_ν.

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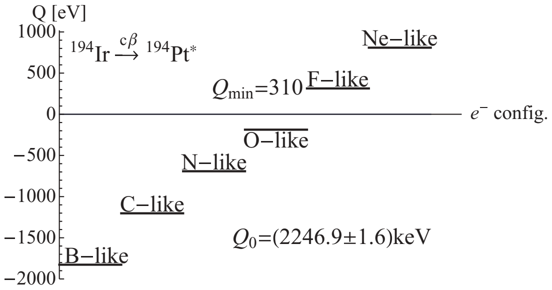

FIG. 1. An example for tuning of a Q value by ionization. Note that energy levels in the decay $^{194}\mathrm{Ir} \rightarrow {}^{194}\mathrm{Pt}^*$ shown here have an uncertainty of $O(1.6\ \mathrm{keV})$, so the figure is to be understood as an illustration of the principal idea only.

In the first equation, $(B_{Z+1,Z} - B_{Z,Z})$ is the energy gain of the spectator electrons in the decay of a neutral atom. By ionization, the effective Q value can be reduced by up to that amount. In bβ decay, ionization can also increase Q by opening up decay modes to low-lying bound states. The maximum possible increase occurs for bβ decay of a hydrogen-like ion into a helium-like daughter state and is consequently of $O(B_{Z,1} - B_{Z+1,2})$. Similarly, for β^+ decay, Q can be increased compared to $(Q_0 - 2m_e)$, the value for neutral atoms, by removing spectator electrons and thus avoiding an energy loss of up to $(B_{Z,Z} - B_{Z-1,Z})$. For EC, Q can be smaller than the atomic mass difference Q_0 by up to the binding energy of the 1s electrons, which is of $O(B_{Z,1})$. Q cannot be made significantly larger than Q_0 for EC.

We list several candidate isotopes for low-Q c$\beta^\pm$, bβ^-, and EC decay in Table I. Since nuclear structure data are still very incomplete for many isotopes, it is quite possible that other suitable decays will be identified in the future. To keep the expected signal-to-background ratio large, we have only considered isotopes for which a low-Q decay is allowed from spin and parity arguments, while other decay modes (if present) are at least first forbidden or otherwise have a very small branching ratio. Note that, for some of our candidate isotopes, decay into the relevant excited daughter state E^* has not been observed yet, so even though it is not forbidden by spin and parity arguments we cannot be sure that it exists. For each decay we have computed Q as a function of the electron configuration. The main uncertainties in this calculation come from the atomic mass differences Q_0, which are typically known to $O(\mathrm{keV})$ [12], and from the binding energies of multielectron configurations. We have estimated these binding energies using (I) the relativistic Hartree-Fock code ATSP2K [13,14] and (II) published atomic physics data and simulation results [15–18] (here we only report the results of method II). The good agreement between the two independent estimates I and II shows that the atomic physics uncertainty in our Q values is $\lesssim$100 eV and thus smaller than the uncertainties in most Q_0 values. An actual neutrino mass measurement would, however, require both Q_0 and the electron binding energies to be known to an accuracy better than $O(m_\nu)$, and we discuss in the following how this could be achieved. Here, we deal with the uncertainties by reporting how small Q can be made if the present best fit values for Q_0 are taken at face value, and by how much Q can change if Q_0 is varied within present uncertainties. In all cases, we assume the degree of ionization and the daughter state E^* to be chosen in the optimum way.

For cβ decay, the most promising isotopes at present are ^{188}W, ^{193}Os, and ^{194}Ir with achievable Q values between 0 and 1.3 keV, depending on the true value of Q_0. A measure for the sensitivity of these low-Q cβ decays to nonzero m_ν is the rate of events with electron energies in a small interval $[Q - \delta E, Q]$ near the spectral endpoint. However, by considering the phase-space factor and the Coulomb correction term (Fermi function) entering in the cβ decay rate, it is easy to show that this number is independent of Q. To zeroth order, and neglecting differences in nuclear matrix elements, this seems to indicate that for achieving the same sensitivity as KATRIN in a low-Q experiment a similar number of stored parent atoms (10^{19}) would be required, which is far beyond the capabilities of present ion traps ($\lesssim 10^6$–10^8) [19,20] and

TABLE I. Candidates for ultralow Q decays. The calculation of Q values is based on data from Refs. [12,15–18].

Decay	$t_{1/2}$	Q_0 (keV)	E^* (keV)	Q (eV)	Comment
Continuum β^- decay					
$^{188}\mathrm{W} \rightarrow {}^{188}\mathrm{Re}$	69.4 d	349 ± 3	346.58	80^{+150}_{-80}	Decay to E^* not yet observed Decay impossible for unfavorable Q_0 daughter spin uncertain
$^{193}\mathrm{Os} \rightarrow {}^{193}\mathrm{Ir}^*$	30.5 h	1140.6 ± 2.4	1, 131.2	50^{+1150}_{-50}	Decay to E^* not yet observed
$^{194}\mathrm{Ir} \rightarrow {}^{194}\mathrm{Pt}^*$	19.15 h	2246.9 ± 1.6	2, 239.8	310^{+200}_{-310}	Decay to E^* not yet observed
Bound state β^- decay					
$^{163}\mathrm{Dy} \rightarrow {}^{163}\mathrm{Ho}$	stable	-2.576 ± 0.016	0	≈1, 500	
Continuum β^+ decay					
$^{189}\mathrm{Pt} \rightarrow {}^{189}\mathrm{Ir}^*$	10.87 h	1971 ± 14	958.6	1880^{+670}_{-1180}	Allowed background modes with %-level Q_0 branching ratio Decay impossible for unfavorable Q_0
Electron capture decay					
$^{159}\mathrm{Dy} \rightarrow {}^{159}\mathrm{Tb}^*$	144.4 d	365.6 ± 1.2	363.51	130^{+1200}_{-130}	Might not require ionization
$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}$	4570 yr	-2.576 ± 0.016	0	≈540	Might not require ionization

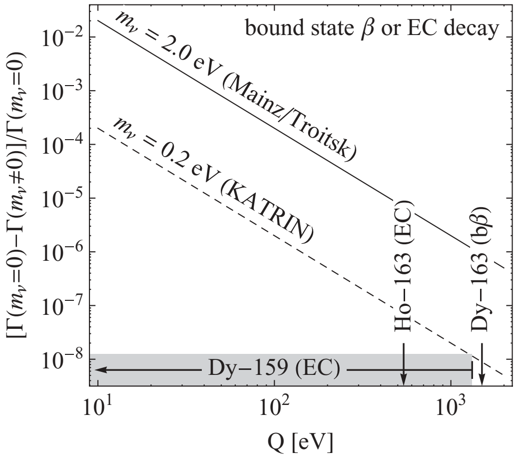

FIG. 2. Relative effect of nonzero m_ν on the decay rate in bβ and EC decay.

storage rings ($\lesssim 10^9$–10^{11}) [21]. However, the larger relative effect of m_ν makes a low-Q cβ decay experiment more robust against many systematic errors. For instance, the required relative spectrometer resolution is smaller than in the tritium case. Moreover, if the time of each decay can be tagged by observing an associated γ or x-ray photon, the spectrometer can be operated in the more sensitive time-of-flight (MAC-E TOF) mode [5]. Finally, it might be possible to combine our ideas with the methods proposed in Refs. [6–8] to measure also the energy and momentum of the recoil nucleus. All these effects should help to reduce the required number of stored ions, even though the experiment will still be extremely challenging.

For bβ decay, ^{163}Dy could provide $Q \sim 1.5$ keV. This isotope has the interesting property of being stable as a neutral atom but becoming unstable to bβ decay when ionized [22]. The most promising isotopes undergoing electron capture are ^{159}Dy and ^{163}Ho, for which M capture with a very low Q value might occur even without ionization, depending on the exact value of Q_0. ^{163}Ho has been studied previously in the context of calorimetric m_ν measurements in Ref. [23]. In Fig. 2, we plot $[\Gamma(m_\nu = 0) - \Gamma(m_\nu \neq 0)]/[\Gamma(m_\nu = 0)]$, the relative effect of nonzero m_ν on the bβ or EC decay rate, as a function of Q. We see that even if $Q \sim 100$ eV is achieved, the effect of $m_\nu = 2$ eV (0.2 eV) is only at the level of 10^{-4} (10^{-6}). Even if all systematic uncertainties could be reduced to that level, detecting a deviation from the $m_\nu = 0$ case would still require the observation of few $\times\, 10^8$ (10^{12}) low-Q decays. To complete the experiment within a few years of measurement time, this would in turn require a very large and continuously replenished sample of about 10^{16} (10^{20}) stored parent particles,[2] implying extreme, and possibly prohibitive, requirements on isotope production and (in the case of ionized parent atoms) storage technology. Part of the problem is the fact that the nuclear matrix elements for the relevant decay mode are small. If they were of $O(1)$, the decay rate would be about 10^4 times larger. Let us emphasize again that decays with larger matrix elements (or even smaller Q values) may exist, but to identify them, more precise data on Q_0 values and on nuclear excitation levels are needed.

III. FEASIBILITY OF A NEUTRINO MASS MEASUREMENT USING LOW-Q DECAYS

To exploit the high m_ν sensitivity of low-Q decays, one has to overcome several severe technological challenges. We consider the most important ones to be (i) producing a sufficient number of parent nuclei, (ii) storing them, (iii) obtaining an accurate prediction for the decay rate (for bβ and EC decays, where no spectral information is available), and (iv) counting the decays. In the following, we discuss some ideas on how these difficulties might be overcome.

(i) *Producing a sufficient number of parent nuclei.* Most of the isotopes listed in Table I are unstable, so they would have to be produced artificially. At future facilities like FAIR at GSI, radioactive beams with at least 10^8–10^{10} ions/s can be produced [24] for nuclei not too far from stability. For isotopes with half-lives of O(days), this is in principle sufficient to sustain a sample of 10^{13}–10^{15} parent particles, but our discussion here shows that a competitive neutrino mass measurement would still require an improvement of several orders of magnitude unless a new, extremely favorable low-Q decay mode is discovered in the future. For an experiment using ionized parent atoms, an additional challenge is to remove ions in other than the desired charge state to avoid decays with larger Q value but identical experimental signature (i.e., identical γ and x-ray fingerprint) as the considered low-Q decay. Owing to the different charge-over-mass ratios of differently charged ions, this should in principle be possible.

(ii) *Storing a sufficient number of parent particles.* Whereas an experiment using neutral atoms (e.g., ^{159}Dy and ^{163}Ho) can use a gaseous, liquid, or solid source, a setup using ions requires a trap or a storage ring. With present technology, it is possible to store a total charge of $10^8 e$ (corresponding to 10^6 heavy ions) in a trap [19,20] and $10^{11} e$ in a storage ring [21]. Traps might be pushed to $10^9 e$ [25] in the future, and the planned FAIR facility at GSI Darmstadt would provide storage rings with a capacity of $10^{12} e$ [24]. As already mentioned, this is still not sufficient to perform a low-Q β or EC decay experiment using ionized parent atoms competitive to KATRIN unless new decay modes with $Q < 1$ eV and a large nuclear matrix element are discovered. This implies that, from the present perspective, decays of neutral atoms look more promising.

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[2] To arrive at this estimate, we have taken the known partial lifetime of the EC decay $^{159}\text{Dy} \rightarrow {}^{159}\text{Tb}^*$ with $E^* = 363.51$ keV [12] and have replaced the phase-space factor and the electron wave function by the expressions appropriate for the low-Q decay.

(iii) *Predicting the decay rate* Γ *for* bβ *or EC decay.* The main unknowns in the computation of Γ are the nuclear matrix element, the nuclear mass difference, and the electron wave functions. To avoid the uncertainty in the matrix element, we propose to study not only the low-Q decay but also a large-Q (i.e. high rate, but small m_ν dependence) decay into the same nuclear final state to measure the nuclear matrix element. The mass difference W_0 between the parent and daughter nuclei can be measured using ion trap mass spectrometry. This technique currently provides an impressive relative accuracy of $O(10^{-11})$ [26,27], but for our purposes, this would still have to be increased by more than one order of magnitude to make the uncertainty in W_0 smaller than the effect of the neutrino mass. The electron wave functions entering in Γ cannot be measured directly and have to be predicted by solving the multiparticle Dirac equation. The uncertainties of these predictions must be smaller than the expected effect of m_ν, but considering that many atomic x-ray spectra can be predicted to an accuracy below one per mille [28], this could be feasible. To minimize the theoretical errors, one could "calibrate" the numerical computation using experimental x-ray spectra, ionization energies, and other atomic physics data for the considered isotope.

(iv) *Counting the number of decays.* For bβ and EC decay, the only observable sensitive to m_ν is the decay rate into the low-Q channel. To measure it, and to reject concurrent large-Q decay modes, we propose to detect characteristic γ or x-ray photons accompanying the decay. The main requirements for the photon detector are good solid angle coverage, high energy resolution, and efficient suppression of backgrounds from cosmic ray interaction products and radioactive impurities. To date, the best γ detectors—employing extremely radiopure materials, active and passive shielding, and several meters of rock overburden—achieve background rates $\lesssim 10^3$ keV^{-1} yr^{-1} and an energy resolution around 1 keV [29]. If the considered low-Q decay is accompanied by several photons, much better background suppression will be possible if the coincidence technique is used. Therefore, we estimate that backgrounds can be brought under control.

IV. CONCLUSIONS

In this paper, we have discussed how continuum β, bound state β, and electron capture decays with extremely small Q values ($\ll$1 keV) can be realized and how they could be used to measure the absolute neutrino mass m_ν. To achieve sufficiently low Q values (i.e., sufficiently high sensitivity to m_ν), we have proposed to consider decays into excited nuclear daughter states and, if necessary, to partially ionize the atoms to tune the electronic contribution to Q. We have discussed the technological challenges that would have to be overcome in such an experiment, including production and storage of a large number of radioactive atoms or ions, obtaining accurate predictions for the decay rate as a function of m_ν, and counting the number of decays. We have found that the most promising decays to date are $^{159}\text{Dy} \to {}^{159}\text{Tb}^*$ and $^{163}\text{Ho} \to {}^{163}\text{Dy}$ because, depending on the exact values of the respective atomic mass differences Q_0, they may have low-Q EC decay modes even when neutral. Experiments using ions are much more challenging owing to the large number of particles that must be stored. As a next step, it is crucial to measure precisely Q_0 for the isotopes listed in Table I to determine how small Q can be made for them. Also, more precise data on nuclear excitation spectra throughout the chart of nuclides are desirable to identify further candidates for low-Q decays.

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