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Search for β-transitions with the lowest decay energy for a determination of the neutrino mass

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Abstract

From a variety of β-transitions only those with decay energies of a few keV and smaller are considered suitable for a determination of the neutrino mass on a sub-eV level. The decay energy of a transition can be very small, if, e.g., in an allowed β-decay or electron-capture transition, a nuclear excited state of the daughter nuclide is populated whose energy is very close to the mass difference of the transition nuclides. Investigation of these transitions can also be useful for the assessment of a validity of the current β-decay theory in the region of vanishingly small decay energies.

The authors of this proposal have found several such β-transitions whose decay energies are expected to be extremely small. In order to assess the suitability of these β-transitions for the determination of the neutrino mass, measurements of the mass differences of the transition nuclides must be carried out with a sub-keV uncertainty. Presently, only high-precision Penning-trap mass spectrometry is capable of achieving this goal, and ISOLTRAP is superior to other installations with respect to the production and investigation of the proposed

candidates. For this proposal we have chosen four relevant allowed electron-capture transitions whose decay energies to excited states can be in a sub-keV region.

Physics Motivation

The interest in the lowest β-decay and electron-capture energies has steeply risen over the last years [Eliseev-AdP] due to a rapid development of Penning-trap mass spectrometry (PTMS) [Eliseev-HI] and cryogenic microcalorimetry (MMC) [Gastaldo]. From a variety of neutrino physics problems, the determination of the absolute neutrino mass is of paramount importance.

The neutrino mass can be determined from the analysis of β-transitions. The smaller the decay energies of these transitions are, the higher the sensitivity to the neutrino rest mass is.

In present experiments on the neutrino mass determination three β-transitions are employed: β^--decays of ^{3}H and ^{187}Re, and electron capture in ^{163}Ho. Recently it has been announced that the β^--decay of ^{115}In to the nuclear excited state in ^{115}Sn with an excitation energy of 497 keV and branching ratio of 10^{-4} % [Cattadori] has the smallest decay energy Q_β=0.155±0.010 keV [Mount].

Meanwhile, a question arises whether there are also other relevant β-transitions for the neutrino mass determination suitable for both PTMS and MMC-methods. A few years ago the proposal was presented to the INTC/CERN for a check of pairs ^{194}Hg → ^{194}Au and ^{202}Pb → ^{202}Tl. The proposal was accepted (IS473), and the mass difference of the first pair was determined. The obtained value of Q_{EC}=29 ± 4 keV [Eliseev-PL] substantially deviates from 69 ± 14 keV given by the AME-2003 and opens a way towards a determination of the neutrino mass at a level of a few eV by a combination of MMC and PTMS.

A thorough analysis of the existing nuclear physics data performed by the authors demonstrates that there are many β-transitions for which mass differences of the transition partners are close to the values for the excited states of the daughter nuclides (including the electron-binding energies in the case of capture) and thus the expected Q-values to these excited states (Q_{ge}-values) should be very small. However, the values are masked by a very large uncertainty in the values of the mass differences between the ground states. In opposite, the energy of the nuclear excited states is usually known with a good precision. Thus, the ground-to-ground state mass differences of the selected β-transitions should be precisely measured in order to obtain definite information on the decay energy to the excited states. Presently, only Penning-trap mass spectrometry is superior in accuracy to all other existing methods.

In our analysis we have chosen only those cases where atomic mass differences are smaller than 1 MeV. Table 1 summarizes appropriate β-transitions. We have collected only those nuclides which can be produced at the ISOLDE-facility (see also Table 2) [ISOLDE]. From columns 10 and 11 of Table 1 it can be seen that the absolute values of the transition energies are typically smaller than their uncertainties.

The most promising β-transitions to nuclear excited states are allowed electron-capture transitions in nuclides ^{131}Cs, ^{134}Ce, ^{159}Dy, and ^{175}Hf. Actually, the branching ratios for β-transitions in ^{134}Ce and ^{159}Dy are known and equal to 2×10^{-3} and 2×10^{-4}, respectively. The electron-capture-transition energies are Q_K = -8.4 ± 29 keV (for K-capture) and Q_{M1}= -0.12 ± 1.2 keV (for M_1-capture) , respectively.

Note that the small transition energies, besides the interest in the neutrino mass determination, may be useful for the investigation of peculiarities in β-decay processes with very small energies which are under influence of atomic screening, electron exchange and overlapping effects, etc. [Bambynek].

Experimental method.

The ISOLTRAP experiment makes use of three ion traps for the preparation, purification, and mass determination of radioactive ions delivered by ISOLDE [Kluge-2013]. The 60-keV ISOLDE continuous ion beam is first stopped, cooled, and bunched in a linear radio-frequency quadrupole (RFQ). The multi-reflection time-of-flight mass spectrometer (MR-ToF MS) installed recently after the linear radio-frequency ion trap significantly improves ISOLTRAP's capability of purification of contaminated ion beams [Wolf]. The ion bunch is then transferred to the first, cylindrically shaped Penning trap for the additional removal of isobaric contaminants that are still present. The isobarically cleaned ion bunch is finally injected into the hyperbolic precision Penning trap, where possible isomeric ions can be removed by application of a resonant dipolar radiofrequency excitation.

As can be seen in Table 1, the required mass measurements need to be performed with an accuracy of at least one keV. The mass determination principle is based on the very precise measurement of the cyclotron frequency $\nu_c=qB/(2\pi m)$ of ions with mass m and charge q that are stored in a strong and homogeneous magnetic field B [Blaum-2006]. The conventional technique for the measurement of the free cyclotron frequency is the Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR) method [Gräff-1980]. For measurements with a ppb-uncertainty the novel Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique [Eliseev-2013] has to be used.

The magnetic field strength is determined by measuring the cyclotron frequency of a reference ion with well-known mass. The mass of the ion of interest is finally deduced from the ratio of the two cyclotron frequencies.

The mass difference between the ground states (Q-value) can be obtained by sequential ν_c measurements of the transition nuclides. Then

$$Q = M(A_m) - M(A_d) = (M(A_d) - m_e)\cdot\left(\frac{\nu_c(A_d^+)}{\nu_c(A_m^+)} - 1\right),$$

where $M(A_m)$ and $M(A_d)$ are the masses of the mother and daughter atoms, respectively, m_e is the electron mass, $\nu_c(A_m^+)$ and $\nu_c(A_d^+)$ are the cyclotron frequencies of the mother and daughter singly charged ions, respectively. The binding energies of the valence electrons have been neglected.

For the four pairs of nuclides that are of interest in this proposal further detailed information on the production yield is given below. A big advantage of proposed measurements is that the mass differences for selected pair of nuclides, being produced with the same target and ion source, can be determined by a simultaneous measurement of the cyclotron frequencies of both nuclides thus reducing systematic uncertainties.

Nuclear pairs proposed for measurements

In this proposal we intend to measure the ground-to-ground state atomic mass differences for four pairs whose mother nuclides undergo allowed electron capture to nuclear excited states: ^{131}Cs→^{131}Xe*(364.49 keV), ^{134}Ce→^{134}La*(355.479 keV), ^{159}Dy→^{159}Tb*(363.545 keV) and ^{175}Hf→^{175}Lu*(672.83 keV). The other nuclides listed in Table 1 have different degrees of forbiddenness in their β-decay or electron capture. It is planned to address them at a later stage. The allowed character of the β-transformation provides a higher probability for the transition to the excited state with very small decay energy to be identified in the spectra. Actually, for two of the chosen four cases, EC in ^{134}Cs and ^{159}Dy, the branching ratios to the excited states of

interest are known. Thus, for them the partial transition probabilities can be determined and compared to those that can be deduced from the theoretical values attributed to the measured decay energies. This comparison will assess whether there are any peculiarities in the β/EC-decay processes with very low decay energies.

^{131}Cs → ^{131}Xe (stable):

The production mechanisms of Cs and Xe ions are different. Cs ions are easily produced with a surface-ionization ion source. Since ^{131}Xe is stable, it can most conveniently be ionized with an off-line electron-impact ion source [Nesterenko]. Thus, an electron-impact ion source for a production of singly charged Xe ions must be available and tested at ISOLTRAP prior to the measurement.

The ISOLDE database gives for the production of ^{131}Cs the values of $5x10^{10}$ and $3.4x10^{9}$ ions/ μC from the La and ThC_x targets, respectively, which are by far sufficient for mass measurements with PTMS. The decay energy to the 364.49 ± 0.04 keV excited state of ^{131}Xe is equal to Q_L = -15 ± 5 keV and Q_M = -9 ± 5 keV (see Table 1). A large uncertainty of the decay energy value is caused by the similar uncertainty in the knowledge of the atomic mass difference between the ground states. Since it is sufficient to reach an uncertainty of about 1 keV, the conventional (Ramsey) ToF-ICR technique can be used. **Six 8-hour shifts are estimated to be needed to reach 1 keV-uncertainty**.

^{134}Ce → ^{134}La (6.67 min):

For a production of Ce and La ions a Ta target with a surface ionization ion source can be used. The yield of ^{134}Ce has not been determined at ISOLDE yet. Only one isotope measured so far is ^{133m}Ce whose yield from the Ta-target is equal to 10^6 ions/μC. Also the yield for ^{134}La is not known. The heaviest lanthanum isotope is ^{129}La with a yield of $7x10^6$ ions/ μC from the Ta target. However, the next isobaric nuclide ^{134}Ba has a yield of about 10^9 ions/ μC. All this information allows one to expect that the yield of ^{134}La could be sufficient for our measurements.

The decay energy of K-capture to the excited state of ^{134}La at 355.479 ± 0.012 keV is known to be equal to Q_K = -8.4 ± 29 keV (see Table 1), where the uncertainty is caused by a poor knowledge of the ground-to-ground states mass differences. To reach a required uncertainty of approximately one keV **we request the six 8-hour shifts**. Here, the conventional (Ramsey) ToF-ICR technique can be used.

^{159}Dy → ^{159}Tb (stable):

Similar to the previous pair, Dy and Tb ions can be produced with a tantalum target and surface ionization ion source. Since ^{159}Tb is stable, its ions can alternatively be produced off-line by laser ablation of the natural terbium. In order to realize this option, a laser-ablation ion source for a production of singly charged Tb ions is available at ISOLTRAP and will be tested prior to the measurement.

The production yield for ^{159}Dy has not been determined at ISOLDE. The heaviest nuclide measured from a Ta-target is ^{158}Dy with a yield of $2.5x10^9$ ions/ μC. Taking into account a very smooth change of yields in all preceding dysprosium isotopes we can expect a yield of about 10^8 ions/ μC for ^{159}Dy, being also sufficient for precise mass measurements with PTMS. The yield for ^{159}Tb is expected on the level of 10^7 ions/ μC with the same target and surface ion source. The decay energy of M_1-capture in ^{159}Dy to the excited state of 363.545 ± 0.002 keV in ^{159}Tb is known to be equal to Q_{M1}= -0.12 ± 1.2 keV. Here, it is necessary to reach an

uncertainty of a few hundred eV, which requires an implementation of the novel Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique. With the PI-ICR method, it should be feasible to reach an uncertainty of a few hundred eV **within twelve 8-hour measurement shifts**.

^{175}Hf → ^{175}Lu (stable):

Hf and Lu ions can be produced with a tantalum target and hot plasma ion source. Due to its refractive character, to extract Hf a CF_4 leak must be used [Koester07]. HfF_4 molecules are then dissociated in the plasma ion source, Hf^+ ions representing a tenth of the total yield [Koester14]. Alternatively, one can extract the HfF_3^+ sideband from the ion source and dissociate it in the buffer gas environment of the ISCOOL or ISOLTRAP RFQ buncher. Although providing lower yield than the direct Hf production, this method might provide excellent purity for the ^{175}Hf beam. Since ^{175}Lu is stable, its ions can alternatively be produced off-line by laser ablation of the natural Lu. In order to realize this option, a laser-ablation ion source for a production of singly charged Lu ions is available at ISOLTRAP and will be tested prior to the measurement.

The ISOLDE database gives for ^{173}Hf and ^{177m}Hf the yields of 2.8×10^8 and 6.1×10^4 ions/μC from the Ta-target, respectively. Therefore, we can expect a yield of 10^6 ions/μC for ^{175}Hf , which is enough for measurements with ISOLTRAP.

The L_1-capture energy in ^{175}Hf to the excited state of ^{175}Lu with the energy of 672.83 ± 0.15 keV is equal to $Q_{L1} = 0 \pm 2$ keV. Here, it is necessary to reach an uncertainty of a few hundred eV, which requires an implementation of the novel Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique. With the PI-ICR method, it should be feasible to reach an uncertainty of a few hundred eV within **twelve 8-hour measurement shifts**.

Beam time request

To realize the goal of the proposal we ask in total for **36 8-hour shifts**.

The following preparatory work must be done in order to perform the experiment in an optimal way:

(1) Electron-impact (EI) and laser-ablation (LA) ion sources must be provided. The LA ion source is available at ISOLTRAP. A production of ^{159}Tb and ^{175}Lu ions with the LA ion source will be tested prior to the experiment. Since the cyclotron-frequency measurements have to be performed alternately on the mother and daughter isotopes throughout the entire duration of the corresponding beam time (the mother/daughter measurements cannot be separated in two different runs), the method of producing the terbium/lutetium beams does not influence the requested number of shifts.

(2) For two of chosen four β-transitions it is highly desirable to use the PI-ICR technique. It still must be implemented and tested at ISOLTRAP.

A summary on the proposed target/ion-source combinations and requested beam time are given in Table 2.

Table 1. The most promising β-transitions to nuclear excited states whose nuclides can be produced at ISOLDE. The β-decay emitters are labeled by β. The other nuclides decay by orbital electron capture. The ground-to-ground state decay energy values Q_{gg} with their uncertainties δQ_{gg}, taken from [AME-2012], are given in columns 3 and 4, respectively. The decay energies from the ground to excited states Q_{ge} corresponding to the indicated capture orbits (column 12) are shown in column 10. Their uncertainties δQ_{ge} in keV are given in column 11. The nuclides with the typical error bar of more than 1 keV are only given. The data for the excited states of daughter nuclides (columns 6, 7 and 9) are taken from [NDS]. Only the possible β-transitions with spin changes not more than ΔI=2 are shown. The transition pairs proposed for measurement in this proposal **are marked bold red**.

Moth. Nucl.	$T_{1/2}$	Q_{gg} (keV)	δQ_{gg} (keV)	Daug. Nucl.	E* (keV)	δE*	I_m	I_d	Q_{ge} (keV)	δQ_{ge} (keV)	De-cay
^{130}Cs	29 m	362	9	^{130}Ba	357.38	0.08	1+	2+	4.6	9	β^-
^{131}Cs	9.7 d	355	5	**^{131}Xe**	364.49	0.004	5/2+	5/2+	-15 -9	5 5	L, M
^{134}Ce	3.2 d	386	29	**^{134}La**	355.479	0.012	0+	1+	-8.4	29	K
^{140}Nd	3.4 d	437	27	^{140}Pr	419.9	0.3	0+	(2,3)	10.3 15.6	27 27	L, M
^{146}Pm	5.6 y	1472	4	^{146}Nd	1470.6	0.1	3-	2+	1.4	4	β^+
^{149}Gd	9.3 d	1314	4	^{149}Eu	1312	4	7/2-	5/2+	2	6	β^+
^{155}Eu	4.7 y	252.1	0.9	^{155}Gd	251.706	0.001	5/2+	9/2-	0.39	0.9	β^-
^{159}Dy	144 d	365.4	1.2	**^{159}Tb**	363.545	0.002	3/2-	5/2-	-0.12	1.2	M_1
^{161}Ho	2.5 h	858	2.2	^{161}Dy	858.792 804.388	0.002 0.003	7/2-	3/2- 3/2-	-2,8 -0.2	2.2 2.2	M K
^{171}Tm	1.2 y	96.6	1.0	^{171}Yb	95.282	0.002	½+	7/2+	1.32	1	β^-
^{175}Hf	70 d	683.7	2.0	**^{175}Lu**	672.83 626.53	0.15 0.15	5/2-	7/2- 1/2+	0 -6.1	2 2	L_1 K
^{201}Tl	3.04 d	484	14	^{201}Hg	464.41 384.602	0.03 0.018	½+	(5/2) (5/2)	4.8 16.3	14 14	L_1 K

Table 2. Expected yields from the ISOLDE targets [ISOLDE], [TS] for the nuclides planned for measurements with ISOLTRAP and requested beam time. SI and HP stand for the surface-ionization and hot-plasma ion sources, respectively. ^{159}Tb and ^{175}Lu are stable and can also be produced off-line, but have to be measured during the radioactive beam time.

Data/Nucl.	^{131}Cs	^{131}Xe	^{134}Ce	^{134}La	^{159}Dy	^{159}Tb	^{175}Hf	^{175}Lu
Yield (SC) ($\mu A^{-1}s^{-1}$)	10^9- $5x10^{10}$	off-line	~10^9	~10^9	10^8	10^7	>10^{7*}	plenty
Target (ISOLDE)	La/UC_x	off-line	Ta					
Ionization	SI	off-line	HP/SI	SI			HP	
No of shifts	6		6		12		12	

* the yield is given for production with a CF_4 leak, considering the yields measured in [Koester07] and a 10% dissociation efficiency of HfF_4 into Hf^+.

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