EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Search for β-transitions with the lowest decay energy for a determination of the neutrino mass: Precision Q-value measurements of ^{159}Dy and ^{175}Hf during the CERN Long Shutdown 2

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Summary of requested shifts: 24

Abstract:

In this letter we propose to perform the high-precision determination of the Q-values of two electron-capture pairs of potential interest for determining the electron-neutrino mass. The two pairs are part of the requested beams of the proposal INTC-P-410 [1]. The large half-lives and good surface-ionization properties of these nuclides make them excellent candidates to be released from pre-irradiated tantalum targets. They are also perfect cases for using the new Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) technique, which is currently being applied for high-precision measurements at ISOLTRAP.

1 Physics case

The determination of the absolute neutrino mass is of paramount importance for a variety of questions in elementary particle physics. The current best upper limit on the electron neutrino mass has been set by microcalorimetry (MMC) experiments [2], from the study of the endpoint of the β-energy spectrum. Transitions of interest for this type of study have low decay energies, which increase the sensitivity of the endpoint of the energy spectrum to the neutrino mass. While efforts are ongoing to perfect MMC experiments with the existing best candidates, an active search is ongoing for alternative electron-capture pairs, which would allow obtaining the same neutrino-mass sensitivity with less statistics. For example, recently it has been found 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} [3] has the currently smallest decay energy $Q_\beta = 0.155 \pm 0.010$ keV [4]. The search for new possible candidates has been fueled by the rapid development of Penning-trap mass spectrometry [5].

Table 1: The most promising β-transitions to nuclear excited states whose nuclides can be produced at ISOLDE. The column of the mother nuclides is followed by that of their half lives $T_{1/2}$, ground-to-ground state e energies Q_{gg} and their uncertainties δQ_{gg}, their daughter nuclides, the excitation energies E^* and their uncertainties δE^*, the spin states of the mother and daughter nuclides I_m and I_d respectively, the ground-to-excited state decay energies Q_{ge} and their uncertainties δQ_{ge} and their decay modes. Only nuclides with mass uncertainties of > 1 $\frac{\text{keV}}{c^2}$ are listed. The data for the excited states of daughter nuclides (column 6, 7, and 9) are taken from [6]. Only the possible β-transitions with spin changes not more than $\Delta I = 2$ are shown. The transition pairs proposed for measurement in this letter of interest are marked in red.

Mother nucl.	$T_{1/2}$	Q_{gg} / keV	δQ_{gg} / keV	Daug. nucl.	E^* / keV	δE^* / keV	I_m	I_d	Q_{ge} / keV	δQ_{ge} / keV	Decay
^{146}Pm	5.6 y	1471.6	4.5	^{146}Nd	1470.6	0.1	3-	2+	1.3	4.5	β^+
^{155}Eu	4.7 y	251.8	1.8	^{155}Gd	251.706	0.001	5/2+	9/2-	0.09	1.8	β^-
^{159}Dy	144 d	365.3	2.0	^{159}Tb	363.545	0.001	3/2-	5/2-	-0.21	2.0	EC_{M1}
^{171}Tm	1.2 y	96.5	1.0	^{171}Yb	95.282	0.002	1/2+	7/2+	1.23	1.0	β^-
^{175}Hf	70 d	683.9	2.6	^{175}Lu	672.83 626.53	0.15 0.15	5/2-	7/2- 1/2+	0.20 -5.94	2.6	EC_{L1} EC_K

In the INTC proposal P-410 several candidates were proposed for the neutrino mass determination via beta-decay which can be produced with a tantalum target at ISOLDE. A thorough analysis of the existing nuclear physics data performed by the authors demonstrates that there are many β-transitions for which the 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, these values are masked by a very large uncertainty in the mass differences between the ground states. In contrast, 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. Penning-trap mass spectrometry is superior in accuracy to all other existing methods. Considering the possibility of performing these measurements with a pre-irradiated target, we have chosen only those cases where the atomic mass difference is smaller than 1 MeV and $T_{1/2} > 1$ month. Table 1 summarizes the resulting β-transition pairs which can be easily produced at the ISOLDE facility with a tantalum target. From columns 10 and 11 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 the nuclides ^{159}Dy→^{159}Tb* (363.545 keV) and ^{175}Hf→^{175}Lu* (626.53 keV). The branching ratio for β-transition in ^{159}Dy is known and equal to $2 \cdot 10^{-4}$. The other nuclides listed in Tab.1 have different degrees of forbiddenness in their β-decay or electron capture. The allowed character of the β-decay provides a higher probability for the transition to the excited state with very small decay energy to be identified in the spectra. The electron-capture-transition energies are $Q_K = -5.9 \pm 2.6$ keV for K-capture of ^{175}Hf and $Q_{M1} = -0.21 \pm 2.0$ keV for M_1-capture of ^{159}Dy. 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. [14].

2 Experimental method

The ISOLTRAP experiment consists of four ion traps for preparation, purification, and mass determination of radioactive ions delivered by ISOLDE [8]. The continuous 50 keV ion beam provided by ISOLDE is first stopped, cooled, and bunched in a linear Radio-Frequency Quadrupole (RFQ). The ion trap Multi-Reflection Time-of-Flight Mass Spectrometer (MR-ToF MS) installed behind the RFQ significantly improves ISOLTRAP's capability of purification of contaminated ion beams [9]. The ion bunch is then transferred to a first, cylindrical Penning trap for the additional removal of isobaric contaminants that are still present. The isobarically cleaned ion bunch is finally injected into a hyperbolic precision Penning trap, where possible isomeric ions can be removed by application of a resonant dipolar radio-frequency excitation.

As can be seen in Tab.1, the required mass measurements need to be performed with an accuracy much higher than one keV. The mass determination principle is based on the very precise measurement of the cyclotron frequency $\nu_c = \frac{qB}{2\pi m}$ of ions with mass m and charge q that are stored in a strong and homogeneous magnetic field B [10]. The conventional technique for measurements of the free cyclotron frequency is the Time-of-Flight Ion-Cyclotron-Resonance (ToF-ICR) method [11]. For measurements with a ppb uncertainty the novel PI-ICR technique [12] has to be used, which was installed at ISOLTRAP in 2016. This technique utilizes a position-sensitive detector to image the ions' motion in the trap and can achieve two orders of magnitude higher resolving power and one order of magnitude higher precision compared to the ToF-ICR technique. The mass difference between the ground states (Q-value) can be obtained by ν_c measurements of both transition nuclides. Then

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

where $M(A_m)$ and $M(A_d)$ are the masses of the mother and daughter atoms, respectively, m_e is the electron mass, $\nu_c(A^+_{d,m})$ are the cyclotron frequencies of the mother and daughter singly charged ions, respectively. The binding energies of the valence electrons have been neglected. A big advantage of the proposed measurements is that the selected pairs of nuclides can be produced with the same target and ion source, thus highly reducing systematic uncertainties.

Following the original proposal INTC-P-410, the INTC endorsed the program in its entirety, but only approved the case not immediately requiring the PI-ICR technique, which was still not implemented at ISOLTRAP at the time when the proposal was made: [13]"The INTC considers the physics case very appealing and encourages the authors to pursue this activity. The ISOLTRAP collaboration has the necessary expertise to perform such experiments adequately. However, there are some issues to be considered. First of all, the experiment requires several (complicated) beams not yet available at ISOLDE. In addition, the authors want to apply the new PI-ICR technique at least for the "hard" cases. However, this technique has not yet been implemented at ISOLTRAP and a clear time line for the installation was not presented. The INTC encourages the collaboration to give priority to the implementation of the PI-ICR technique prior to performing these experiments since all measurements would profit from it. Nonetheless, the INTC recommend 6 shifts of online beam time for the ^{131}Cs case, which is already feasible using the conventional technique, and 6 online shifts for the development of the PI-ICR method. The INTC recommends the necessary beam development for the remaining cases."
Since 2014 the ISOLTRAP team has performed the necessary steps for implementing the PI-ICR technique. Following a series of on-line tests in 2016 showing the high-resolving power of the technique, we could perform during ISOLTRAP's last online run in May 2017 a wide range of systematic high-precision PI-ICR measurements on the well-known Q-value pair ^{88}Rb→^{88}Sr (160 eV uncertainty [17]). The entirety of the performed measurements are presented in Fig. 1. The uncertainty of the final weighted average of the Q-value is as low as 120 eV. A representative detector image is shown in Fig. 2, containing two ion spots - one corresponding to ions ejected from the center of the trap and the other to ions moving at the reduced cyclotron frequency. For more details on the phase-imaging principle see [12]. As a result of one day of online beam time the achieved statistical uncertainty was improved compared to the AME value (see Tab. 2) and will be published soon.

Table 2: Q-value comparison between AME16 [17] and ISOLTRAP (IS490). The uncertainty derives from the Q-value calculation (see Eq. 1).

Tab.2	**^{88}Rb-^{88}Sr-Q-value / keV**	**unc. / keV**
AME2016	5312.62	0.16
ISOLTRAP 2017	5312.55	0.12

Table 3: Expected yields from the ISOLDE targets [15], [16] for the nuclides planned to be measured with ISOLTRAP and requested amount of beam time. SI and HP stands for surface-ionization and hot-plasma ion sources, respectively. ^{159}Tb and ^{175}Lu are stable but have to be measured during the beam time.

Data/Nucl.	**^{159}Dy**	**^{159}Tb**	**^{175}Hf**	**^{175}Lu**
Yield (SC) / μA^{-1}s^{-1}	~ 10^8	~ 10^7	> 10^{7*}	plenty
Target (ISOLDE)	Ta			
Ionization	SI		HP	
# shifts	12		12	

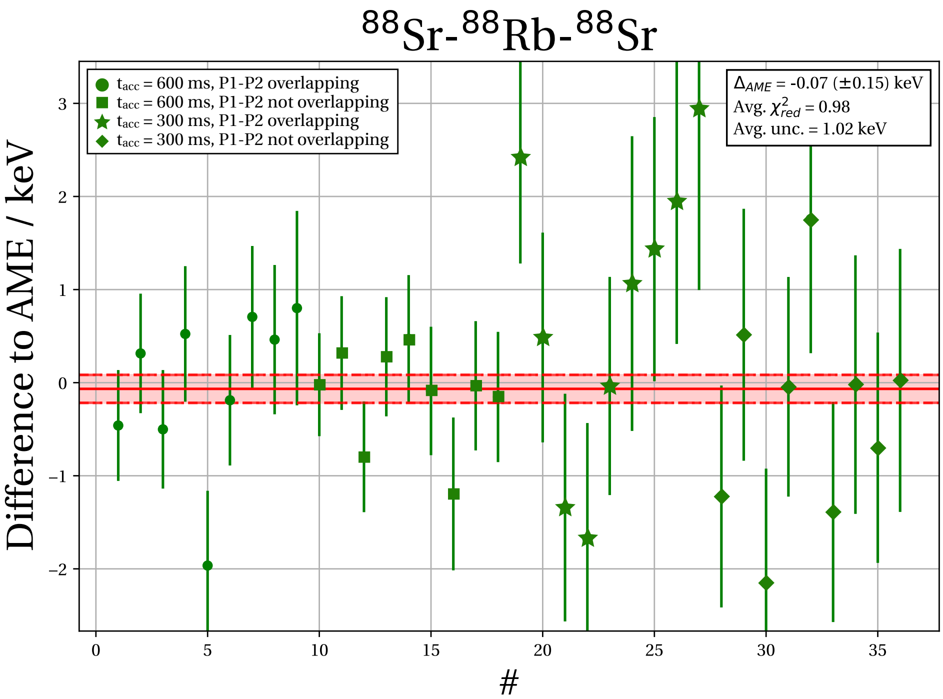

Figure 1: Difference between the determined mass of ^{88}Rb and the corresponding AME16 value [17], shown for four different PI-ICR measurements (9 data points each) taken during May 2017. Each data point corresponds to approximately 5000 ions. The accumulation time for the first two measurements was 600 ms and for the last two 300 ms. In the first and third measurement the P1 and P2 spots were overlapping and in the second and fourth it was not the case. The difference to the AME16 value of the average ISOLTRAP mass value is given with its uncertainty (this is not the uncertainty on the Q-value) as well as the χ^2_{red} and the average uncertainty of the single measurements.

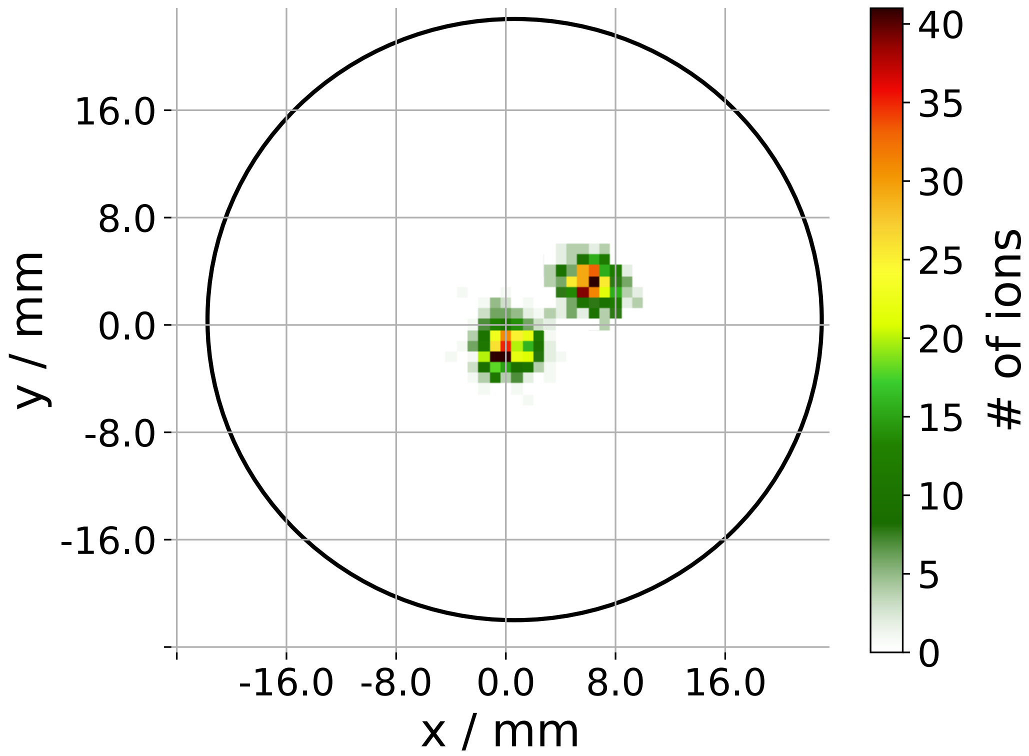

Figure 2: Two ion spots on the position-sensitive detector for ^{88}Rb (data taken during online run in May 2017). The right spot represents the final phase of the ion motion at the reduced cyclotron frequency after 600 ms evolution time. The left spot marks the symmetry center of the circular motion in the trap.

3 Beam requirements

The achievable statistical precision is a function of the mass (cyclotron frequency) of the measured pair. Having almost twice the mass of the $A = 88$ doublet, the experiment requires four time more shifts to achieve the same ~100 eV precision on the Q-value of one pair. Adding to this the necessity to confirm the results against systematic variations of the measurement parameters (double the measurement time), and the requirement of optimizing the PI-ICR technique with the pair of interest, the measurement of each Q-value can be performed with 12 shifts.

Summary of requested shifts: 24.

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