EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Proposal for the ISOLDE and Neutron Time-of-Flight Committee

Q_{EC} value determination of the superallowed β-decay of ^{70}Br

submission date: 31 May 2017

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CERN-INTC-2017-047 / INTC-P-514
31/05/2017

Abstract

This proposal is aimed at performing a new measurement of the Q_{EC} of the superallowed beta decay transition of ^{70}Br. Recent results from an experiment conducted at RIKEN has provided a new half-life value and an estimate of the superallowed branch. This allowed to deduce the corrected *Ft* value for this decay and to compare it with the world average corrected *Ft* value. For the calculation of the new corrected *Ft* value for the ^{70}Br decay there were two different Q_{EC} values available in the literature, which lead to a large discrepancy between the two estimates. This situation calls for a new high-precision measurement of the Q_{EC} of this important decay, which we propose to perform with the ISOLTRAP setup at ISOLDE. The new experimental Q_{EC} value, which will have to have a better relative precision than 10^{-4}, will pave the way for the inclusion of the ^{70}Br decay in the calculation of the world average *Ft* value.

Requested shifts: 12

1. General motivation

There are several links between modern nuclear physics and particle physics apart from the historical ones, but probably one of the most relevant connections is the possibility of testing the Conserved Vector Current (CVC) hypothesis and determining in the most precise way the V_{ud} matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix from nuclear transitions.

A basic concept of the electroweak standard model is the unitarity of the CKM matrix, which connects the quark weak-interaction eigenstates with the quark mass eigenstates [1]. Superallowed transitions between $J^\pi = 0^+$, $T = 1$ analog states have provided until now the most precise value for the largest matrix element, the up-down term V_{ud}. The V_{ud} matrix element can be extracted from the ratio between G_V, the vector-coupling constant for a semileptonic decay and G_F, the weak-interaction constant for a pure leptonic decay. The CVC hypothesis assumes that G_V is a universal constant independent of the nuclear medium. This implies that the strength or *ft* value of the superallowed Fermi transitions, which are only mediated by the vector current, is the same for all such transitions connecting states with identical isospin. As a consequence, a mean *ft* value from superallowed Fermi transitions can be used to determine G_V and subsequently V_{ud} [2].

In the past, this approach has been extensively exploited by Hardy *et al.* [1, 2]. To determine the *ft* values several experimental inputs are needed: the transition energy Q_{EC}, which is required for the calculation of the value of the statistical rate function *f*, the half-life of the parent state $t_{1/2}$, and the branching ratio of the superallowed Fermi transition *R*, these last two quantities are required for the calculation of the partial half-life *t*.

To determine G_V some additional corrections are needed that take into account radiative and isospin symmetry-breaking effects. These corrections are incorporated as discussed in Ref. [2], resulting in a "corrected" *Ft* value defined as:

$$Ft \equiv ft(1+\delta_R')(1+\delta_{NS}+\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} \quad ,$$

where *K* is a constant, δ_C is the isospin symmetry breaking correction, Δ_R^V is the transition-independent part, and δ_R' and δ_{NS} are the transition-dependent parts of the radiative correction [2].

Until now, only 14 superallowed Fermi decays have met the requirements to be used to determine the world-average corrected *Ft* = 3072.27±0.72 s [2] value, which consist in reaching a precision of the order or better than 1 part in a thousand in all three decay quantities: Q_{EC} value, half-life and branching ratio. The superallowed decay of ^{70}Br has not been included in these calculations until now for several reasons: a) conflicting results for the Q_{EC} value [3, 4], which was already highlighted in [2], b) limited precision of the half-life, which is at present one order of magnitude above the required uncertainty [2], c) lack of information on the superallowed decay branching ratio *R*.

The beta decay of the ^{70}Br low- and high-spin isomers ($J^\pi = 0^+$, $T = 1$ and $J^\pi = 9^+$, $T = 0$) has been studied in a recent experiment performed at RIKEN using the fragmentation of ^{78}Kr beam at 345 MeV/nucleon [5, 6]. The simultaneous study of the beta decay of both isomers allowed us to improve the precision on the corresponding half-lives and, with the help of previous shell model calculations [7], provide for the first time an estimate of the superallowed branching ratio [6]. This estimation is based on the determination of the intensity of the $2^+_1 \rightarrow 0^+_{gs}$ transition in ^{70}Se populated in the $J^\pi = 0^+$, $T = 1$ decay, that collects many weak branches from states populated in the decay [6] and on a theoretical value obtained from shell model calculations, which provides the fraction of GT states populated in the decay that de-excites through the 2^+ state in ^{70}Se [7].

The new half-life of the $J^{\pi} = 0^{+}$, $T = 1$ ground state decay and the newly estimated superallowed branch can be used to test the CVC hypothesis for this decay. The results are presented in Table 1 where the corresponding correction factors were taken from [2], and the partial half-life *t* has been obtained using the following relation:

$$t = \frac{t_{1/2}}{R}(1 + P_{EC}) \ ,$$

with *R* the superallowed branch taken from [6] and P_{EC} the electron capture fraction.

Table 1. Corrected *Ft* values for the superallowed beta decay of ^{70}Br. The uncertainties of the quoted values are given in parenthesis. The first line shows the *f* and corrected *Ft* value obtained from the new half-life, the estimated branching ratio *R* taken from [6], and the Q_{EC} from [3] (deduced from a positron end-point measurement). For this calculation, the *f* and P_{EC} values quoted in [2] for the corresponding Q_{EC} were used. In the second line the *ft* and corrected *Ft* value determined for the Q_{EC} from [4] (trap measurement) is presented. In this case the *f* and P_{EC} value were obtained using the code LOGFT from the NNDC [8].

Q_{EC} (keV)	$t_{1/2}$ (s)	*f*	*R* (%)	P_{EC} (%)	*ft* (s)	*Ft* (s)
9970 ± 170 [3]	0.07842(51)	38600(3600) [2]	97.94 (175)	0,173	3096(293)	3086(293)
10504 ± 15 [4]		50979(385) [9]		0,133	4087(83)	4078(83)

Table 1 shows clearly that the obtained *Ft* value with the new experimental information ($t_{1/2}$, *R*), but using the Q_{EC} from [3], shows a nice agreement with the world-average corrected *Ft* = 3072.27±0.72 s [2] value within the error. The large uncertainty of the *Ft* in this case is dominated by the large uncertainty of *f*, a consequence of the large Q_{EC} uncertainty from [3]. In case we use the Q_{EC} value of 10504 ± 15 keV from [4] instead of the one from [3], the deduced value of *Ft* is in clear disagreement with the world-average corrected *Ft* value.

The serious discrepancy between the Ft value deduced with the Q_{EC} value from [4] and the world average Ft value justifies a new measurement of the Q_{EC} for the superallowed decay of ^{70}Br. The Q_{EC} from the work of Davis [3] comes from a positron end-point measurement using a plastic scintillator, which is less precise than the values that can be deduced from modern Penning-trap mass measurements. The more recent Q_{EC} value from [4], which is also the accepted value in the new atomic-mass evaluation AME2016 [9], leads to a *Ft* value that is not consistent with the CVC hypothesis and requires further testing. This Q_{EC} value comes from a Penning-trap measurement, but as it was already discussed in [2] (see Fig. 1 of the reference) it does not follow the trend of the rest of Q_{EC} values for T_z=0 superallowed transitions versus *Z*, and shows a deviation of 500 keV from the systematic behavior. The half-life and the excitation energy systematic taken from [9] are presented in figure 1.

Even though the new improved *Ft* value will not have a significant impact on the world average *Ft* value, it will solve a prominent conflict in the experimental data available. Furthermore, the pinned down input parameters, which are influencing the average *Ft* determined from ^{70}Br, will allow a possible improvement of the theory that is needed to calculate the δ_C correction. In the region of ^{70}Br the largest deviations to theory can be found [10].

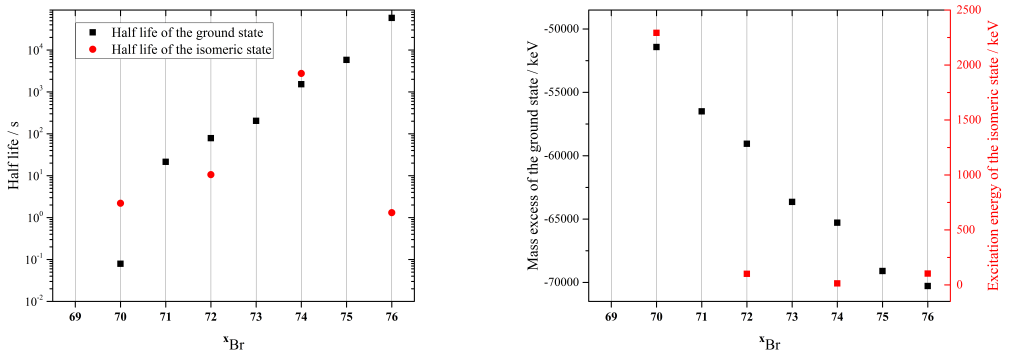

Fig. 1: Left: Half-lives for the different Br isotope and their isomeric states taken from [9]. Right: Mass excess and excitation energies for the different Br isotope and their isomeric states taken from [9].

2. Experimental techniques

The proposed measurements shall be performed using the ISOLTRAP [11] setup at ISOLDE/CERN. It combines three different ion-trapping techniques to allow an accurate determination of the masses of the ions under investigation, even if they are accompanied by unwanted ions being orders of magnitude more abundant.

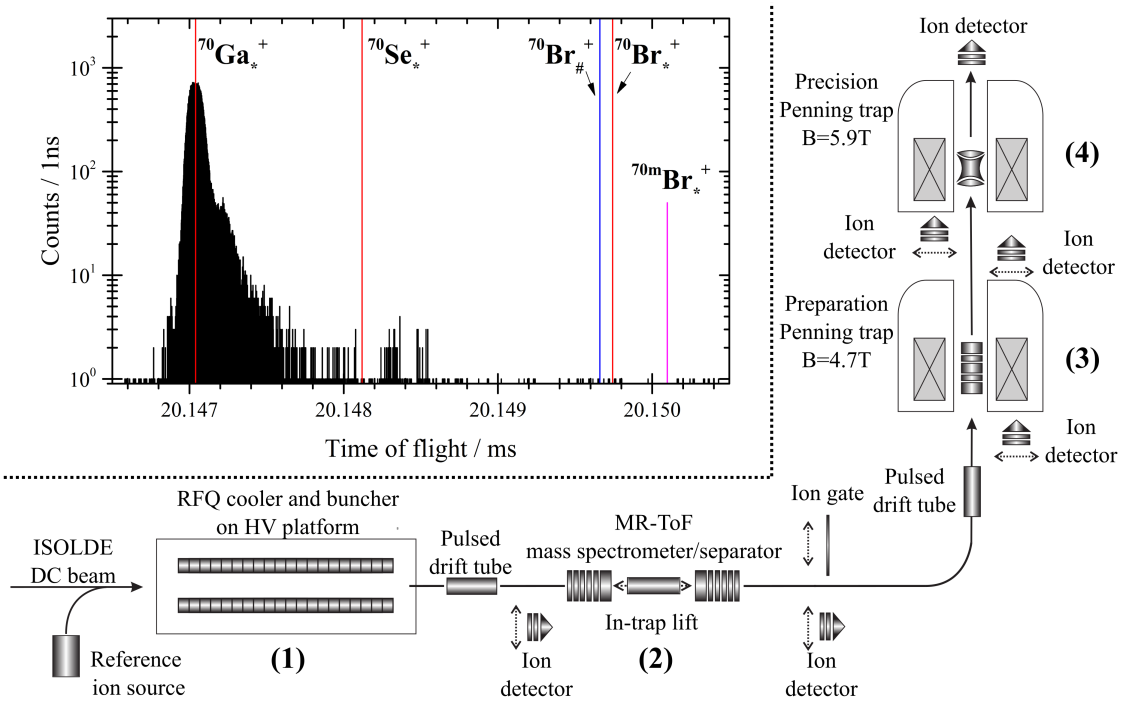

Fig. 2: Schematic overview of the ISOLTRAP setup at the ISOLDE/CERN facility. Inset: Typical time-of-flight spectrum that was obtained for A=70 ions after 1000 revolutions in the MR-ToF MS. The ions were produced with a standard ISOLDE UCx target (not the type intended to use in this experiment). The positions in the time-of-flight spectrum of the ions marked with an asterisk were calculated with data taken from the AME2016 [9]. The ^{70}Br ion tagged with a hashtag marks the position in the time-of-flight spectrum if we assume its mass to be about 530 keV lighter compared to the AME, which would correspond to a Q_{EC} value equal to the one inferred from an end-point positron measurement.

A schematic overview of the setup is presented in figure 2. The main components are: the RFQ cooler and buncher (1) to cool and bunch the quasi-continuous beam delivered by ISOLDE into short pulses with a longitudinal emittance of about $100\text{ns} \cdot \text{eV}$. The bunched beam is injected into the multi-reflection time-of-flight mass spectrometer (MR-ToF MS) (2), which is used for the identification of the beam constituents and the subsequent selection of a particular species. Those can then be forwarded to the Penning traps, of which first is the cooler Penning trap (3), which is used for further reducing the beam emittance. Finally the ions reach the precision Penning trap (4) in which the high-precision time-of-flight ion-cyclotron-resonance (ToF-ICR) [11] or the phase-imaging ion-cyclotron-resonance (PI-ICR) [13] techniques can be used for the determination of the mass of the ion of interest.

Already the MR-ToF MS offers enough precision ($\delta m/m$=10^{-6}) [14] to determine significant differences of the mass of the measured ion compared to literature values as can be seen in the inset of figure 2. The inset shows a typical time-of-flight spectrum that was observed in one of the previous runs of ISOLTRAP with the MR-ToF MS on mass A=70. The ions were produced from a standard UCx target of ISOLDE through surface ionization. The expected positions of $^{70}Se^{+}$ and $^{70}Br^{+}$ in the time-of-flight spectrum are shown. Furthermore, the expected time of flight of the isomeric state $^{70m}Br^{+}$, which is about $2.2\text{MeV}/c^2$ heavier than the ground state, are included in the plot. The lighter ^{70}Br (marked with a hashtag) represents the position in the time-of-flight spectrum that the ion should have if the smaller Q_{EC}-value is assumed to be the correct one. Using the MR-ToF MS only, will already allow a determination of the Q_{EC}-value even if the yield is significantly lower than expected since the efficiency up to the MR-ToF MS is higher (1-4%) and the measurement cycle faster compared to measurements that can be performed in the precision Penning trap.

For a high-precision determination of the mass of ^{70}Se and ^{70}Br the accompanying ions will be removed from the ion bunch using the refined in-trap lift technique [15]. With this method, we will be able to forward a clean beam (supressing up to 4 orders of magnitude more abundant species) to the precision Penning trap.

With the classical ToF-ICR technique the sum of the two radial eigenfrequencies, which equal the cyclotron frequency in the ideal Penning trap, can be determined and compared to the cyclotron frequency of a well-known reference ion that can be provided by ISOLTRAP's offline ion source. A precision of $\delta m/m$=10^{-8} can be easily reached even with just one measured resonance spectrum at 600ms excitation time that utilizes the Ramsey-excitation scheme [16]. This technique will be perfectly suited to measure the mass of ^{70}Se and the longer lived isomeric state of ^{70}Br.

Since the ground state of ^{70}Br is rather short lived (about 79ms) the PI-ICR technique, successfully commissioned at ISOLTRAP recently, will be very helpful. The method is based on the fact that the ions are circling around the magnetic field lines with their cyclotron frequency. By converting this fast ion motion to the significantly slower magnetron motion (another eigenmotion in the ideal Penning trap) the amount of full turns for a given phase accumulation time including the residual phase (in case of non-integer cyclotron periods) of the ion can be determined by use of a position-sensitive detector. This information leads directly to the cyclotron frequency of the ion. Again, this frequency is compared to the cyclotron frequency or the phase accumulation of a reference ion for the determination of the mass of the ion of interest. This new technique is advantageous in terms of the time needed to reach a certain precision in comparison to ToF-ICR as well as the MR-ToF MS. For phase accumulation times of only 50 ms a relative mass precision of a few 10^{-8} is reachable. The PI-ICR technique was recently applied in a test measurement at ISOLTRAP to determine the Q value of the beta decay between ^{88}Sr and ^{88}Rb with a precision better than 200 eV. A comparison of the techniques (in terms of mass resolving power) available at ISOLTRAP, using the parameters of the experiment, is shown in figure 3.

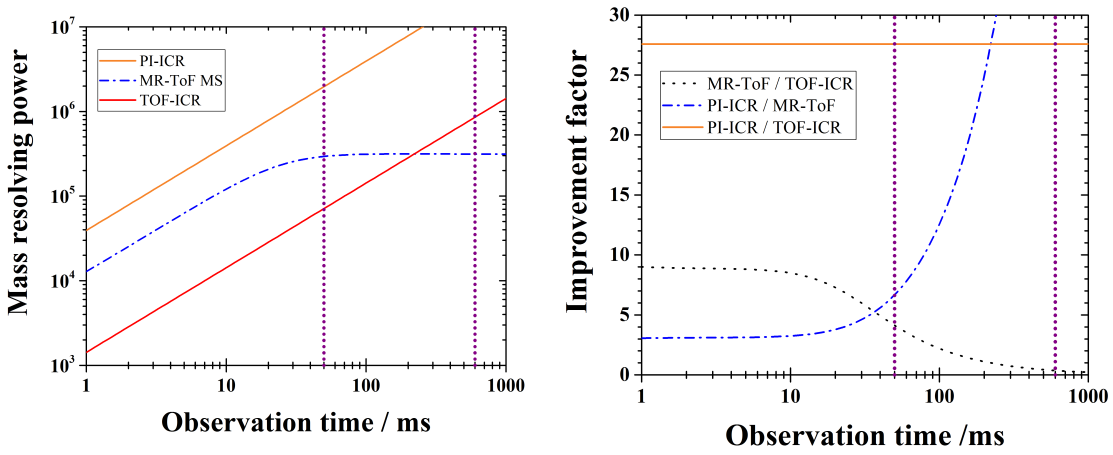

Fig. 3: left: resolving power as a function of the observation time of the ion under investigation for the different techniques available at ISOLTRAP. right: improvement factors between the different techniques as function of the observation time. The dotted vertical lines represent the excitation or phase accumulation times referred to in the text.

3. Beam time request

We propose to use a ZrO or a Nb foil target with a hot VADIS ion source where yields of ^{70}Br and ^{70}Se of 10^3 to 10^4/uC have already been reported [17]. However, strong Ga and Ge contaminations are expected at mass *A*=70, which a RILIS-based ionization scheme cannot suppress. Therefore, we plan to use a target equipped with a calibrated leak of a few 10^{-5} mbar*l/s to supply carbon dioxide and support the formation of carbonyl selenide. Bromine can be extracted as $AlBr^+$ which has been already shown to work and was used for mass measurements at ISOLTRAP up until $^{72}Br^{27}Al^+$ [18]. The yields that were extracted from those measurements are presented in figure 4.

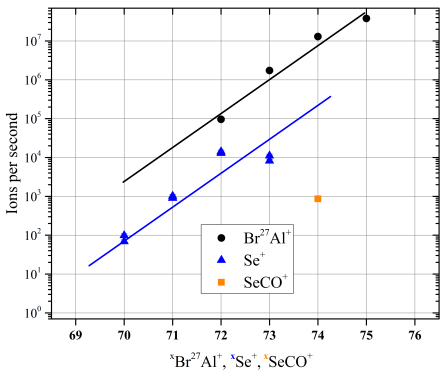

Fig. 4: Ions/s of $Br^{27}Al^+$, $SeCO^+$ and Se^+ measured at ISOLTRAP and corrected for the efficiency of the setup at the time, including extrapolation to $^{70}Br^{27}Al$. The data was extracted from a beam time at ISOLTRAP in 2002.

The goal is to extract Se and Br as molecular sidebands in the heavier mass region in order to avoid contaminants, although previous experiments at ISOLTRAP have shown that the in case of Se, measurements of the mass of the atomic ion are possible [18]. Since the masses of C, O and Al are well known (^{12}C being the mass standard, ^{16}O is known with a relative mass precision of 10^{-11}, ^{27}Al with better than $2{\cdot}10^{-9}$ [9]) and atomic binding energies can be neglected, the use of a molecular sideband for the mass measurements does not cause any limitation. However, due to possible molecular breakup in our RFQ cooler and buncher we expect an overall transport

and detection efficiency at ISOLTRAP of only about 0.01%. Assuming a yield of 10^3 ions / pulse (with about 5 pulses in 12 s), the need to get about 600 ions per resonance and 8-10 Ramsey-type (10ms excitation, 80ms waiting, 10ms excitation) resonances to achieve a relative statistical mass uncertainty of about 1E-8 which corresponds to an error of 1 keV on the mass excess, 5 shifts of radioactive beam per nuclide are needed (including reference measurements on ^{85}Rb after every 3-4h for 30min). In addition, 2 shifts are needed to prepare the transport between ISOLDE and ISOLTRAP, to find the optimal conditions for the MR-ToF MS, as well as to optimize the most efficient way to produce the two beams and to make additional checks to understand/minimize the systematic uncertainties associated with the injection into the measurement trap. For systematic cross-checks a few PI-ICR resonances will be taken for a direct *Q*-value measurement. In summary, we request:

5 shifts for ^{70}Br, ZrO or Nb-foil target with VADIS ion source

5 shifts for ^{70}Se, ZrO or Nb-foil target with VADIS ion source

2 shifts for transport, production and MR-ToF MS optimization

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