Half-life of the β decay $^{115}In(9/2^+) \rightarrow ^{115}Sn(3/2^+)$

Erica Andreotti,[1,*] Mikael Hult,[1,†] Raquel González de Orduña,[1] Gerd Marissens,[1]
J. S. Elisabeth Wieslander,[1] and Marcin Misiaszek[2]
[1]*European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, Retieseweg 111, B-2440 Geel, Belgium*
[2]*M. Smoluchowski Institute of Physics, Jagiellonian University, ulica Reymonta 4, PL-30-059 Krakow, Poland*
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The half-life of the rare β^- decay of ^{115}In (9/2+) to ^{115}Sn (3/2+) was determined by measuring the subsequent 497.334(22) keV γ-ray emission in a high-purity indium sample. The measurements were carried out by means of ultralow-level γ-ray spectrometry in the HADES underground laboratory, using three different high-purity germanium detectors. The value of the partial half-life for this low-Q_β^- transition was measured to be 4.3(5) $\times$ 10^{20} yr.

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I. INTRODUCTION

The β^- decay of ^{115}In (9/2+) to ^{115}Sn (3/2+) was identified for the first time by Cattadori *et al.* [1] in 2005 by observing the 497.334(22) keV γ-ray when measuring an indium rod using an ultralow-background γ-ray spectrometer at Laboratori Nazionali del Gran Sasso. The measurement gave as a result a partial half-life of 3.7(10) $\times$ 10^{20} yr with 27% relative uncertainty. Figure 1 shows the decay scheme of ^{115}In and ^{115}In^m based on ENSDF [2] and including the rare β^- decay from the ^{115}In ground state to the ^{115}Sn first excited state. This transition is a second forbidden unique decay ($\Delta J = 3$, with no change of parity). The decay probability is 1 $\times$ 10^6 times lower than that of the main branch.

Following the first observation (which was a spinoff from a radiopurity measurement in support of the LENS solar neutrino experiment), the first project solely devoted to study this rare decay was carried out as a collaboration between the Institute for Reference Materials and Measurements (IRMM) and Jyväskylä University [3]. The work included (i) a new mass determination at the JYFLTRAP Penning-trap facility [4], (ii) a theoretical β^--decay calculation [5], and (iii) an ultralow-level γ-ray spectrometry (ULGS) measurement of the half-life. The aim of that ULGS measurement was to confirm (or refute) the observation by Cattadori and co-workers and, in case of a confirmation, to reduce the uncertainty of the half-life by using a sample and a geometry more suitable from a metrological point of view. As a result the value of the partial half-life was determined to be 4.1(6) $\times$ 10^{20} yr, with relative combined standard uncertainty of 15% dominated by counting statistics (14%).

In this article we describe the details of the ULGS measurement and we report a new half-life value with reduced uncertainty, obtained by increasing the measurement time and improving the efficiency calibration. Furthermore, we present the results of a careful evaluation of the sources of systematic uncertainty, which are mainly linked to the detection efficiency calculations.

A major motivation for studying this decay is that it has the lowest β^--decay energy of any known β^- decay. The recent measurement using the JYFLTRAP resulted in a positive Q_β-value of 350 $\pm$ 170 eV. Prior to this measurement, it was uncertain whether this rare process was energetically possible, because the decay energy from the most recent mass evaluation [6] was 1.7 $\pm$ 4.0 keV. The JYFLTRAP value was subsequently confirmed with a lower uncertainty by Mount *et al.* [7] in a measurement performed using the Florida Penning-trap mass spectrometer. The result for the Q_β- value was in this case 155 $\pm$ 24 eV.

Measuring the end-point region of the electron spectrum for this decay precisely has the potential of giving information on the neutrino mass. Over the past decade, experiments studying neutrino oscillations proved that neutrinos are massive [8]. In such experiments, which employ neutrino sources from nuclear reactors, accelerator beams, and the sun, only the difference of the mass squared can be deduced. The bounds on the absolute neutrino mass scale can be determined only if the effective neutrino mass m_β is known. The determination of the neutrino mass is the main scientific goal for β-decay and neutrinoless double-β-decay experiments. A massive neutrino might play a key role in the large-scale structure formation in the early universe.

The β^- decay of ^{115}In (9/2+) to ^{115}Sn (3/2+) also provides an opportunity for studying a possible effect on the decay constant from the chemical surroundings. To study such an effect it is important to know the half-life with a lower uncertainty than what is presently available.

II. MATERIALS AND METHODS

A. Sample

The sample used in this work was a disc of ultrapure indium of natural isotopic abundance 95.71(5)% ^{115}In according to the International Union of Pure and Applied Chemists [9]. The sample was submerged for 10 min in a 65% HNO_3 solution to remove any surface impurity. As a result a somewhat uneven surface was produced. The disc mass after the cleaning procedure was 2566.13 g and its dimensions were 10.6 cm diameter and 4.0 cm thickness. The sample

*erica.andreotti@ec.europa.eu
†mikael.hult@ec.europa.eu

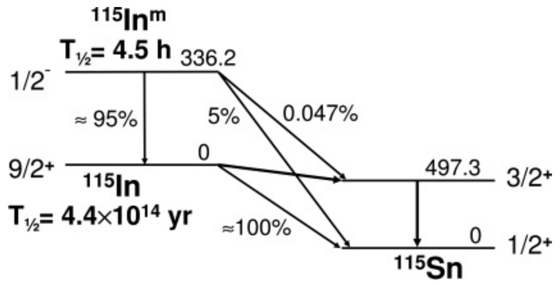

FIG. 1. Decay scheme of ^{115}In updated with the rare decay branch and with inclusion of ^{115}In^{m}.

was stored in the underground laboratory for 29 weeks before the measurement commenced to ensure that no contribution from the cosmogenically induced ^{115}In^{m} could interfere with the results (see the decay scheme in Fig. 1), as well as to reduce the activity of any other cosmogenic radionuclide. The radiopurity of the sample was assessed during the γ-spectrometry measurements. The net activity of all the γ lines identified in the indium disc spectrum was found to be below the decision thresholds (95% C.L.) reported in Table I, which were assessed according to ISO 11929-3 [10] for the radionuclides commonly present as impurities (this issue is further discussed in Sec. III).

B. Experimental setup

The indium disc sample was measured on three p-type ultralow-background high-purity germanium (HPGe) detectors at the HADES underground laboratory, located 225 m below ground (=500 m water equivalent) [12]. The choice of the spectrometers used for this experiment was based on their main characteristics (shown in Table II), which should ensure high efficiency, low background, and good energy resolution, all at a γ-ray energy of 497 keV.

Detectors Ge-6 and Ge-7 are placed in a "sandwich" configuration, which means they face each other inside a common shielding, and the sample is placed between them (Fig. 2). This configuration improves the detection efficiency by increasing the solid angle between the sample and the detectors [13]. The sample is placed in direct contact with detector Ge-6 (the lower spectrometer), while it is possible to adjust the position of detector Ge-7 according to the source thickness (the maximum available distance between the detectors is 70 mm). The sandwich detector is surrounded by an 18.5-cm lead shield, of which the inner part is low in ^{210}Pb content (2.0 Bq/kg), plus an inner lining of 3.5 cm of freshly produced electrolytic copper. Furthermore, a pair of large-area plastic scintillators, operating in coincidence (coincidence time 1.6 μs), is placed on top of the sandwich spectrometer, thus reducing the muon contribution to the background with about 15% in the energy region around 500 keV and about 25% above 1460 keV, where the contribution of natural radionuclides to the background is lower. The muon-induced-events contribution to the 511-keV peak is reduced as well by about 15%.

The spectra resulting from the two detectors are usually added together to fully exploit the advantages of such a configuration for detection of rare events. However, when a γ-ray peak of interest is clearly seen in the spectra from each detector (like in this work), the spectra from the two detectors are analyzed separately to avoid the influence of the small differences in the resolution of the two spectrometers.

The Ge-4 detector combines a large mass and a thin upper dead layer (and consequently high efficiency at all energies) with good resolution [14]. It is placed in a more conventional low-level shielding composed of 15-cm lead shield, of which the inner 5 cm is low in ^{210}Pb content (1.3 Bq/kg), plus an inner lining of 10 cm of freshly produced electrolytic copper.

All detectors are connected to the Genie-2000 acquisition system [15], but in the case of the sandwich spectrometer it is the output of a multiparameter system, named DAQ2000, that is used for the data analysis. The DAQ2000 is based on LabView and it was designed and manufactured by IRMM. The output consists of time-stamped list-mode data files in binary format [13]. Three time-stamped parameters (step 0.100 μs) are stored: the signals from the lower plastic scintillator when in coincidence with the upper plastic scintillator and the signals from the two HPGe detectors. When an event is registered in one of the three detectors, all three channels of the multiparameter system are read out and time stamped. The muon spectrum, acquired with the plastic scintillators, is subtracted from the HPGe γ spectra using a dedicated offline software based on the ROOT environment [13]. The time window for coincidences between the plastic scintillators and any of the two HPGe detectors can be freely selected. In this work it was set to 1 ms. The stability of the experimental

TABLE I. Decision thresholds (95% C.L.) for the indium sample calculated for selected radionuclides commonly present as impurities according to Ref. [10].

Radionuclide	Measured radionuclide	Activity decision threshold (mBq)	Specific activity[a] decision threshold (mBq/kg)
^{238}U	^{234}Th	263	102.5
^{235}U	^{235}U	50	19.5
^{226}Ra	^{214}Pb and ^{214}Bi	0.8	0.3
^{228}Ra	^{228}Ac	0.7	0.3
^{228}Th	^{212}Pb, ^{212}Bi, and ^{208}Tl	0.3	0.1
^{210}Pb	^{210}Pb	340	132.5
^{40}K	^{40}K	3	1.2
^{60}Co	^{60}Co	0.3	0.1

[a]Activity divided by the mass of sample [11].

TABLE II. Main characteristics of the three ultralow-background HPGe detectors used for the indium disc measurements. Two values for the full width at half maximum (FWHM) are reported at 497 keV: the first related to a 1-day measurement (short measurement), the second related to a long measurement (i.e., spectrum resulting from the sum of several 1-day measurements). The differences, within 0.04% and 0.07%, are related to the small energy calibration drift (~0.04%).

	Ge-4[a]	Ge-6	Ge-7[a,b]
Crystal type	p type coaxial	p type coaxial	p type coaxial
Relative efficiency (%)	106	80	90
Mass (kg)	2.19	2.10	1.73
Window material	Al	Cu	Al
FWHM (keV) @ 1332 keV	1.99	2.15	2.08
FWHM (keV) @ 497 keV (short measurement)	1.63	1.79	1.74
FWHM (keV) @ 497 keV in final added spectrum (long measurement)	1.63	1.86	1.86

[a]Submicron top deadlayer;
[b]inverted endcap.

setup in terms of energy calibration and resolution is regularly monitored (every 1-2 weeks) using quality assurance point sources. The systems are stable in terms of energy within about 0.04%.

C. Activity calculation and efficiency determination

The partial half-life for the considered transition is calculated using the area of the 497-keV peak in the acquired γ-ray spectra according to the following formula:

$$T_{1/2}(^{115}\text{In}(9/2^+) \rightarrow {}^{115}\text{Sn}(3/2^+)) = \frac{\ln 2 N\varepsilon t}{S(1+\alpha)}, \qquad (1)$$

where S represents the net counts in the 497-keV peak, N is the number of ^{115}In nuclei in the sample, $\alpha = 8.1 \times 10^{-3}$ is the electron conversion coefficient for the transition [16], t is the measurement live time, and ε is the full energy peak (FEP) efficiency of the detector in the measurement configuration.

The FEP detection efficiency is determined by measuring a multi-γ reference source and fitting an efficiency curve to data. In this work we used an aqueous solution prepared by the National Physics Laboratory [17] for an intercomparison exercise, containing 10 radionuclides with specific activities known with uncertainty varying from 0.2% to 0.8% (median 0.6%). A specially designed Perspex container, with dimensions and shape reproducing those of the indium disc, was filled with the reference solution.

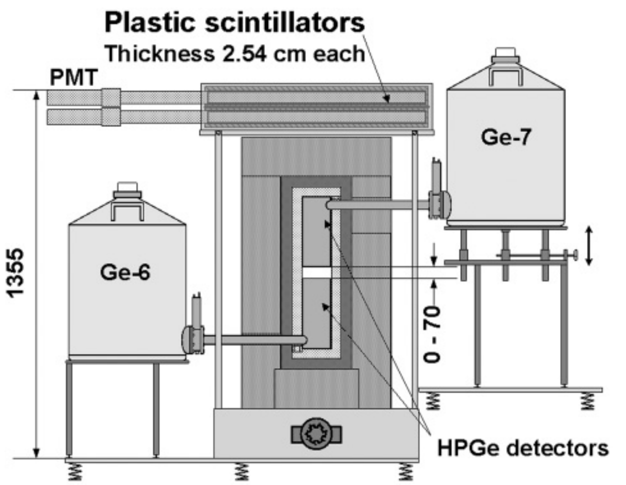

FIG. 2. The sandwich spectrometer. Dimensions in millimeters if not otherwise specified.

To correct for the differences between the calibration source and the indium sample, a computer model in the Monte Carlo code EGS4 was set up. The correction factor was the ratio between the FEP efficiency calculated for the indium sample and that for the reference source at the energy of interest (here 497 keV).

When the computer model is carefully implemented [18–20], this procedure results in a systematic uncertainty on the order of less than 3%, as can be concluded from the participation in 12 proficiency testing schemes. This is also clear from Fig. 3, which shows the relative difference between the measured FEP efficiencies of the reference source and those calculated with EGS4 at different energies. The standard deviation of the relative difference is a good indicator of the residual systematic uncertainty due to efficiency calculations. The resultant values for the standard deviation are 2.5% for Ge-4, 2% for Ge-6, and 3% for Ge-7. In the previous article [3], the FEP efficiency was determined solely from the Monte Carlo calculations.

D. Validation of the FEP efficiency

In the work described in Ref. [3], the efficiency calculation method was validated by measuring point sources (^{85}Sr, ^{137}Cs, ^{134}Cs) sandwiched between indium discs of various thicknesses. The results obtained confirmed that the calculated efficiencies agree within 3%. However, a better validation procedure should be carried out by measuring a sample as similar as possible to the measured one. For the present work a validation sample was prepared by filling a container similar to the one used for the reference sample (same material, shape, and dimensions) with an aqueous solution ($SrCl_2$ 30 mg/L in HCL 0.1 mol/L) containing ^{85}Sr of certified activity. The choice of ^{85}Sr is due to the characteristic γ-ray emission at 514.00(48) keV, close to the γ transition studied in this article.

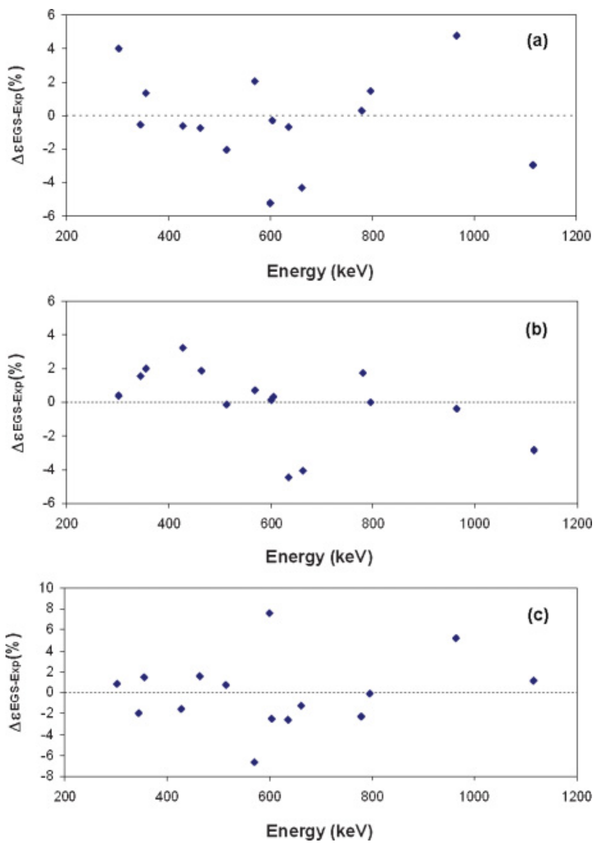

FIG. 3. (Color online) Relative difference between experimental efficiency and EGS4 efficiency at different energies for detectors (a) Ge-4, (b) Ge-6, and (c) Ge-7.

The ^{85}Sr activity of the sample was evaluated starting from the specific activity reported on the certificate 58.1 ± 0.5 kBq/g.

The validation sample was measured on all three detectors (Ge-4, Ge-6, and Ge-7). The results showed in all three cases a good agreement between the measured and certified activities, with relative differences around 2%. The final values for the systematic uncertainties due to efficiency calculations can be estimated therefore as 2.5% for Ge-4 and 2% for Ge-6. In the case of Ge-7, a final systematic uncertainty of 4% can be considered, which accounts for the imprecision in the evaluation of the distance between the spectrometer and the sample.

III. RESULTS

The indium disc was measured on the three detectors described in Sec. II B for a total measurement time of about 215.5 days (one day in the sandwich detector counted as 2 days). The peak net counts are calculated by subtracting the continuum background counts from the gross peak area, calculated by summing the counts in a region encompassing the 497-keV peak [21]. No peak fitting was performed due to the relatively poor counting statistics. The background is taken to be a linear function and the background counts are calculated by summing in an energy interval on either side of the 497-keV peak. The sum of the net counts in the 497.334(22)-keV γ-ray peak from the three detectors was

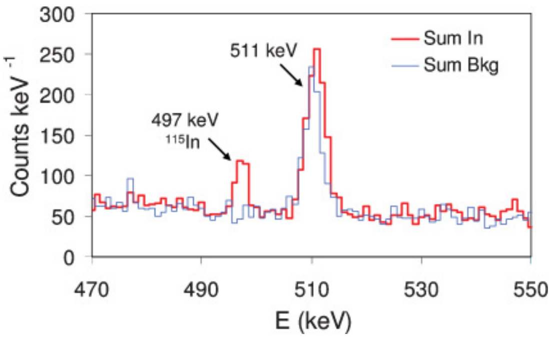

FIG. 4. (Color online) Summed indium spectrum of the three detectors used for qualitative analysis, compared to the summed background (normalized to the measurement time of the indium disc). Bin width 1 keV.

173.2 counts. This corresponds to more than twice the counts obtained in the preceding work, or 83.7 counts. Figure 4 shows the summed spectrum of the three detectors (used for qualitative purposes only) in the energy region of interest compared to the summed background. One clearly sees the 497-keV peak. Prior to the measurements it was cause for concern if the tail of the 511-keV peak would deteriorate the detection of the 497-keV peak. Although the underground location and the presence of the muon veto help in reducing the contribution of muon-induced events to the 511-keV peak, we estimated that the tail of the 511-keV peak contribution to the continuum background is not negligible (~0.5 counts/day in the region of interest for the 497-keV peak). This means that efforts to further reduce this source of background would help improve the quality of the measurements even more, particularly in the region of interest for the 497-keV peak. However, this is not of concern for the half-life calculation because the contribution due to the tail of the 511-keV peak is subtracted with the continuum background counts.

The half-life calculation was performed by analyzing individually the spectra obtained for each detector in order to subtract the correct background values and to preserve the resolution. All the background measurements considered in this article were performed with the same conditions as for the indium disc measurement (i.e., with same detector configuration and shielding). Table III shows the results obtained for the partial half-life ($T_{\frac{1}{2}}$) and branching ratio (BR) of the rare β^- decay on the three spectrometers and Fig. 5 shows the spectra collected by each HPGe detector. All the uncertainties quoted in this article are combined standard uncertainties given at 1σ. The numerical results of the measurements are stated in the format $xxx(y)$, where the number in parentheses is the numerical value of the standard uncertainty referring to the corresponding last digit of the quoted result.

The weighted mean activity of the three measurements was 0.65(7) mBq, which converts into a final value of the partial half-life of $4.3(5) \times 10^{20}$ yr (reported in Table III as weighted mean value). The final relative combined standard uncertainty was determined to 11.7%, dominated by counting statistics (11.3%). The other sources of uncertainty are related to efficiency calculations (2.8%), isotopic abun-

TABLE III. Measurement parameters and the resulting partial half-life ($T_{\frac{1}{2}}$) and branching ratio (BR) of the rare β^- decay of ^{115}In from the present measurements in HADES. Rel. Unc. represents the relative combined standard uncertainty [22].

Spectrometer	Live time (days)	Net counts in 497 keV peak	FEP efficiency at 497 keV	$T_{\frac{1}{2}}$ ($\times 10^{20}$yr)	Rel. Unc. of $T_{\frac{1}{2}}$ (%)	BR ($\times 10^{-6}$)
Ge-4	47.9	48(7)	0.0168(4)	4.1(6)	16	1.08(17)
Ge-6[a]	83.8	52(16)	0.0116(2)	4.5(14)	31	1.0(3)
Ge-7[a]	83.8	73(14)	0.0167(7)	4.6(9)	20	1.0(2)
Weighted mean value[b]	215.5			4.3(5)	11.7	1.02(13)

[a]The results concerning Ge-6 and Ge-7 are reported after subtracting the muon contribution, measured by the two plastic scintillators placed on top of the sandwich spectrometer.
[b]Calculated from the weighted mean activity of the three measurements.

dance (0.058%), and internal conversion coefficient (0.12%). The final result for the branching ratio is $1.02(13) \times 10^{-6}$, where an additional 5.7% relative uncertainty due to the half-life of the main branch was also considered.

A careful visual inspection of the complete spectra for both the indium and the background measurements was carried out.

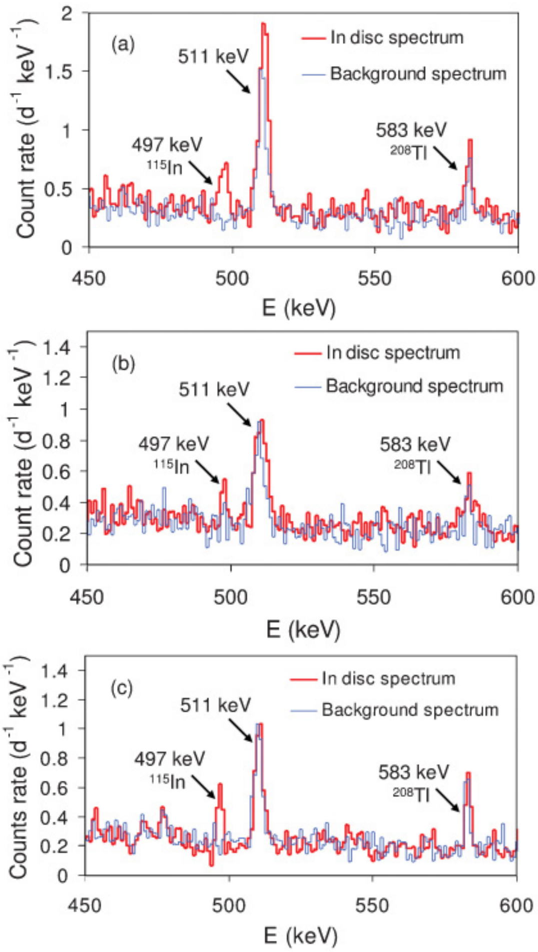

FIG. 5. (Color online) The γ-ray spectra for the indium disc sample, compared to the background spectra, in the energy region of the 497-keV γ line: (a) Ge-4, (b) Ge-6, and (c) Ge-7. Bin width 1 keV.

All the peaks found in the indium spectra are also present in the background except for the 497.334(22)-keV line. The origin of each line found in the indium spectra was identified and the corresponding net activity (calculated from the net peak area after subtracting the background peak area) was compared to the decision thresholds reported in Table I. As stated in Sec. II A, the radiopurity of the indium sample was confirmed as the resulting net activities were all below the decision thresholds. All the identified background lines are due to naturally occurring (^{40}K, ^{238}U, ^{235}U, ^{332}Th) or cosmogenic (^{60}Co) radionuclides, usually present as contaminants in copper, lead, and detector materials.

Figure 6 shows the indium and background spectra from 40 to 600 keV collected using detector Ge-7. The bremsstrahlung induced by electrons from the ^{115}In β decay with end-point energy 499 keV is clearly visible.

Possible alternative explanations for the 497-keV peak were also considered. A series of other effects can potentially mimic the considered indium γ-ray emission, but luckily they are all accompanied by other emissions, which enable identification and subsequent rejection.

The ^{115}In^m isomeric state undertakes a β decay to the first level of ^{115}Sn (see Fig. 1) with probability 0.047% and the subsequent emission of a 497-keV γ ray. However, ^{115}In^m also emits a γ line at 336.2 keV with higher probability (45.84%):

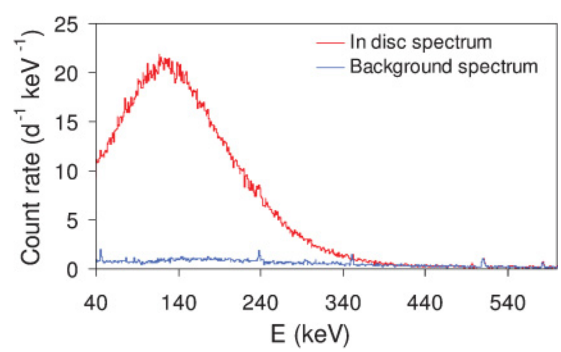

FIG. 6. (Color online) The γ-ray spectrum of the indium disc compared to the background for detector Ge-7; the bremsstrahlung spectrum from the ground-state-to-ground-state β^- decay is clearly visible.

in the measured indium spectra no presence of such a peak was detected.

Nuclear reactions due to thermal or fast neutrons, such as capture of thermal neutrons by ^{115}In and ^{113}In, are accompanied by γ quanta emissions of energy close to 497 keV. Also in this case more intensive γ lines should be observed, i.e., 273 keV (100%), 492.5 keV (8.68%), 311.6 keV (100%), 502.6 keV (5.00%), and 115.4 keV (53%).

Thanks to the underground location of the laboratory, and the consequently low neutron and muon flux (less than 0.2 and 2 m^{-2} s^{-1}, respectively [12]), we can conclude that (n,γ), (p,n), and inelastic reactions such as (n,n'), do not contribute to the considered peak. The activation induced by neutrons and muons in germanium and shielding materials in the underground laboratory HADES was studied in Ref. [23] and several other recent studies. No peaks at energy 497 keV were observed in the background spectra. Concerning possible activation in the indium sample, induced by (p,n) and inelastic scattering,[1] the same conclusion is valid (see also Ref. [1]). This argument is furthermore supported by the results of dose rate measurements performed at various locations in the underground laboratory: values between 5 and 15 nSv/h were obtained in the area were the HPGe detectors are located [12].

Also ^{103}Ru emits a γ ray at 497.08 keV with high probability (89.5%). However, the absence of the other major γ line at 610.33 keV from the same radionuclide and its relatively short half-life (39.255 days) allows excluding ^{103}Ru as the origin for the observed peak.

Finally, some γ rays with energy around 497 keV are emitted by radionuclides belonging to the natural ^{238}U and ^{232}Th chains, albeit with very low intensities so their contribution to the peak under analysis can be neglected (considering the small contribution to the background of their stronger associated γ lines).

Another potentially interfering effect is that due to the so-called germanium escape peak associated to the 511-keV annihilation line, which should appear at around 501 keV. We estimated the expected contribution due to such γ-quanta interaction, because it occurs at energy very close to the investigated γ line, thus potentially contributing to the measured net counts (taking into account the energy resolution). The evaluation was performed by means of a Monte Carlo simulation (using again the EGS4 code). As a result a contribution of 0.095% to the net counts at 497 keV was determined (corresponding to 0.07 net counts), being thus negligible.

IV. DISCUSSION

The results presented in this work further confirm the two previously reported values of the measured half-life of the lowest β^--decay energy of any known β^- decay (albeit this measurement is not independent of the second measurement reported in Ref. [3]). The weighted mean of the half-life presented in this work and in Ref. [1] is $4.2(4) \times 10^{20}$ yr. The combination of this value with the weighted mean of the two Q_β- measurement results (Refs. [3,7]), equal to 159(24) eV, points to a closer agreement between experimental results and theoretical calculations with respect to Ref. [3]. However, they still differ by more than 1σ. As stated elsewhere [3,25], the most plausible explanation for this discrepancy is the exceptionally low Q value of this decay, which motivates to take into account effects thus far neglected in the theoretical models. In particular, Mustonen and Suhonen [25] point out that it is not clear which is the role played by atomic corrections. Furthermore, the latest experimental results still point to the need for further theoretical work. Another effect which could possibly affect the decay rate is related to molecular final-state interactions: evaluations in this regard exist for tritium β decay [26,27], but not for the case of heavy nuclei, which remains a field open to further investigations. Observations of decay-rate variation related to chemical environment and temperature were recently published for the electron-capture process of ^{7}Be [28].

In this regard, an important issue tackled in this work is the reduction of the total relative uncertainty from the previous 15% to the present ~12%. For the sake of studying a possible effect on the half-life, caused by the chemical surrounding of the indium atoms due to the extremely low β-decay energy, it would be necessary to reduce the uncertainty of the half-life even further. It should be possible to reduce the systematic uncertainty from the current 2–3% down to 1% by studying in depth all the effects occurring during a validation measurement and by improving the models of the detectors. To obtain a counting statistical uncertainty of 1%, the measurements presented here would need to run for more than 11 years (using all three detectors), which is of course unrealistic. We would estimate that the ultimate uncertainty attainable with this approach would be 5%. As a consequence, a possible half-life effect must in principle be greater than 10% to be detectable using "conventional" underground HPGe detectors. One can think of conceiving a dedicated underground measurement system for measuring the half-life with higher precision, making use of techniques developed for large underground science projects (such as, e.g., the Germanium Detector Array [GERDA] [29] and Borexino [30]). Such collaborations are seeking extremely radiopure detector materials to reduce the detection limits of the system. The GERDA goal is to achieve a background of less than 10^{-3} counts/(kg yr keV) at 2 MeV. The background level already achieved in the Borexino detector, which employs a liquid scintillator, is three orders of magnitude lower. Owing to the very high radiopurity, Borexino is able to measure low-energy solar neutrino fluxes.

The other major impact of studying this rare decay is the possibility to measure the end-point energy with high precision. The existence of a nonzero neutrino mass should in fact produce a distortion of the β spectrum in proximity of the end-point energy. The main issue to face in such a direct search for neutrino mass is related to the relatively low statistics expected because it involves extremely rare events, which need to be discriminated among several background sources. The fraction of events occurring in the energy region of interest, when looking for the effect of a finite neutrino

[1] According to Ref. [24], no γ quanta of energy 497 keV accompany inelastic reactions on ^{115}In and ^{113}In.

mass, is inversely proportional to the cube of the end-point energy. For this reason, very-low-decay-energy β emitters are the most suitable candidate isotopes for developing direct search experiments.

The third-lowest known decay energy is that of tritium ($E =$ 18.57 keV), and many measurements have been performed to evaluate its end-point energy. A large-scale experiment based on the use of an electrostatic spectrometer, KATRIN [31], is at present being constructed in Karlsruhe with this aim. The expected upper limit of the neutrino mass from this experiment will be 0.2 eV. The second-lowest known decay energy is that of ^{187}Re (2.47 keV). Similarly to the case of tritium, a large-scale experiment, MARE [32], is being set up, based on the use of microcalorimeters. The expected upper limit of the neutrino mass is about the same as for KATRIN.

Measuring the end-point energy region of the electron spectrum for the rare β decay of ^{115}In constitutes a magnificent challenge. The fraction of events in the interesting part of the β spectrum will be about four orders of magnitude higher than in the case of ^{187}Re, given the most recent Q_β- evaluations. One possible technique would be based on tagging the electrons using the 497-keV γ rays to reduce the background due to the main β^--decay branch. If the bolometric technique could be applied to indium, one can possibly think of conceiving an experiment based on calorimeters surrounded by γ detectors, but that is of course many years down the line. Using the same approximated approach for evaluating the statistical sensitivity as is used in MARE [33], it is possible to estimate the experimental conditions required for an indium-based calorimetric experiment in order to be competitive. With a total statistics of about 1×10^{14} β decays, in zero background conditions, it would be possible to reach a limit on neutrino mass lower by about one order of magnitude ($\sim$0.02 eV) with respect to an analogous rhenium-based calorimetric experiment (same statistics and zero background conditions). The main issues in the case of ^{115}In concern the intrinsic background reduction and the feasibility of single module detectors with size optimized to match the required statistics, while pushing the available detector technologies to their ultimate limits. The rare β decay in natural indium is of the order of 0.1 nBq/mg (according to the most recent results on the half-life), to be compared to $\sim$1 Bq/mg in the case of rhenium. This means that, in the case of indium, larger detectors should be realized while preserving energy resolution and all other basic detector performances. By applying to indium the presently available technology for rhenium-based calorimeters (assuming energy resolution 1 eV and zero background), it would be possible to reach a total statistics of $\sim 1 \times 10^3$ β decays, by running an experiment for 5 yr with an array of detectors of 50 g total mass (to be compared with a total statistics of about 1×10^{14} β decays attainable with an analogous rhenium-based experiment). This would set a limit of 6 eV on neutrino mass (estimated using the same approximated approach stated earlier). This shows that a further development of calorimetric techniques applied to indium is necessary to reach a competitive statistics, because the 0.2-eV limit on neutrino mass can only be achieved with a total mass of 100 ton of natural indium. However, the advantage of an indium-based experiment lays in the relatively low indium activity, which offers in principle the possibility to build larger single-module detectors while keeping a low level of pile-up fraction. Another important question to face concerns the detector threshold energy, which should be suited to detect the extremely low energy β events. At present, microcalorimeters show energy thresholds of the order of a few hundreds of eV.

The study of this β-decay spectrum would also offer the possibility to investigate another effect, analogous to extended x-ray absorption fine structure, known as beta environmental fine structure (BEFS). BEFS takes place when β particles are emitted by an atom embedded in a molecule or crystal. The existence of the BEFS effect, giving rise to an oscillatory pattern on the spectrum of β-decaying nuclei, was theoretically proposed in 1991 by Koonin in the case of ^{3}H and ^{14}C [34] and was experimentally observed in rhenium [35,36]. According to theoretical models, the BEFS effect should dominate at low energies (below 2 keV), whereas with increasing energy it should become negligible. Measuring the spectrum of the β^- decay with the lowest known Q_β^- value could give the opportunity to study the BEFS effect in the case of ^{115}In, particularly if combined with the use of calorimetric techniques, which allows very good energy resolutions and extremely low detection limits to be reached. However, this study requires a parallel development of theoretical models to extend Koonin theory to the case of the second forbidden unique decay of ^{115}In.

V. SUMMARY

In this article we presented an experimental value for the half-life, $4.3(5) \times 10^{20}$ yr, of the second forbidden unique β^- decay of ^{115}In (9/2+) to ^{115}Sn (3/2+) measured by means of γ-ray spectrometry. The relative uncertainty was reduced from 15% to 11.7% compared to Ref. [3] as an effect of better counting statistics and improved efficiency calculations. This work provides a stronger confirmation of the existence of this rare decay with an extremely low decay energy. A comparison between theoretical calculations and the combination of the experimentally measured relevant half-life and Q_β^- values clearly points to the need for an improvement of the theoretical models. Furthermore, all efforts made so far to measure the effective neutrino mass m_β in β decay and to determine bounds on neutrino mixing parameters may be encouraged by the measurement of the lowest Q_β^- value decay.

[1] C. M. Cattadori, M. De Deo, M. Laubenstein, L. Pandola, and V. I. Tretyak, Nucl. Phys. A **748**, 333 (2005).

[2] J. Blachot, Nucl. Data Sheets **104**, 967 (2005).

[3] J. S. E. Wieslander *et al.*, Phys. Rev. Lett. **103**, 122501 (2009).

[4] A. Jokinen, T. Eronen, U. Hager, I. Moore, H. Penttilä, S. Rinta-Antila, and J. Äystö, Int. J. Mass Spectrom. **251**, 204 (2006).

[5] M. T. Mustonen and J. Suhonen, Phys. Lett. B **657**, 38 (2007).
[6] G. Audi, A.H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 337 (2003).
[7] B. J. Mount, M. Redshaw, and E. G. Myers, Phys. Rev. Lett. **103**, 122502 (2009).
[8] G. Bellini *et al.* (Borexino Collaboration) Phys. Rev. D **82**, 033006 (2010).
[9] K. J. R. Rosman and P. D. P. Taylor (IUPAC), Pure Appl. Chem. **70**, 217 (1998).
[10] International Organization for Standardization, ISO 11929-3, (International Organization for Standardization, Geneva, 2000).
[11] International Organization for Standardization, ISO 31-9, (International Organization for Standardization, Geneva, 1992).
[12] E. Andreotti, M. Hult, R. González de Orduña, G. Marissens, M. Mihailescu, U. Wätjen, and P. Van Marcke, in *Proceedings of the 3rd International Conference on Current Problems in Nuclear Physics and Atomic Energy, Kyiv, 2010* (Publishing Department of KINR, Kyiv, 2011), p. 601, [http://www.kinr.kiev.ua/NPAE-Kyiv2010/html/Proceedings/8/Andreotti.pdf].
[13] J. S. E Wieslander, M. Hult, J. Gasparro, G. Marissens, M. Misiaszek, and W. Preusse, Appl. Radiat. Isot. **67**, 731 (2009).
[14] P. Lindahl, M. Hult, F. Cordeiro, J. Gasparro, A. Maquet, G. Marissens, and P. Kockerols, in *Improvements in underground gamma-ray spectrometry and the application of measuring radioactivity in agricultural samples*, edited by P. Warwick (Royal Society of Chemistry Publishing, Cambridge, 2007), Special Publication No. 312, pp. 86-94.
[15] Canberra, Genie-2000 Applications Software, [http://www.canberra.com/products/831.asp].
[16] J. Blachot, Nucl. Data Sheets **86**, 151 (1999).
[17] National Physics Laboratory website, [http://www.npl.co.uk/].
[18] J. Gasparro, M. Hult, and P. N. Johnston, Czech. J. Phys. **56**, 1 (2006).
[19] J. Gasparro, M. Hult, P. N. Johnston, and H. Tagziria, Nucl. Instrum. Methods Phys. Res., Sect. A **594**, 2 (2008).
[20] P. N. Johnston, M. Hult, and J. Gasparro, Appl. Radiat. Isot. **64**, 1323 (2006).
[21] K. Debertin and R. G. Helmer, *Gamma- and X-ray Spectrometry with Semiconductor Detectors* (Elsevier, Amsterdam, 1988), p. 176.
[22] ISO/IEC/OIML/BIPM, *Guide to the Expression of Uncertainty in Measurement* (International Organization for Standardization, Geneva, 1995).
[23] R. Wordel, D. Mouchel, A. Bonne, P. Meynendonckx, and H. Vanmarcke, in *Proceedings of the 3rd International Summer School, Huelva, Spain, 1993*, edited by M. Garcia-León and R. Garcia-Tenorio (World Scientific, Singapore, 1993), p. 141.
[24] Nuclear Data Sheets, National Nuclear Data Center, Brookhaven National Laboratory,Upton, NY [http://www.nndc.bnl.gov/].
[25] M. T. Mustonen and J. Suhonen, J. Phys. G: Nucl. Part. Phys. **37**, 064008 (2010).
[26] Yu. A. Akulov and B. A. Mamyrin, Phys. Lett. B **600**, 41 (2004).
[27] A. Saenz and P. Froelich, Phys. Rev. C **56**, 2132 (1997).
[28] T. Ohtsuki, K. Ohno, T. Morisato, T. Mitsugashira, K. Hirose, H. Yuki, and J. Kasagi, Phys. Rev. Lett. **98**, 252501 (2007).
[29] A. Smolnikov (GERDA Collaboration), J. Phys. (Conf. Ser.) **203**, 012059 (2010).
[30] G. Alimonti (Borexino Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **600**, 568 (2009).
[31] J. Wolf (KATRIN Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **623**, 442 (2010).
[32] A. Nucciotti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **617**, 509 (2010).
[33] The MARE Collaboration(unpublished), [http://crio.mib.infn.it/wig/silicini/proposal/proposal_MARE_v2.6.pdf]
[34] S. E. Koonin, Nature (London) **354**, 468 (1991).
[35] F. Gatti, F. Fontanelli, M. Galeazzi, A. M. Swift, and S. Vitale, Nature (London) **397**, 137 (1999).
[36] A. Monfardini, G. Benedek, O. Cremonesi, A. Filipponi, A. Nucciotti, and M. Sisti, AIP Conf. Proc. **882**, 144 (2007).