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DOUBLE-BETA DECAY AND RARE PROCESSES
(Elementary Particles and Fields: Experiment)

Beta Decay of ^{115}In to the First Excited Level of ^{115}Sn: Potential Outcome for Neutrino Mass*

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Abstract—Recent observation of β decay of ^{115}In to the first excited level of ^{115}Sn with an extremely low Q_β value ($Q_\beta \leq O(1)$ [keV]) could be used to set a limit on neutrino mass. To give a restriction potentially competitive with those extracted from experiments with ^{3}H ($\simeq$2 eV) and ^{187}Re ($\simeq$15 eV), the atomic mass difference between ^{115}In and ^{115}Sn and energy of the first ^{115}Sn level should be remeasured with higher accuracy (possibly of the order of $\sim$1 eV).

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1. INTRODUCTION

Development of new real-time solar neutrino detectors is of great interest for current particle physics [1]. ^{115}In was proposed long ago [2] as a promising target for solar neutrino spectroscopy, having a low threshold of 114 keV for ν_e capture [3], which allows one to measure the flux of low-energy solar *pp* neutrinos, and a high natural abundance of 95.71% [4]. The process of ν_e capture can be effectively discriminated from the background processes using a specific tag: the emission of a prompt electron after the ν_e capture $^{115}\mathrm{In} + \nu_e \rightarrow {}^{115}\mathrm{Sn}(E_{\mathrm{exc2}} = 613\ \mathrm{keV}) + e^-$ with the subsequent emission, after a typical time delay of $\tau = 4.7\ \mu$s, of two γ quanta with energies of $E_{\gamma 1} = 116$ keV and $E_{\gamma 2} = 497$ keV from deexcitation of the second excited level of ^{115}Sn. Notwithstanding these attractive features, the building of a ^{115}In-based detector is a challenging task because ^{115}In is unstable: it β decays to the ground state of ^{115}Sn (albeit with a big half-life of $T_{1/2} = 4.41 \times 10^{14}$ yr [5]), creating intensive irremovable background. This makes it necessary to divide the detector into small cells and search not only for time but also for space correlation between the emitted electron and the gamma quanta.

The possibility to create a solar neutrino detector with ^{115}In as a target is under investigation in the LENS (Low-Energy Neutrino Spectroscopy) project [6]. In this framework, in particular, In radiopurity and bremsstrahlung from beta decay $^{115}\mathrm{In} \rightarrow {}^{115}\mathrm{Sn}$ were investigated, being important characteristics which could prevent the successful exploitation of time and space correlations. Measurements of an In sample with HPGe detectors were performed deep underground, in the Gran Sasso National Laboratories (Italy), at a depth of 3800 m w.e. As a by-product of these measurements, the β decay of ^{115}In to the first excited level of ^{115}Sn ($E_{\mathrm{exc1}} = 497.4$ keV) was observed for the first time [7]. It has an extremely low intensity (1.2×10^{-6} in comparison to the β decay to ^{115}Sn ground state) and long half-life of $T_{1/2} = 3.7 \times 10^{20}$ yr [7]. These extreme values are related to the very low energy release, $Q_\beta = 1.6 \pm 4.0$ keV, that makes this process the β decay with probably the lowest known Q_β value.

After a brief summary of the experiment and data analysis, we discuss in this paper a possible use of the $^{115}\mathrm{In} \rightarrow {}^{115}\mathrm{Sn}(E_{\mathrm{exc1}} = 497\ \mathrm{keV})$ decay for setting a limit on the neutrino mass.

2. DETECTORS AND MEASUREMENTS

A sample of natural high-purity In with a weight of 928.7 ± 0.1 g was measured with four HPGe detectors mounted in one cryostat with a well in the center. The HPGe detectors were of 225.2, 225.0, 225.0, and 220.7 cm^3 volume and had a typical energy resolution of 2.0 keV (FWHM) at the 1332-keV line of ^{60}Co. The experimental setup was enclosed in a lead and copper passive shielding and had a nitrogen ventilation system against radon. Data were collected

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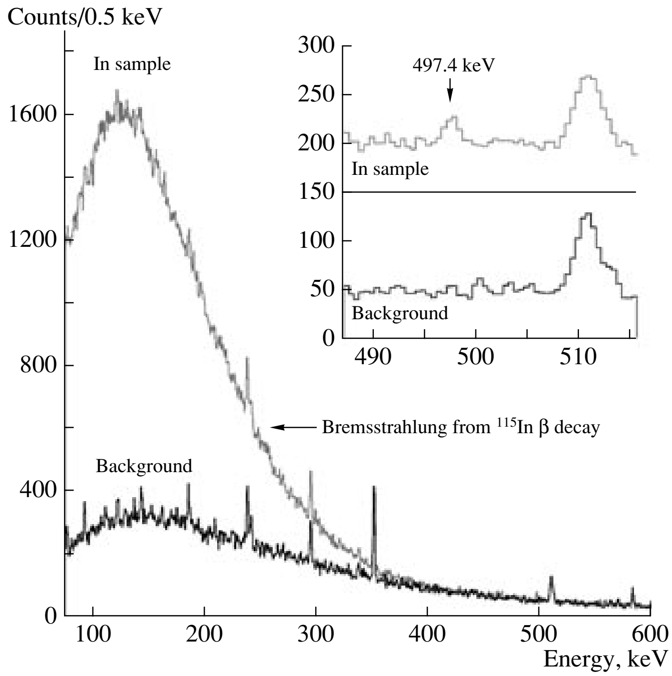

Fig. 1. Experimental spectrum of the In sample (accumulated for 2762.3 h) and background spectrum (1601.0 h) measured with four HPGe detectors at LNGS in the energy interval 70–600 keV. The region of 600–2800 keV, where the spectra are practically indistinguishable, is not shown. Background is normalized to the same counting time. In the inset, the region of the 497.4-keV peak is shown in more detail; here, the In spectrum is shifted upward by 150 counts.

in the Gran Sasso National Laboratories, at a depth of 3800 m w.e. for 2762.3 h for the In sample and for 1601.0 h for the background, in both cases with complete shielding around the detectors.

Statistics in the In and background measurements were accumulated in a few independent runs that resulted in some minor shifts in position of peaks present in the spectra. Internal peaks of known origin and with good statistics were used to recalibrate spectra from individual runs to obtain summed spectra with the help of the SAND0 routine [8]. As a result, the positions of the peaks in the summed spectra deviate from their table values by less than 0.1 keV in the range of 300–2615 keV for both the In and the background measurements.

Efficiency of the detectors for photons emitted from the In sample was calculated with a GEANT4-based code [9]. The results were checked in measurements with a ^{60}Co source, performed with the same setup. The measured absolute efficiencies agree with the computed ones within 12% and are consistent within their statistical uncertainties. In the following, we estimate the systematic uncertainty of the Monte Carlo efficiencies to be 10%.

The measured spectra for the In sample and for the background are presented in Fig. 1. The bremsstrahlung emission from the ^{115}In β decay with end point of 499 keV is clearly visible as the continuous component in the In spectrum. In both spectra, 42 γ lines with energy above 200 keV were found. All lines (except the line with an energy of 497.4 keV in the In sample) were identified; they come from the natural radionuclides and radioactive series (^{40}K, ^{238}U, ^{235}U, ^{232}Th) and from cosmogenic or antropogenic nuclides (^{60}Co, ^{137}Cs, ^{207}Bi, ^{26}Al) that are usually present as contaminations in copper and lead [7]. The counting rates of the γ lines for the In sample and the background were equal within their statistical uncertainties.

The only γ line of the In spectrum which is not present in the background measurement and cannot be ascribed to the usual radioactive contaminants is located at the energy of 497.48 ± 0.21 keV (see inset in Fig. 1). From the fit of the In spectrum in the energy region 487–508 keV with a Gaussian peak and linear background assumption, the net area is 90 ± 22 counts, inconsistent with zero at more than 4σ. Variations of the energy interval for the fit result in changes of the area inside the quoted uncertainty. With the same procedure applied to the background spectrum, no Gaussian peak could be found, and the resulting area is 0 ± 14 counts; the corresponding upper limit derived with the Feldman–Cousins method [10] is 23 counts at 90% C.L. It can hence be concluded that the peak at 497.4 keV is statistically significant and related to the In sample, being absent in the background measurement.

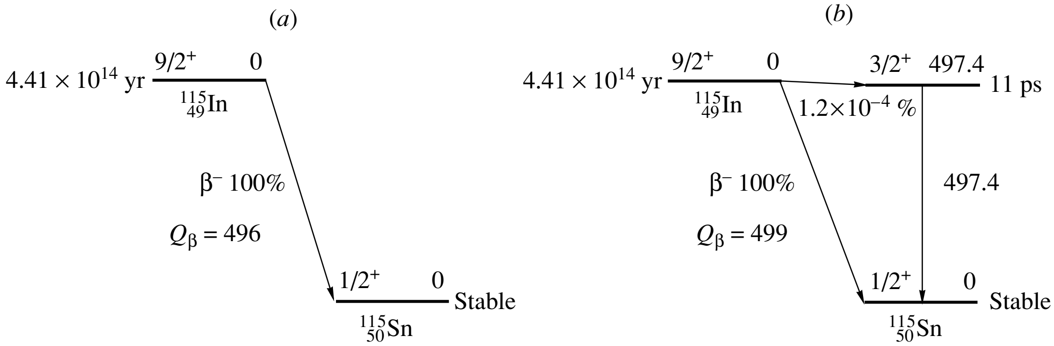

Fig. 2. Old (a) and new (b) schemes of ^{115}In $\to$ ^{115}Sn β decay (energy in keV).

3. DATA ANALYSIS AND INTERPRETATION

The energy of the first excited level of ^{115}Sn, the daughter nucleus after ^{115}In β decay, is equal to 497.35 ± 0.08 keV. If populated, this level deexcites with the emission of a γ quantum with energy $E_\gamma = 497.358 \pm 0.024$ keV [3, 11], which is in nice agreement with that of the observed peak at 497.48 ± 0.21 keV. However, the Q_β value (i.e., atomic mass difference ΔM_a between ^{115}In and ^{115}Sn) given in the atomic mass tables of Audi & Wapstra, known at the time of our measurements, was equal to 495 [12] and 496 keV [13]. Thus, the transition to the first excited level of ^{115}Sn was energetically forbidden[4)], and the β decay of ^{115}In was considered as going exclusively to the ground state of ^{115}Sn [3, 11] (see Fig. 2a).

However, the revised value of $Q_\beta = 499 \pm 4$ keV in the last tables [14] allowed to avoid this contradiction: with this value, the decay to the first excited level $^{115}\mathrm{In} \to {}^{115}\mathrm{Sn}(E_{\mathrm{exc1}} = 497.4\ \mathrm{keV})$ is kinematically allowed, though with an extremely small Q_β value, $Q_\beta = 1.6 \pm 4.0$ keV.

Using the area of the 497-keV peak observed in the indium spectrum, the corresponding partial half-life for the transition to the first excited level of ^{115}Sn can be calculated as

$$T_{1/2}(^{115}\mathrm{In} \to {}^{115}\mathrm{Sn}^*) = \frac{\ln 2 \cdot N \cdot \varepsilon \cdot t}{S \cdot (1+\alpha)}, \qquad (1)$$

where N is the number of ^{115}In nuclei in the sample, ε is the efficiency to detect the full energy γ with the four HPGe detectors, t is the measurement time, S is the area of the peak, and α is the coefficient of conversion of γ quanta to electrons for the given nuclear transition.

The full peak efficiency at 497 keV was calculated with the Monte Carlo simulation as $\varepsilon = (3.32 \pm 0.33)\%$. Taking into account the total mass of the indium sample (928.7 g), the atomic weight of indium (114.818 g mol^{-1} [15]), and the isotopic abundance of ^{115}In (95.71% [4]), the number of ^{115}In nuclei in our sample is $N = 4.66 \times 10^{24}$. With the area of the peak being 90 ± 22 counts, the electron conversion coefficient for the transition $\alpha = 8.1 \times 10^{-3}$ [11], and $t = 2762.3$ h, the $T_{1/2}$ value is equal to

$$T_{1/2}(^{115}\mathrm{In} \to {}^{115}\mathrm{Sn}^*) = (3.73 \pm 0.98) \times 10^{20}\ \mathrm{yr}. \qquad (2)$$

The half-life for the ground state to ground state β decay of ^{115}In, because of the large change in the nuclear angular momentum ($9/2^+ \to 1/2^+$, which classifies this decay as a 4-fold forbidden transition) and of the relatively small Q_β value, is equal to $T_{1/2} = 4.41 \times 10^{14}$ yr [3, 5, 11, 16]. Thus, the probability of decay to the first excited level is nearly one million times lower than for the transition to the ground state of ^{115}Sn; the experimental branching ratio is $b = (1.18 \pm 0.31) \times 10^{-6}$.

The uncertainty on the half-life and on the branching ratio mainly comes from the statistical error on the net area of the 497-keV peak. An updated scheme of the ^{115}In $\to$ ^{115}Sn β decay is presented in Fig. 2b.

4. POSSIBLE IMITATION OF THE EFFECT

In some nuclear processes, γ rays with energies close to 497 keV are emitted. This could give an alternative explanation of the peak observed in the experimental spectrum. Luckily, additional γ rays are also emitted in such decays, allowing one to tag those mimicking effects.

The ^{115}In nucleus has an isomeric state ^{115m}In with the energy $E_{\mathrm{iso}} = 336.2$ keV and a half-life of 4.5 h [3]. With the probability of 0.047%, the ^{115m}In nucleus β decays to the first excited level of ^{115}Sn, with the subsequent emission of a 497-keV γ ray [3, 11]. However, in this case, a γ ray with the energy $E_{\mathrm{iso}} = 336.2$ keV is emitted with much higher probability (45.84% [3]) because of the electromagnetic

[4)]If one forgets about 4-keV uncertainty in the Q_β value [12, 13].

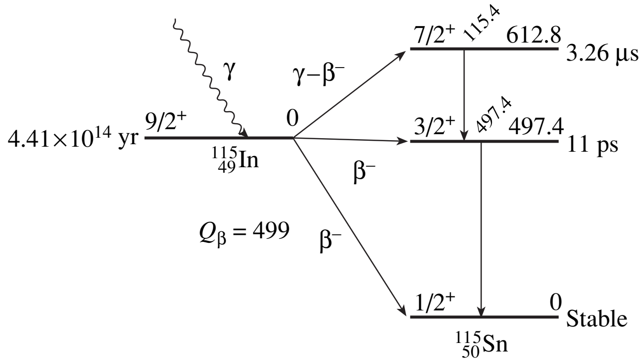

Fig. 3. $\gamma{-}\beta$ Decay of ^{115}In $\rightarrow$ ^{115}Sn. The absorption of the external γ quantum increases the nucleus energy and makes possible the β decay to the excited levels of ^{115}Sn, otherwise energetically forbidden (energy in keV).

transition from the isomeric ^{115m}In to the ground ^{115}In state. This huge peak at 336.2 keV, whose area should be $\sim 10^3$ times bigger than that of the observed 497.4-keV peak, is absent in the experimental spectrum; only a peak at 338.3 keV is observed, with the net area of 138 ± 50 counts, which corresponds to the decay of ^{228}Ac from the ^{232}Th natural chain. Therefore, the decay of the isomeric state ^{115m}In is absolutely negligible and the 497-keV peak cannot be ascribed to it, not even in part.

Thermal-neutron capture by ^{115}In leads to the formation of ^{116}In in an excited state and to a subsequent photon cascade. In particular, a photon of energy 497.7 keV will be emitted with a relative yield of 1.32% [17].[5)] However, the spectrum does not feature an intense accompanying peak at 273.0 keV and, for example, a peak at 492.5 keV (8.68%) (see Fig. 1). Thermal-neutron capture by ^{113}In (its natural abundance being 4.29% [4]) also leads to photon emission at a similar energy of 496.7 keV (0.75%) [17]. However, more intense peaks at 311.6 keV (100%) and 502.6 keV (5%) do not appear in the spectrum either. Thus, owing to underground location of the experimental setup and the low flux of neutrons [18], we conclude that (n, γ) reactions cannot contribute to the peak under analysis.

Protons produced by fast neutron or cosmic ray muons can populate the second excited level of ^{115}Sn ($E_{\text{exc2}} = 612.8$ keV) via the (p, n) reaction on ^{115}In ($E_{\text{thr}} = 0.9$ MeV); the ^{115}Sn nucleus quickly returns to the ground state with the emission of two γ rays of energy 115.4 and 497.4 keV. The contribution originated by fast neutrons is practically zero (see, for instance, [19]) because of the deep-underground location and the lack of hydrogenous materials in the setup. On the other hand, since the muon flux in the laboratory is extremely low (1 $\mu/(\text{m}^2$ h) [20]), also the contribution of (p, n) reactions induced by cosmic rays (see also [21]) to the 497-keV peak is negligible ($<10^{-3}$ counts).

Some decays from the natural ^{238}U and ^{232}Th chains can also give γ rays in the energy region of interest, though with very low intensity. They are, in particular, ^{214}Bi ($E = 496.7$ keV, $I = 0.0069\%$), ^{228}Ac ($E = 497.5$ keV, $I = 0.0059\%$), and ^{234m}Pa ($E = 498.0$ keV, $I = 0.062\%$) [3]. However, the summed contribution of these decays to the 497-keV peak is less than 1 count and can be estimated using their stronger associated γ lines. For instance, the area of the 338.3-keV line of ^{228}Ac, whose relative intensity is 11.27%, is only 138 ± 50 counts. Therefore, if the contamination were located in the In sample, the estimated contribution to the 497-keV peak, taking also into account the different full peak efficiency, would be $(7.3 \pm 2.6) \times 10^{-2}$ counts.

5. β, $\gamma{-}\beta$, AND $\beta{-}\gamma$ DECAYS OF ^{115}In

In addition, possible imitation of the effect could come from the so-called $\gamma{-}\beta$ decay of ^{115}In. In this process, also called induced "photobeta" decay [22], an external γ quantum is absorbed by the nucleus, thereby providing additional energy. This allows the β transition to excited levels of daughter nucleus, otherwise energetically forbidden, or even stimulates the β decay of stable nuclei. In cases when the decay to ground state is strongly suppressed by a large change in the spin (as for ^{115}In $\rightarrow$ ^{115}Sn), transitions to excited levels would be preferable.

The process could be actual in the case of strong electromagnetic fields in stars [22] or in a field of synchrotron radiation [23], but also in the searches for extremely rare processes, like ours. If the ^{115}In nucleus absorbs a γ quantum with energy $E_\gamma > 114$ keV from an external source, or even a bremsstrahlung γ from ^{115}In β decay itself, the second excited level of ^{115}Sn, with energy 612.8 keV, could be populated

5) The intensity of the 273.0-keV γ line is taken to be 100%.

(spin changes from $9/2^+$ to $7/2^+$, and this is an allowed β transition). In the subsequent deexcitation process, two γ's with energies of 115.4 and 497.4 keV will be emitted, thus leading to the peak at 497.4 keV (Fig. 3).

The calculated cross sections of the $\gamma-\beta$ process are quite low: of the order of $10^{-49}-10^{-45}$ cm^2, depending on the Z of the parent nucleus, on E_γ, and on the energy threshold [23]. Nevertheless, it was calculated that, in a field of intensive synchrotron radiation from the SPring-8 source (Japan), the β decay of ^{115}In could go faster by two orders of magnitude [23]. However, in scaling the SPring-8 intensity of $\sim10^{17}$ $\gamma/(\text{s mm}^2\ \text{mrad}^2\ \text{keV})$ to the γ-radiation intensity in our measurements, < 0.1 $\gamma/(\text{s keV})$ (Fig. 1), it is evident that the contribution of $\gamma-\beta$ decay to the 497.4-keV peak is negligible.

It is interesting to note here another interesting process, the so-called $\beta-\gamma$ decay [24]: when the direct β transition to the ground state of the daughter nucleus is highly forbidden, a process could take place in which a γ quantum is emitted simultaneously with the electron and antineutrino. Such a process is second order in perturbation theory and is similar to the double β decay of a nucleus. The branching ratio of such decay for ^{115}In was calculated in [25] as 6.7×10^{-7}. Because in this case three particles (γ, β, and $\bar{\nu}_e$) are emitted with total energy equal to Q_β, and the γ's energy distribution is continuous, the 497.4-keV peak could not be imitated. However, it should be noted that it could be an additional source of γ quanta in the In-based solar neutrino detector (with the branching ratio of $\simeq10^{-6}$, as in β decay $^{115}\text{In} \to {}^{115}\text{Sn}^*$), which also should be taken into account [25].

6. POSSIBLE OUTCOME FOR THE NEUTRINO MASS

With the value of $Q_\beta = 1.6 \pm 4.0$ keV, the decay $^{115}\text{In} \to {}^{115}\text{Sn}^*$ possibly is the β decay with the lowest known Q_β value (to be compared with that of ^{163}Ho, 2.555 keV, and ^{187}Re, 2.469 keV [14]). Below, we will try to determine the Q_β value more exactly on the basis of the systematics of $\log(ft)$ values for such kind of decay and the measured value of $T_{1/2}$.

Nuclear spin and parity are changed in the observed transition from the initial $9/2^+$ of the ^{115}In ground state to $3/2^+$ of $^{115}\text{Sn}^*$; this is therefore a 2-fold forbidden unique β decay. The recent compilation of $\log(ft)$ values [26] gives for such a decay the average value $\log(ft) = 15.6 \pm 1.2$; for the 12 known experimental cases, the range is from 13.9 to 18.0. With the measured value of the half-life of $(3.73 \pm 0.98) \times 10^{20}$ yr, the "experimental" $\log f$ value is $\log f = -12.47 \pm 1.21$. On the other hand, the $\log f$ can be estimated with the help of the LOGFT tool at the National Nuclear Data Center, USA [27], which is based on the procedure described in [28]. For $Q_\beta = 1.6$ keV, the value calculated with the LOGFT code is $\log f = -10.8$; this means that, with such a Q_β, the β decay should go nearly 50 times faster.

One can solve the inverse problem and use the LOGFT code to adjust the Q_β value corresponding to the "experimental" $\log f = -12.47 \pm 1.21$. Such a procedure gives a value of $Q_\beta = 460^{+700}_{-280}$ eV. The lowest value of $\log(ft) = 13.9$ in the range of the known 2-fold forbidden unique β decays [26] corresponds to $Q_\beta = 120$ eV, while the highest value ($\log(ft) = 18.0$) gives $Q_\beta = 2.85$ keV[6].

While possibly the LOGFT tool was not intended to be applied for such low energies, in any case it is clear that the Q_β value in the β decay $^{115}\text{In} \to {}^{115}\text{Sn}^*$ is very close to zero[7]. Such a unique situation could be used to establish a limit on the antineutrino mass, in addition to the experiments with ^{3}H and ^{187}Re, where up-to-date limits are in the range of $\simeq2$ [29] and $\simeq15$ eV [30], respectively. Two approaches could be proposed.

(1) To measure the shape of the β spectrum $^{115}\text{In} \to {}^{115}\text{Sn}^*$, detecting a β particle in coincidence with γ 497 keV, which allows one to reduce the background due to the β decay of ^{115}In to the ground state of ^{115}Sn. New In-based semiconductor detectors or fast bolometers could be used for this purpose. The mass of the antineutrino could be derived from distortion of the spectrum shape (as in ^{3}H experiments). It should be noted, however, that such measurements would be quite difficult because (i) the Q_β value is extremely low, and (ii) the shape of the 2-fold forbidden β decay has to be theoretically calculated very precisely, which may not be so easy also due to the low Q_β value.

(2) Just to use the evident relation $m_\nu < Q_\beta$. Thus, a low Q_β value means also a low limit on neutrino mass. Because the predictive power of any theoretical calculation for such low energies is uncertain, the best way to derive a potentially good limit on m_ν is to measure experimentally with accuracy

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[6] We can derive on this basis the atomic mass difference $^{115}\text{In}-{}^{115}\text{Sn}$: it is equal to $497.9^{+2.3}_{-0.4}$ keV (with the error bars corresponding to the whole range of 13.9–18.0 of $\log(ft)$ values), which is more precise than the recent value of 499 ± 4 keV [14].

[7] Even the history of the Q_β evaluation for ^{115}In gives some indication of this: the Q_β value was slightly lower than 497.4-keV energy of the first excited ^{115}Sn state in accordance with older tables of atomic masses, $Q_\beta = 495 \pm 4$ [12] and 496 ± 4 keV [13], while it is slightly higher in the last evaluation, 499 ± 4 keV [14].

better than current: (i) the atomic mass difference $\Delta M_a(^{115}\mathrm{In}-^{115}\mathrm{Sn})$; (ii) the energy of the first excited level of ^{115}Sn.

The energy of the γ quantum emitted from the first excited ^{115}Sn level is known currently to be 497.358 ± 0.024 keV [3, 11], i.e., with a precision of 24 eV. However, this uncertainty could be reduced further in measurements of the electron capture $^{115}\mathrm{Sb} \to {}^{115}\mathrm{Sn}$. It should be noted that many calibration lines of radioactive sources were already measured with accuracy of 0.1–0.3 eV, also in the ~500-keV region of our interest [3].

The current uncertainty $\delta(\Delta M_a)$ on the atomic mass difference between ^{115}In and ^{115}Sn is equal to 4 keV [14]. It should be noted that modern facilities (Penning traps) make it possible to reach a precision not poorer than 10^{-10} in atomic-mass measurements [31–33], which corresponds to about 10 eV for $A \cong 100$ nuclei. For example, the absolute masses of ^{32}S and ^{33}S were determined in [33] to a precision of 1.5 eV, while the masses of ^{129}Xe and ^{132}Xe were found to within 9 eV. Even smaller uncertainties could be expected in measurements of atomic-mass differences. As the first step, it could be useful to measure $\Delta M_a(^{115}\mathrm{In}-^{115}\mathrm{Sn})$ with a not challenging accuracy of $\simeq$100 eV: if, for example, ΔM_a will be equal to 460 ± 100 eV, it will be enough not to expect a good limit on m_ν. However, if it will be measured as $\simeq 0 \pm 100$ eV, the uncertainty on ΔM_a should be further reduced. In the event that we are lucky and $\Delta M_a(^{115}\mathrm{In}-^{115}\mathrm{Sn}) \simeq E_{\mathrm{exc1}}(^{115}\mathrm{Sn})$, we could obtain $\lim m_\nu$ possibly concurrent with that from experiments with ^{3}H ($\simeq$2 eV) or ^{187}Re ($\simeq$15 eV). Both measurements of E_{exc1} and $\Delta M_a(^{115}\mathrm{In}-^{115}\mathrm{Sn})$ require strong experimental efforts but the physical result could be very interesting and important.

7. CONCLUSIONS

Evidence for the previously unknown β decay of ^{115}In to the first excited state of ^{115}Sn at 497.4 keV was found from the measurement of the γ spectrum of a sample of metallic indium performed with HPGe detectors in the Gran Sasso Laboratory. The Q_β value for this channel is $Q_\beta = 1.6 \pm 4.0$ keV, which could be the lowest of all the known β decays. The branching ratio is found to be $b = (1.2 \pm 0.3) \times 10^{-6}$.

With the measured value of $T_{1/2} = (3.7 \pm 1.0) \times 10^{20}$ yr and calculation of $\log f$ value with the LOGFT code, the derived atomic mass difference between ^{115}In and ^{115}Sn is equal $497.9^{+2.3}_{-0.4}$ keV, which is more exact than the recent value 499 ± 4 keV [14].

The low value of Q_β could be used to set a limit on the neutrino mass. In the case when $\Delta M_a(^{115}\mathrm{In}-^{115}\mathrm{Sn}) \simeq E_{\mathrm{exc1}}(^{115}\mathrm{Sn})$, there is a chance to obtain a result similar to that from the experiment with ^{3}H ($\simeq$2 eV), if we are able to accurately measure $\Delta M_a(^{115}\mathrm{In}-^{115}\mathrm{Sn})$ and E_{exc1} (^{115}Sn), possibly with $\simeq$1 eV uncertainty.

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