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Precise measurement of energies in ^{115}Sn following the (n,γ) reaction

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The first measurement of γ rays from the ^{114}Sn(n,γ) reaction using cold neutrons, performed with an array of Ge detectors at the PF1B facility of the Institute Laue-Langevin in Grenoble, has provided the most accurate energy, $Q_\beta = 173(12)$ eV, of β^- decay of the ^{115}In ground state to the first excited state in ^{115}Sn. This is the lowest of all such energies in the known nuclear landscape. The accuracy of the neutron binding energy of ^{115}Sn and the mass of ^{114}Sn have been improved.

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Precise measurements of the end-point energy of the electrons emitted in β^- decay can be used to determine mass of the electron antineutrino. The fraction of counts in the region of interest, at the end of a spectrum, is inversely proportional to the cube of the end-point energy. Therefore, one should use β^- emitters with low decay energies, Q_β. Two such emitters are tritium, with $Q_\beta = 18.57$ keV (KATRIN experiment [1]) and ^{187}Re with $Q_\beta = 2.47$ keV (MARE experiment [2]).

In 2005 Cattadori *et al.* [3] observed a 497.48(21)-keV γ line populated in β^- decay of ^{115}In and assigned it to the decay of the known $3/2^+$ level in ^{115}Sn [4]. This is schematically shown in Fig. 1. A subsequent Penning trap measurement has determined the Q_β energy of the decay to the ground state of ^{115}Sn to be 497.489(10) keV [5]. Together with the 497.334(22)-keV energy of the $3/2^+$ level in ^{115}Sn [6], this gives $Q_\beta = 155(24)$ eV for the decay to the $3/2^+$ level, which is the lowest known of all such energies. Therefore, the decay of ^{115}In to the $3/2^+_1$ level in ^{115}Sn becomes an interesting candidate for the measurement of the neutrino mass [7] and, importantly, for testing various properties and corrections to β decay measurements, which are indispensable at such low energies. The high accuracy of the Q_β value is of paramount importance for such tests.

The neutron-capture reaction on stable targets is a reliable source of precise γ-energy information, providing neutron-binding energies and rich γ-spectroscopy data for atomic nuclei. As demonstrated in our recent works [8–10], accurate energy measurements from such reactions are possible using an array of Ge detectors. In this work we demonstrate further the potential of this largely unexploited technique, reporting on a precise energy, Q_β, of β^- decay of the ground state of ^{115}In to the first excited state in ^{115}Sn.

The measurement has been performed at the PF1B cold-neutron facility of the Institute Laue-Langevin in Grenoble using an array of 8 large Ge detectors in a close, octagonal geometry [8] to measure γ radiation from the (n,γ) reaction. The 30-mg target enriched to 70% in the ^{114}Sn isotope had the form of a ball of 2 mm in diameter. About 2.3×10^9 single events, collected in triggerless mode using digital acquisition system running with a 40-MHz clock, were sorted into various 2- and 3-dimensional histograms for further analysis.

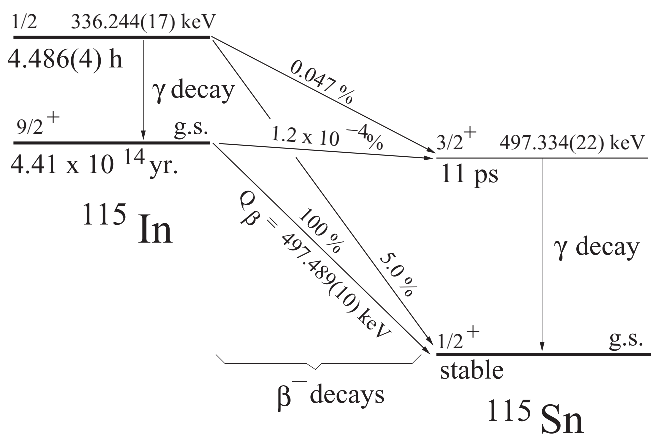

FIG. 1. A scheme of β^- decay of ^{115}In into ^{115}Sn. The data shown in the figure are taken from Refs. [3–6]. See text for further explanation.

Figure 2(a) shows a spectrum of γ rays from the ^{114}Sn$(n,\gamma)^{115}$Sn reaction, with the 497.3-keV line of interest clearly visible. The spectrum is a fragment of the total projection of a $\gamma\gamma$ coincidence matrix sorted with a 200-ns time window. Figure 2(b) shows a spectrum gated on the 489.2-keV line of ^{115}Sn, corresponding to a transition feeding the 497.3-keV level. The gating condition has removed possible contaminations from other nuclei and the 497.3-keV line here is a single, symmetric peak with a well-defined background. This allowed precise determination of the centroid position of the line in channel 482.064(6). Similar, consistent values were obtained from spectra gated on other lines feeding the 497.3-keV level in ^{115}Sn and the weighted average position obtained for the 497.3-keV line is in channel 482.062(5).

To convert this position into an accurate transition energy, precise energy calibration is needed. We have performed various energy calibrations based on energies of known lines

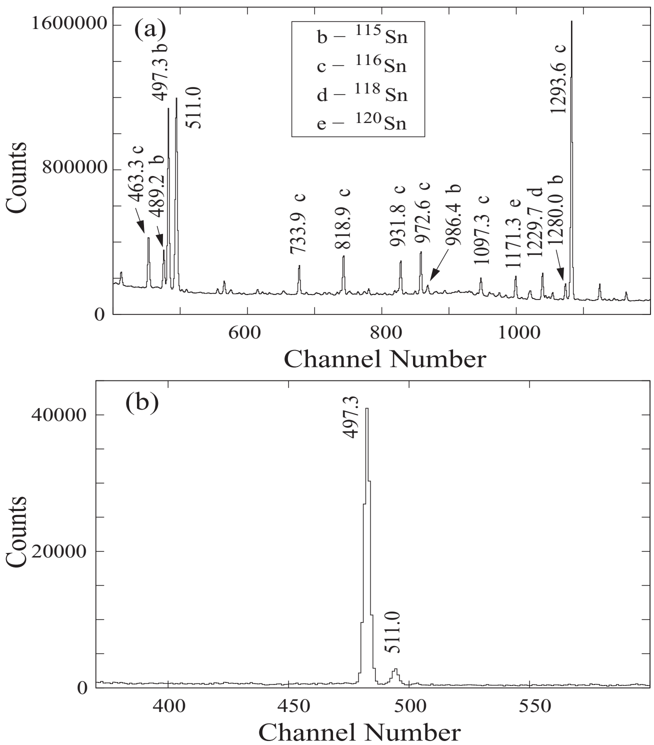

FIG. 2. A γ-ray spectrum from the (n,γ) reaction on the ^{114}Sn target with admixture of other Sn isotopes. Panel (a) shows a fragment of the total projection of a $\gamma\gamma$ matrix and panel (b) shows fragment of a spectrum gated on the 489-keV line.

present in the $\gamma\gamma$ matrix, which are listed in Table I, showing one of the calibrations used in this work to illustrate its precision. This calibration, applied to the position of the discussed line, provides its energy of $E_\gamma = 497.315(7)$ keV, where the statistical uncertainty of the position, 0.005 keV, and the uncertainty of the calibration of 0.005 keV at channel 482.062 are added in quadrature. As a check of the calibration we determined the energy of the nearby 511-keV annihilation line. Its centroid, found in another spectrum gated on the 511-keV line, is in channel 493.803(3). This determines the line energy of 510.994(6) keV (including the 0.005-keV uncertainty of the calibration), which should be compared to the mass of the electron of $m_e c^2 = 510.9989(1)$ keV [17].

We also performed other calibrations using higher-order polynomials and taking a wider range of calibration energies. These calibrations provided consistently similar γ energies for the discussed line, varying between 497.312 and 497.318 keV. Therefore, we adopted the mean value of $E_\gamma = 497.315(7)$ keV. This γ energy corrected for the recoil of the ^{115}Sn nucleus gives the energy of the $3/2^+$, the first excited level in ^{115}Sn, $E_{\rm ex}(3/2^+) = 497.316(7)$ keV. The new excitation energy, together with the 497.489(10)-keV difference between ground-state masses of ^{115}In and ^{115}Sn taken from Ref. [5], provides new $Q_\beta = 173(12)$ eV of the β^- decay of the ground state of ^{115}In to the $3/2^+$ level of ^{115}Sn.

The present Q_β value with improved accuracy is a challenge for theoretical modeling of β decay of ^{115}In, reported recently by Wieslander *et al.* [18]. With their nuclear matrix elements

TABLE I. Data for the energy calibration used in this work. Columns 1, 2, and 3 show, respectively, the origin, energy, and channel position of a calibration line and column 4 displays energies fitted at these positions, using second-order polynomials. Energies of calibration lines are taken from Refs. [11–16].

Nucleus	E_γ (keV)	Position (channel)	Fitted energy (keV)
^{116}Sn	355.481(18)	356.220(15)	355.488
^{116}Sn	416.860(30)	411.620(15)	416.844
^{116}Sn	463.249(26)	452.540(10)	463.255
^{20}F	583.561(16)	555.020(20)	583.555
^{74}Ge	595.851(5)	565.225(10)	595.853
^{116}Sn	656.018(20)	614.480(15)	656.020
^{116}Sn	733.890(30)	676.640(10)	733.868
^{116}Sn	818.721(14)	742.522(10)	818.713
^{74}Ge	867.899(5)	779.900(15)	867.917
^{116}Sn	931.819(20)	827.580(10)	931.807
^{116}Sn	972.585(15)	857.528(10)	972.579
^{116}Sn	1097.325(20)	946.990(15)	1097.334
^{120}Sn	1171.260(20)	998.570(15)	1171.276
^{118}Sn	1229.680(20)	1038.610(20)	1229.691
^{116}Sn	1252.118(24)	1053.820(15)	1252.113
^{116}Sn	1356.850(22)	1123.750(15)	1356.853
^{28}Al	1408.344(9)	1157.480(15)	1408.340
^{28}Al	1622.877(18)	1293.815(15)	1622.869
^{116}Sn	2112.313(22)	1583.190(15)	2112.315

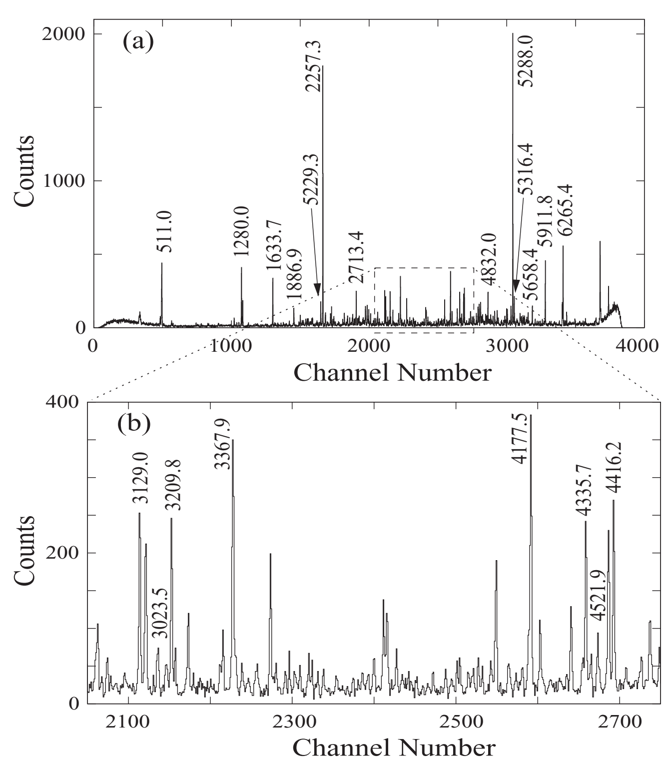

FIG. 3. (a) A γ spectrum from the ^{114}Sn$(n_{th},\gamma)^{115}$Sn reaction, obtained in the present work, containing pairs of γ lines summing to 7545 keV. Panel (b) shows an enlarged fragment of the spectrum shown in panel (a).

(NME) the authors have reproduced well the rate of the β^- decay of the ^{115}In ground state to the ground state of ^{115}Sn. However, for the β^- decay to the $3/2^+$ level, they calculated the half-life much longer than the experimental value of $T_{1/2} = 4.41(6) \times 10^{20}$ yr when using their experimental Q_β. They have shown that their NME values are realistic by reproducing well the decay branching of the $1/2^-$, first excited state at 336.2 keV in ^{115}In to both the ground state and the $3/2^+$ level in ^{115}Sn (see Fig. 1). In this situation, in order to match their calculations to the experiment, they proposed that the decay energy to the $3/2^+$ level is $Q_\beta = 57$ eV. The present $Q_\beta = 173(12)$ eV, which is 8 standard deviations off their calculations, shown in Fig. 6 of Ref. [18], indicates serious discrepancy between state-of-the-art theory and the experimental results.

Wieslander *et al.* have also discussed possible corrections to their calculations, which may occur due to screening by atomic electrons [19,20], changes of the atomic shells [21], the exchange effects [21,22], and the molecular final-state interaction [23]. Modeling of these effects, which are poorly known at low Q_β while being strongly dependent on Q_β, also requires precise Q_β values.

The high accuracy of our E_γ measurements, possible in a wide range of energies from 30 to 8 MeV [8] thanks to the precise energy calibrations based on γ lines of ^{28}Al measured with the Bragg spectrometer GAMS [16], has allowed significant improvement of the neutron binding energy of ^{115}Sn.

We used the characteristic feature of (n,γ) reactions with slow neutrons, namely the precisely defined energy of the capture level, equal within milli-electron-volts to the neutron binding energy, S_n. The capture level decays via various cascades of γ transitions to the ground state. The average value of summed energies of several cascades may provide a very precise S_n value.

To find such cascades, we created a 2-dimensional histogram, sorting on the first axis a signal corresponding to a sum of γ-ray energies observed simultaneously (here within 200 ns) with various Ge detectors of the array and on the second axis the individual energies of these γ rays. In

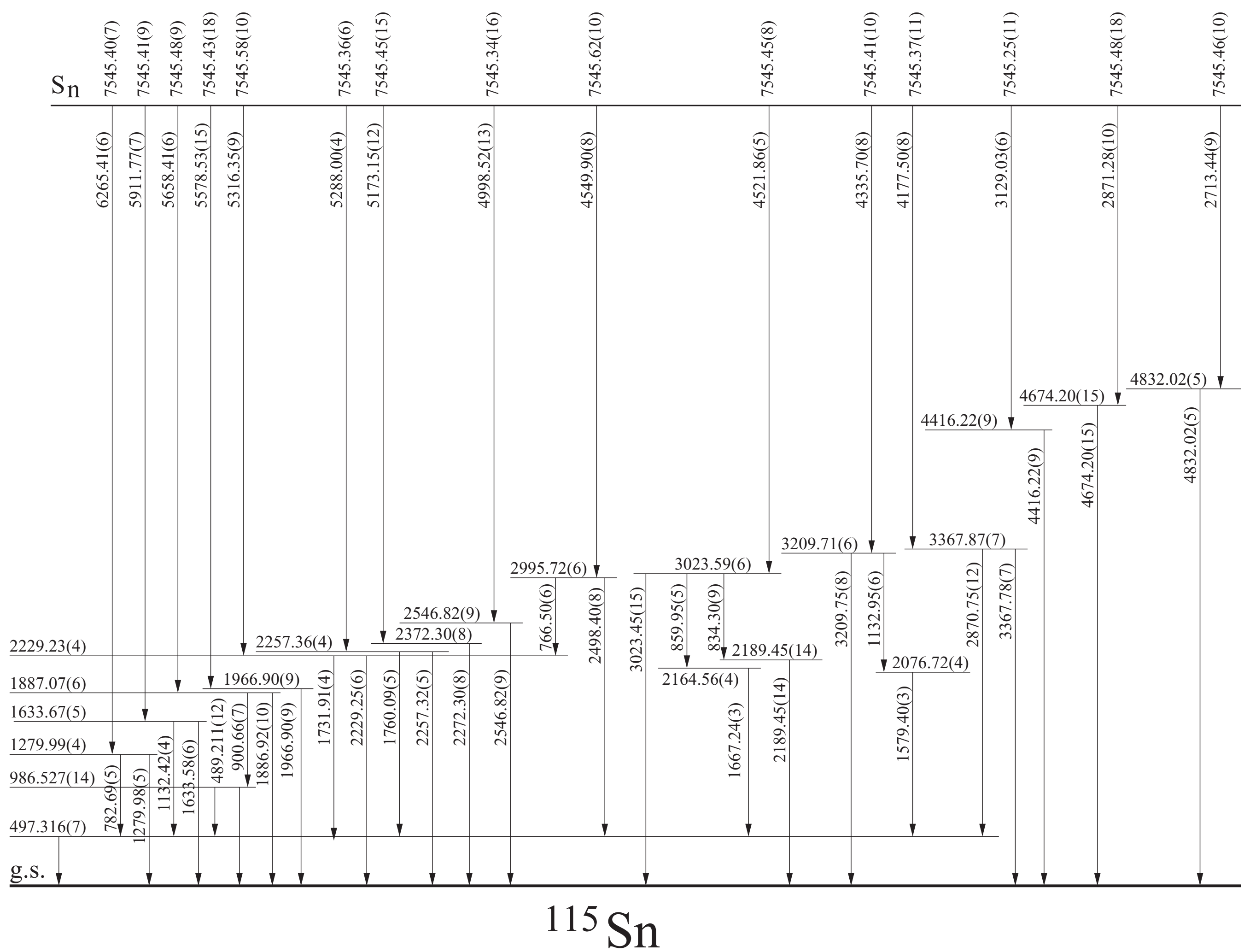

FIG. 4. Partial excitation scheme of ^{115}Sn, populated in the ^{114}Sn$(n,\gamma)^{115}$Sn reaction, using cold neutrons. Energies of transitions shown in the figure are corrected for the recoil of the nucleus. Energies of levels are calculated based on energies of transitions depopulating them.

Fig. 3(a) we show a spectrum gated on the first axis on the line corresponding to the summed energy of 7545 keV, approximately the S_n value of ^{115}Sn. The gate was extending from 7540 to 7550 keV to cover the full sum peak. In the spectrum one observes pairs of transitions summing to 7545 keV. The enlarged fragment of the spectrum shown in Fig. 3(b) reveals further, well-defined $\gamma\gamma$ cascades decaying the capture level in ^{115}Sn.

Using this and other histograms we have extended the previous excitation scheme of ^{115}Sn populated in the ^{114}Sn$(n,\gamma)^{115}$Sn reaction [24]. A full account of the work will be published elsewhere [25] and in this Rapid Communication we show in Fig. 4 a partial decay scheme, with 15 clean transitions decaying the capture level in ^{115}Sn. Energies of all transitions shown in the scheme are corrected for the recoil of the nucleus.

We used energies of primary γ transitions and excitation energies of the levels populated by these transitions to determine excitation energy of the capture level of ^{115}Sn. The 15 independent values shown in Fig. 4 above the capture level are consistent with each other within uncertainties. Their weighted average value, $S_n(^{115}\text{Sn}) = 7545.427(25)$ keV, can be compared to the recent AME12 compilation, $S_n(^{115}\text{Sn}) =$ 7547.8(10) keV [26], and the Nuclear Data Sheets compilation, $S_n(^{115}\text{Sn}) = 7545.8(15)$ keV [6]. Our result is 40 times more accurate. The new $S_n(^{115}\text{Sn})$ value together with the recent precise mass excess of ^{115}Sn of $-90033.833(15)$ keV [26], based on the measurement of Ref. [5], allows significant improvement of the mass of ^{114}Sn. The new mass-excess value of ^{114}Sn, $-90559.72(3)$ keV, can be compared to the $-90557.3(10)$-keV mass excess of ^{114}Sn, reported in the AME2012 compilation [26].

In summary, the first measurement of γ rays following the ^{114}Sn(n,γ) reaction induced by cold neutrons allowed an accurate determination of excitation energies in ^{115}Sn. The 497.316(7)-keV energy of the $3/2^+$, first excited state in ^{115}Sn, measured in this work, together with the accurate masses of ^{115}I and ^{115}Sn [5], provide a very precise energy, $Q_\beta = 173(12)$ eV of β decay of the ^{115}I ground state to the $3/2_1^+$ state in ^{115}Sn. This Q_β value, which is the lowest of all such energies known, points to a significant discrepancy between the experiment and the state-of-the-art calculations of β decays at low energies. The understanding of various corrections in such calculations may be of importance for modeling the shape of the electron spectrum in this decay, which is a potential candidate for the neutrino-mass measurement. The neutron binding energy in ^{115}Sn of 7545.427(25) keV, measured in this work, is more accurate by factor of 40 than the recent AME2012 compilation value [26].

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