Double-β transformations in isobaric triplets with mass numbers $A = 124$, 130, and 136

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The Q values of double-electron capture in ^{124}Xe, ^{130}Ba, and ^{136}Ce and double-beta decay of ^{124}Sn and ^{130}Te have been determined with the Penning-trap mass spectrometer SHIPTRAP with a few hundred eV uncertainty. These nuclides are members of three isobaric triplets with common daughter nuclides. The main goal of this work was to investigate the existence of the resonant enhancement of the neutrinoless double-electron-capture rates in ^{124}Xe and ^{130}Ba in order to assess their suitability for the search for neutrinoless double-electron capture. Based on our results, in neither of these cases is the resonance condition fulfilled.

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I. INTRODUCTION

The discovery of neutrino oscillations has manifested that neutrinos are massive particles. However, it is unknown whether they are their own antiparticles or not, i.e., of Majorana or Dirac type, respectively. At present, the only practical way to answer this question is the observation of neutrinoless double-beta transformations: double-beta or double-positron decay, single-electron capture with an emission of one positron, and double-electron capture. These processes can only occur if the total lepton number is not conserved in weak interaction. In addition, the determination of their half-life can shed light on the magnitude of the effective Majorana neutrino mass. This possibility to explore a set of fundamental problems in one experiment inspired many attempts to search for this unique process in various projects running over reccent decades [1,2], all of them concern the double-electron emission.

A promising alternative to neutrinoless double-beta decay can be neutrinoless double-electron capture: If the initial and final states of the double-electron-capture transition are degenerate in energy, its rate is resonantly enhanced by many orders of magnitude [3]. The neutrinoless double-electron-capture rate is given by

$$\lambda_{\epsilon\epsilon} = |V_{\epsilon\epsilon}|^2 \frac{\Gamma_{2h}}{\Delta^2 + \Gamma_{2h}^2/4} = F|V_{\epsilon\epsilon}|^2, \qquad (1)$$

with the degeneracy parameter $\Delta = Q_{\epsilon\epsilon} - B_{2h} - E^*$, where $Q_{\epsilon\epsilon}$ is the difference between the masses of the mother and daughter nuclides of the transition (Q value), B_{2h} is the energy of the double-electron hole in the atomic shell of the daughter nuclide, and E^* is the nuclear excitation energy of the daughter nuclide. Γ_{2h} is the sum of the widths of the double-electron hole and the nuclear excited state in the daughter nuclide, and F is the resonance enhancement factor. As can be seen from Eq. (1), if the degeneracy parameter Δ is comparable to the value of Γ_{2h}, then the capture rate is resonantly enhanced. $V_{\epsilon\epsilon}$ is the transition amplitude of the process and contains weak current constants, and atomic, nuclear, and neutrino matrix elements [4].

To identify resonantly enhanced transitions it is crucial to know their Q values with an accuracy of a few hundred eV. Recent progress in high-precision Penning-trap mass spectrometry [5] has made it possible to measure the Q values of potential resonantly enhanced transitions [4] with the required accuracy. This has initiated the search for such transitions with Penning traps [6–8]. This search has grown into a systematic measurement campaign mainly conducted with SHIPTRAP [9–14] but also with contributions from other facilities [15,16]. Among the results of this campaign is the identification of a resonant enhancement of neutrinoless double-electron capture in ^{152}Gd [9] and a multiple resonance phenomenon in ^{156}Dy [12].

Here we report on the determination of the Q values of double-electron-capture transitions in ^{124}Xe and ^{130}Ba with the Penning-trap setup SHIPTRAP [17]. These are two out of the three remaining transitions whose Q values have not been known precisely enough before our work. The only transition still not addressed by Penning traps is the double-electron capture in ^{194}Pt. However, even in the case of maximal resonant enhancement this nuclide will not be suitable for the search for neutrinoless double-electron capture due to a vanishingly small abundance of ^{194}Pt in natural platinum and thus unacceptably high costs associated with the necessary enrichment of this isotope. Thus, the present work can be considered the completion of the measurement campaign for the determination of the Q values of potentially enhanced transitions.

In addition, the Q values of the double-beta decays of ^{124}Sn and ^{130}Te and of the double-electron capture in ^{136}Ce have been measured within this work. The Q value of the latter has been measured recently with JYFLTRAP with an uncertainty of 270 eV [16] and deviates by 40(13) keV from

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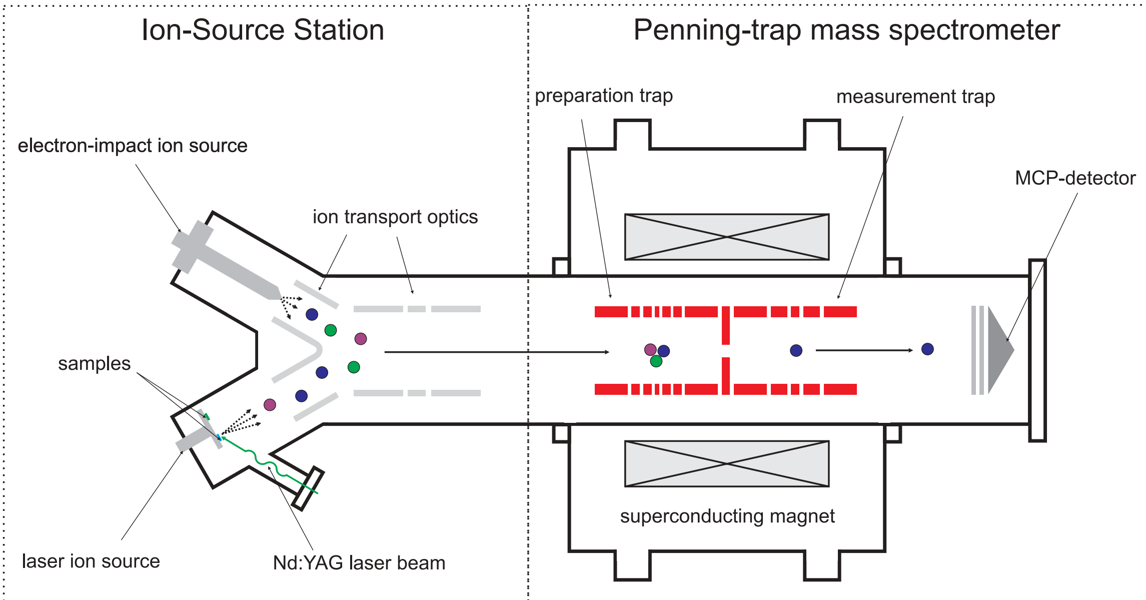

FIG. 1. (Color online) Schematic experimental setup used for the measurements of the Q values at SHIPTRAP.

the value based on the Atomic-Mass Evaluation 2003 [18]. Taking into account the importance of an accurate Q value for the determination of the resonance enhancement in ^{136}Ce an independent measurement of this Q value was warranted.

The Q value of the double-beta decay of ^{130}Te has recently been measured with high precision with JYFLTRAP [19], CPT [20], and FSU-TRAP [21]. The measurement of the FSU group has yielded an uncertainty of only 13 eV. Thus, it provides an ideal opportunity to confirm the reliability of our Q-value measurements.

Another motivation for measuring the Q values of the double-beta transitions in ^{124}Sn, ^{130}Te, and ^{136}Ce along with ^{124}Xe and ^{130}Ba was the fact that these nuclides are members of three isobaric triplets with $A = 124$, $A = 130$, and $A = 136$, respectively. Each triplet contains two nuclides which can undergo double-electron capture and double-beta decay, respectively, to a common daughter nuclide. Only four such triplets are known in the entire chart of nuclides. These are ^{96}Zr $\rightarrow$ ^{96}Mo $\leftarrow$ ^{96}Ru, ^{124}Sn $\rightarrow$ ^{124}Te $\leftarrow$ ^{124}Xe, ^{130}Te $\rightarrow$ ^{130}Xe $\leftarrow$ ^{130}Ba, and ^{136}Xe $\rightarrow$ ^{136}Ba $\leftarrow$ ^{136}Ce. The direction of the arrows indicates a double-beta decay (right) and a double-electron capture (left). These triplets contain common daughter nuclides, namely, ^{96}Mo, ^{124}Te, ^{130}Xe, and ^{136}Ba, respectively. In order to estimate the probabilities of these transitions, it is necessary to calculate their nuclear matrix elements. It is worthwhile to note that a joint consideration of the transitions belonging to the same triplet in such a calculation may be advantageous for the accuracy of this calculation. A definite answer on this is expected from theoreticians who perform such calculations.

^{124}Xe is considered for usage in the large-scale experiment LENA, which plans to utilize 50 kilotons of a liquid scintillator [22], in which up to hundreds of tons of xenon can be dissolved. ^{124}Sn is of interest for the future neutrino cryogenic bolometer station in India [23].

II. EXPERIMENTAL METHOD AND RESULTS

The reported measurements were performed with the Penning-trap mass spectrometer SHIPTRAP [17] by direct high-precision measurements of the cyclotron frequencies of the pairs of singly-charged ions ^{124}Te$^+$-^{124}Xe$^+$, ^{130}Xe$^+$-^{130}Ba$^+$, ^{124}Te$^+$-^{124}Sn$^+$, ^{130}Xe$^+$-^{130}Te$^+$, and ^{136}Ba$^+$-^{136}Ce$^+$. The part of the setup used for this measurement is shown in Fig. 1. It consists of two ion sources for the production of singly charged ions from various chemical compounds and the Penning-trap mass spectrometer. Ions of ^{130}Xe and ^{124}Xe were produced from natural xenon and ^{124}Xe from an enriched sample (grade 99.9%) using a commercial electron-impact ion source SPECS IQE 12/38. A laser-ablation ion source [25] was employed for ionization of the other species, namely ^{124}Sn, ^{124}Te, ^{130}Te, ^{130}Ba, ^{136}Ce, and ^{136}Ba, by irradiating the corresponding samples in oxide or metallic forms with a frequency-doubled pulsed Nd-YAG laser beam.

The ions created were guided from the ion sources into a first trap. This preparation trap acts as a high-resolution mass separator. For the present measurements only the nuclide of interest was forwarded to the second trap. In this measurement trap the cyclotron frequency $\nu_c = qB/(2\pi m)$ of the ion with charge-to-mass ratio q/m in the magnetic field B is measured with the time-of-flight ion-cyclotron-resonance technique (ToF-ICR) [26].

The cyclotron frequencies of ions of the mother and daughter nuclides of a certain transition were measured alternately. To measure the frequencies of the ions with mass numbers 124 and 130 a Ramsey-excitation pattern [24,27,28] of 60-2280-60 ms and/or of 25-950-25 ms was used. The frequency ratios of ^{136}Ba and ^{136}Ce ions were measured with a Ramsey-excitation pattern of 50-900-50 ms. Figure 2 shows typical time-of-flight ion cyclotron resonances of ^{124}Xe$^+$ and ^{130}Te$^+$, respectively. Each resonance contains in total 600 to 800 ions and its acquisition lasted approximately 10 min

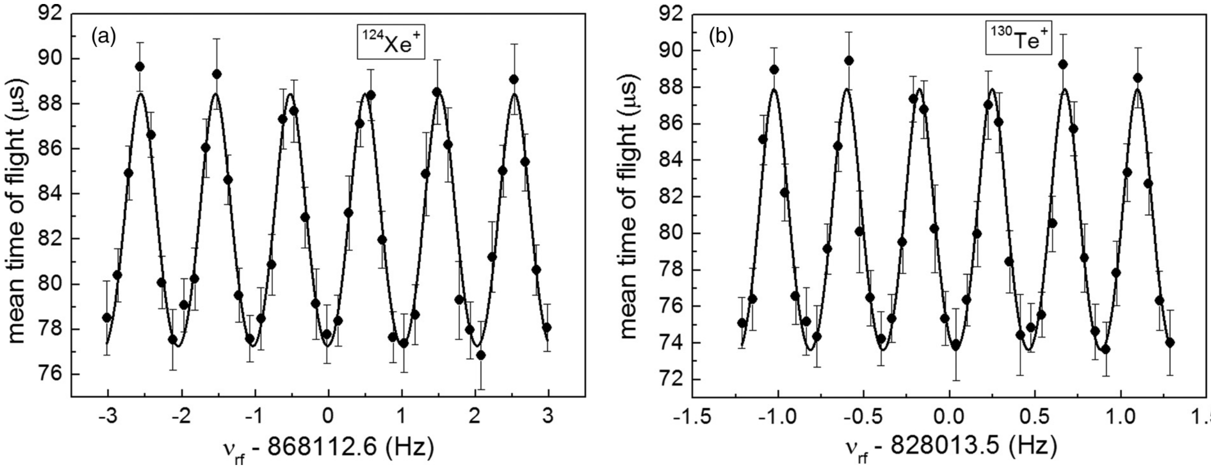

FIG. 2. Typical time-of-flight ion cyclotron resonances of $^{124}Xe^{+}$ (a) and $^{130}Te^{+}$ (b) with 25-950-25 ms and 60-2280-60 ms Ramsey excitation patterns, respectively. The solid line is a fit of the theoretical curve to the data points [24].

for the 25-950-25 ms and 20 min for the 60-2280-60 ms Ramsey-excitation pattern, respectively.

The neighboring measurements of the cyclotron frequency of the reference nuclide, e.g., mother nuclide, performed before and after the frequency measurement of the daughter nuclide in pair were linearly interpolated to the time of the actual measurement of the daughter nuclide, and the frequency ratio of the daughter and mother nuclides at the same time was determined. The frequency ratio for a series of such single frequency ratios is the weighted mean. The nonlinear drift of the magnetic field between two neighboring frequency measurements was negligible and thus was not taken into account. The maximum error of the inner and outer error has been chosen for the weighted mean frequency ratios. The mass-dependent and residual uncertainty were neglected since we measured ratios of the cyclotron frequencies of mass doublets.

The data were divided into five groups according to the number of detected ions in order to investigate possible frequency-ratio shifts due to ion-ion interactions, and only the data with up to 5 ions/cycle were taken into account. No dependence of the ratio on the number of detected ions was revealed. A stabilization system for the temperature in the magnet bore and the pressure in the liquid helium cryostat was implemented to reduce the magnetic field fluctuations [29].

Since the nuclides ^{136}Ce and ^{136}Ba have similar and low first ionization potentials and the same ion production mechanism was employed, it was possible to ensure equal measurement conditions for these nuclides in the measurement trap. It implies that possible shifts of the measured frequencies due to static imperfections of the measurement trap were equal, thus not affecting the frequency ratio on the level of the obtained uncertainty. For the other pairs of nuclides one cannot *a priori* guarantee exactly the same measurement conditions in the measurement trap. Each pair contains dissimilar nuclides with respect to their chemical properties and the employed ion production mechanism. In order to account for a possible

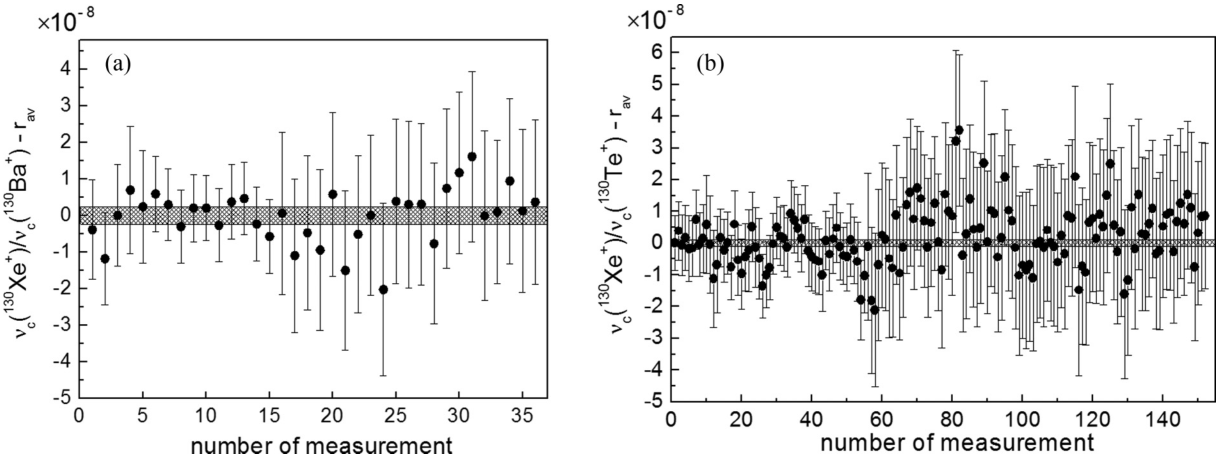

FIG. 3. Cyclotron-frequency ratios of $^{130}Xe^{+}$ to $^{130}Ba^{+}$ (a) and of $^{130}Xe^{+}$ to $^{130}Te^{+}$ (b) measured in this work. The grey shaded band represents the total uncertainty of the weighted mean frequency ratio r_{av}. Frequency ratios 1 to 15 (a) and 1 to 55 (b) have been measured with a Ramsey pattern of 60-2280-60 ms, whereas a Ramsey pattern of 25-950-25 ms has been employed to measure frequency ratios 16–36 (a) and 56–153 (b). For r_{av} see Tables I and II.

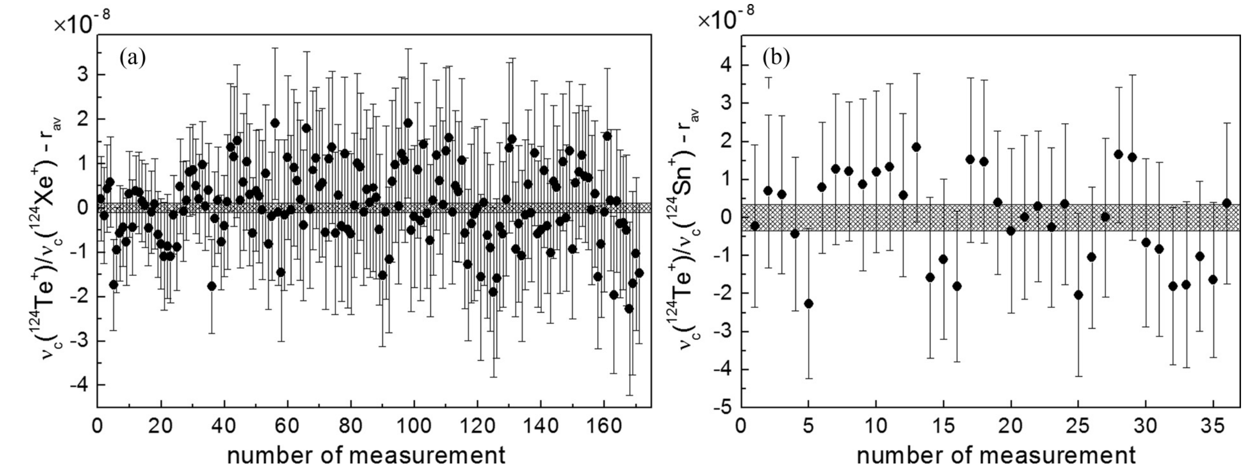

FIG. 4. Cyclotron-frequency ratios of $^{124}Te^+$ to $^{124}Xe^+$ (a) and of $^{124}Te^+$ to $^{124}Sn^+$ (b) measured in this work. The grey shaded band represents the total uncertainty of the weighted mean frequency ratio r_{av}. Frequency ratios 1 to 39 (a) have been measured with a Ramsey pattern of 60-2280-60 ms, whereas a Ramsey pattern of 25-950-25 ms has been employed to measure frequency ratios 40–171 (a) and 1–36 (b). For r_{av} see Tables I and II.

systematic shift in the frequency ratios of the transitions which contain xenon isotopes, the mass difference of ^{130}Te and ^{130}Xe was measured with an uncertainty of approximately 100 eV and compared with the values obtained by three other groups [19–21] (see discussion).

A more detailed description of the analysis of the experimental data obtained with SHIPTRAP during the entire measurement campaign devoted to the Q values of double-electron-capture transitions will be published elsewhere [30].

About 150 frequency-ratio measurements of $^{130}Xe^+$ to $^{130}Te^+$ were performed [Fig. 3(b)]. Similar statistics was acquired for the frequency-ratio measurements of $^{124}Te^+$ to $^{124}Xe^+$ [Fig. 4(a)]. The frequency ratios of $^{130}Xe^+$ to $^{130}Ba^+$ and $^{124}Te^+$ to $^{124}Sn^+$ were measured 36 times each [Figs. 3(a) and 4(b), respectively], whereas 24 measurements were made for the frequency ratios of $^{136}Ba^+$ to $^{136}Ce^+$ (Fig. 5). The weighted mean frequency ratios and the total uncertainties for these transitions were calculated and are listed in the second column of Table I.

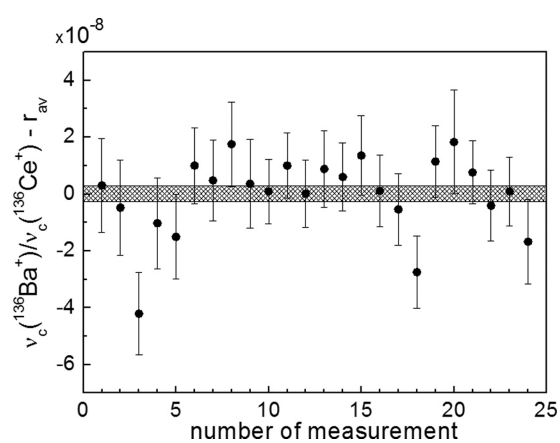

FIG. 5. Cyclotron-frequency ratios of $^{136}Ba^+$ to $^{136}Ce^+$ measured in this work. The grey shaded band represents the total uncertainty of the weighted mean frequency ratio r_{av} as cited in Table I.

From the frequency ratios the Q values are given by

$$Q = M_i - M_f = (M_f - m_e)\left(\frac{\nu_c(M_f^+)}{\nu_c(M_i^+)} - 1\right), \qquad (2)$$

where M_i and M_f are the masses of the mother and daughter atoms, respectively, m_e is the electron mass, and $\nu_c(M_i^+)$ and $\nu_c(M_f^+)$ are the cyclotron frequencies of singly charged ions of the mother and daughter, respectively. The binding energies of the valence electrons of only a few eV have been neglected. The Q values are presented in the third column of Table I.

III. DISCUSSION

A. The isobaric triplet at $A = 124$

In the isobaric triplet with $A = 124$ double-electron capture in ^{124}Xe and double-beta decay of ^{124}Sn proceed to the daughter nuclide ^{124}Te. The decay scheme of these processes is presented in Fig. 6.

The new Q value of double-beta decay of ^{124}Sn measured with an uncertainty of 390 eV deviates from the AME-evaluated value [18] by 4.8(2.1) keV, i.e., by more than two standard deviations. The deviation exceeds the typical resolution of future large-scale experiments [23]. Thus, the present refinement of the Q value is very important for the search for neutrinoless double-beta decay of this nuclide.

In the case of double-electron capture in ^{124}Xe the deviation of [7.7(2.4) keV] between the new and AME-evaluated Q values exceeds three standard deviations.

The main contribution to the mass values of AME for ^{124}Sn, ^{124}Te, and ^{124}Xe is from Ref. [32], performed with the mass spectrometer Manitoba II in 1984. Our Q values for the pairs ^{124}Sn-^{124}Te and ^{124}Xe-^{124}Te differ from the Q values given in Ref. [32] by 2.6(1.0) keV and 8.5(1.8) keV, respectively. Taking into account a rather large discrepancy of our and Manitoba Q values of double-beta decay of ^{124}Te, we compared some Q values as well as absolute masses of

TABLE I. Parameters of potential neutrinoless double-electron-capture transitions ^{124}Xe→^{124}Te, ^{130}Ba→^{130}Xe, and ^{136}Ce→^{136}Ba investigated in this work. The cyclotron frequency ratios r_{av} $\nu_c(^{124}\mathrm{Te}^+)/\nu_c(^{124}\mathrm{Xe}^+)$, $\nu_c(^{139}\mathrm{Xe}^+)/\nu_c(^{130}\mathrm{Ba}^+)$, and $\nu_c(^{136}\mathrm{Ba}^+)/\nu_c(^{136}\mathrm{Ce}^+)$ are given in the second column. $Q_{\epsilon\epsilon}$ is the difference between the initial and final atomic mass, E_γ is the excitation energy of the daughter nuclide, I_f is the total angular momentum and parity of the final state, $B_1 + B_2$ is the sum of the binding energies of two captured electrons; B_{2h}—the energy of the double-electron hole in the atomic shell of the daughter nuclide—is given for ^{124}Te. Also shown are the atomic orbitals of the captured electrons, the determined degeneracy parameter $\Delta = Q_{\epsilon\epsilon} - B_{2h} - E_\gamma$, and the sum of the widths of the double-electron hole Γ_{2h}.

Transition	Frequency ratio r_{av}	$Q_{\epsilon\epsilon}$ (keV)	E_γ (keV)	I_f	$B_1 + B_2$ (keV)	Orbitals	Δ (keV)	Γ_{2h} (eV)
^{124}Xe→^{124}Te	1.0000247520(11)	2856.73(12)	2790.41(9)	(0^+)	$B_{2h} = 64.457(12)$	KK	1.86(15)	20
^{130}Ba→^{130}Xe	1.0000216831(24)	2623.74(29)	2533.4(3)	0^+	69.129	KK	21.21(42)	23
^{136}Ce→^{136}Ba	1.0000187884(27)	2378.49(35)	2315.32(7)	0^+	74.881	KK	−11.71(36)	26

certain nuclides obtained with the Manitoba II spectrometer and the setups based on the Penning traps. The Q value of double-beta decay of ^{130}Te obtained with Manitoba II [33] agrees within the error limits with our Q value measured in this work. The mass value of Manitoba II for ^{28}Si [34] is in agreement with the values performed by MIT [35] and SMILETRAP [36]. The Q values of Manitoba II for the pairs ^{128}Te-^{128}Xe [33] and ^{74}Se-^{74}Ge [37,38] agree with CPT [20] and FSU [8], respectively. The Q value of Manitoba II for double-beta decay of ^{136}Xe [39] differs from FSU [40] and JYFLTRAP values [16] by 0.90(67) keV and 0.87(74) keV, respectively. Thus, the data obtained with Manitoba II in the last two decades are in agreement with the data obtained with the Penning-trap mass spectrometers. On the other hand, the early Q value for ^{76}Ge-^{76}Se obtained with Manitoba II in 1984 [37] differs by more than three standard deviations from their more recent measurement [38] and from Penning-trap measurements [8,41,42]. In addition, a discrepancy between Manitoba II and SMILETRAP for the mass of ^{198}Hg is reported [43]. Therefore, we can conclude that generally the modern data from Manitoba II agrees with the data from Penning trap facilities within two standard deviations but the earlier data might be inaccurate, as in the case of ^{76}Ge-^{76}Se. It is worthwhile to note that we have deviations for the Q values of pairs ^{124}Sn-^{124}Te and ^{124}Xe-^{124}Te which have been measured in a single experiment with Manitoba II. To make a definite conclusion on the Q value of the pair ^{124}Xe-^{124}Te, which is very important for investigations of the double-electron capture in ^{124}Xe, at least one more independent measurement of this Q value should be performed.

Among the possible neutrinoless double-electron capture transitions only those populating nuclear excited states with spin 0 and 1 are expected to result in a reasonable decay rate even for a weak resonant enhancement. Thus, only the transition of ^{124}Xe to the nuclear excited state of ^{124}Te with an energy of 2790.41(9) keV is of interest due to its relatively small degeneracy parameter $\Delta = 1.86(15)$ keV considering a capture of two K electrons. Unfortunately, there is no definite spin-parity assignment for this nuclear state, but a 0^+ spin parity is not excluded. We have estimated the half-life of this particular transition to be approximately 10^{28} years, assuming 0^+ spin parity, a typical nuclear matrix element M of 3, and an effective Majorara neutrino mass of 1 eV.

B. The isobaric triplet at $A = 130$

This triplet is connected by the double-beta decay of ^{130}Te and the double-electron capture in ^{130}Ba to the common daughter nuclide ^{130}Xe. The process scheme is presented in Fig. 7.

The Q value of double-beta decay of ^{130}Te has already been measured with three Penning-trap mass spectrometers [19–21] and hence allows a cross-check of the reliability of the present

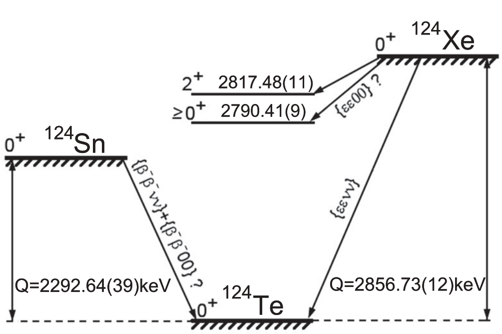

FIG. 6. Decay scheme of double-beta decay of ^{124}Sn and double-electron capture in ^{124}Xe, which both end in a common daughter nuclide ^{124}Te. The nuclear excitation energies [31] and Q values measured in this work are given in keV.

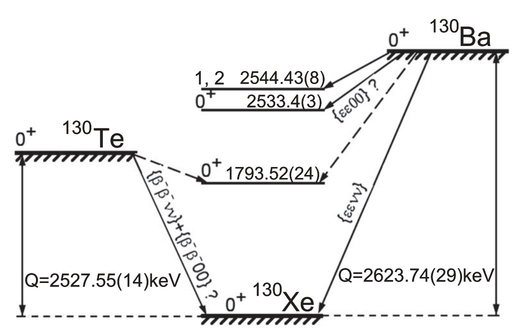

FIG. 7. Decay scheme of double-beta decay of ^{130}Te and double-electron capture in ^{130}Ba, which proceed to a common daughter nuclide ^{130}Xe. The nuclear excitation energies [44] and Q values measured in this work are given in keV. The assignment of the spin value to the nuclear excited state with energy 2533.4(3) keV was made in this work (see text for details).

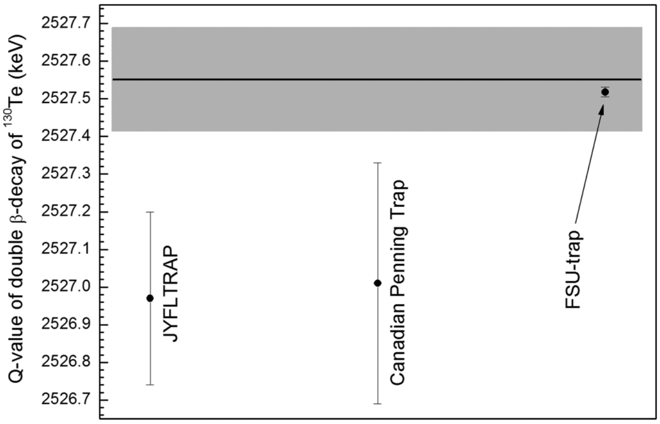

FIG. 8. Comparison of the Q values of double-beta decay of ^{130}Te obtained by JYFLTRAP [19], the Canadian Penning Trap [20], and the FSU-trap [21] with the Q value of this transition determined in this work, represented by the black line and grey shaded band for the weighted mean and its uncertainty, respectively.

measurements. The comparison of our measurements with the Q values obtained by JYFLTRAP, CPT, and FSU-trap is shown in Fig. 8. It is worthwhile to note that JYFLTRAP, CPT, and SHIPTRAP are very similar Penning-trap mass spectrometers which are optimized for mass measurements of short-lived nuclides, have their traps at room temperature, and employ the ToF-ICR detection technique. Since all three Q values of ^{130}Te agree within about two standard deviations and especially the two most precise ones, ours and the one from FSU, are overlapping within one standard deviation, the agreement is very good. Since the pairs from the other isobaric triplets containing xenon isotopes were measured in the same measurement run under similar experimental conditions, their measured Q values can well be considered accurate on the level of the stated precision.

The reported measurement of the Q value of double-electron capture in ^{130}Ba has confirmed the AME-evaluated value on the level of 300 eV. Unfortunately, at present no substantially resonantly enhanced transition in this nuclide is found. The most interesting transition is the one to the nuclear excited state with an energy of 2533.4(3) keV, but without a certain spin assignment in Ref. [44]. According to Ref. [44] this nuclear state has either spin $I = 0^+$ or $I = 1^+$. It is strongly populated in the single beta decay ^{130}Cs→^{130}Xe. Based on the known spin of ^{130}Cs of $I = 1^+$ and with $\log_{10}(ft) = 5.9$, typical for an allowed transition, an assignment as $1^+ \rightarrow 0^+$, $1^+ \rightarrow 1^+$, or $1^+ \rightarrow 2^+$ is possible. Then, this nuclear state decays with a strong γ ray (1997.3 keV) into the nuclear state with an energy of 536.95 keV and spin $I = 2^+$, but there are no photon transitions from the considered nuclear state to the nuclear states with spin $I = 0^+$. Thus, the spin of the nuclear state of interest is presumably $I = 0^+$. If our spin assignment is correct, then double-electron capture to this nuclear state can proceed with a capture of two K electrons, resulting in a degeneracy parameter $\Delta = 21.21(42)$ keV. To calculate the degeneracy parameter, we have approximated the double-electron binding energy B_{2h} by the sum of the binding energies of two K electrons, $B_{2h} = B_K + B_K$ [45]. Such a large degeneracy parameter rules out this transition as a suitable candidate for the search for neutrinoless double-electron capture.

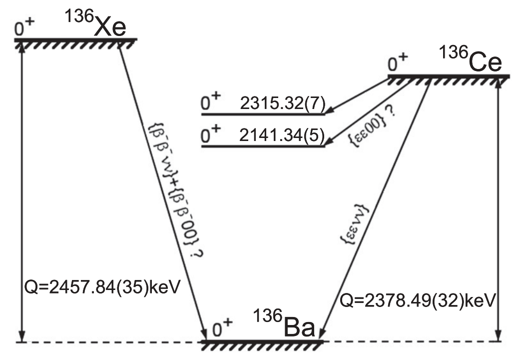

FIG. 9. Decay scheme of double-beta decay of ^{136}Xe and double-electron capture in ^{136}Ce. The nuclear excitation energies [46] and Q values are given in keV. The given Q value of double-electron capture in ^{136}Ce is taken from this work whereas the Q value of double-beta decay of ^{136}Xe is taken as the weighted mean of the Q values from Refs. [16,40].

C. The isobaric triplet at $A = 136$

The decay scheme of this triplet is given in Fig. 9.

Our Q value of double-electron capture in ^{136}Ce with an uncertainty of 350 eV deviates from the AME-evaluated value [18] by 40(13) keV, i.e., by more than three standard deviations. The mass of ^{136}Ba in AME has been derived from reactions ^{135}Ba$(n,\gamma)^{136}$Ba [47,48]. The mass value of AME for ^{136}Ce has been measured in β^+ decay of ^{136}Pr [49] and ^{136}Ce$(n,\gamma)^{137}$Ce reactions [47,50], and with the Minnesota mass-spectrometer [51] giving a small contribution to the mass value of AME. The masses derived from such indirect methods such as β-decay spectroscopy might be inaccurate in a broad range of mass numbers, and have shown already earlier discrepancies with direct methods in a wide range of nuclei [52], which could explain the present disagreement. Our result for the Q value between ^{136}Ce and ^{136}Ba is in a good agreement with the Q value from Ref. [16], and thus confirms the deviation and the conclusion given in Ref. [16] that ^{136}Ce is at present not relevant for the search for neutrinoless double-electron capture.

The present results are summarized in Tables I and II. The Q values $Q_{\epsilon\epsilon}$ have been determined by Eq. (2). In Table I the nuclear excitation energies of the daughter nuclides E_γ and the spin values I_f have been taken from Refs. [31,44,46]. In case the degeneracy parameter was much larger than the width of the intermediate state, the sums of the binding energies $B_1 + B_2$ of the captured electrons have been taken from Ref. [45]. Otherwise B_{2h}—the energy of the double-electron holes in

TABLE II. Final cyclotron frequency ratios r_{av} and $Q_{\beta\beta}$ values for double-beta-decay nuclides measured in this work.

Transition	Frequency ratio r_{av}	$Q_{\beta\beta}$ (keV)
^{124}Sn→^{124}Te	1.0000198645(34)	2292.64(39)
^{130}Te→^{130}Xe	1.0000208882(11)	2527.55(14)

the atomic shell of the daughter nuclide—was calculated within the framework of the Dirac-Fock method [53] including the Breit, quantum electrodynamic, and electron-correlation corrections. The calculations were performed for the Fermi model of the nuclear charge distribution with $\langle r^2\rangle^{1/2} = 4.7621$ fm for ^{124}Xe [54]. The sum of the widths of the double-electron holes Γ_{2h} is taken from Ref. [55].

We have explored in this work three isobaric triplets out of four existing in the chart of the nuclides. The Q value of double-electron capture in ^{96}Ru—the member of the fourth triplet with $A = 96$—has already been determined earlier [11]. Thus, it remains to measure the Q value of the other member of this triplet: double-beta decay of ^{96}Zr by Penning-trap mass spectrometry.

IV. CONCLUSION

The atomic mass differences of ^{136}Ce and ^{136}Ba, ^{130}Ba and ^{130}Xe, ^{130}Te and ^{130}Xe, ^{124}Xe and ^{124}Te, as well as ^{124}Sn and ^{124}Te in the isobaric mass triplets at $A = 136$, 130, and 124 have been determined. Each triplet contains a double-electron-capture and double-beta-decay transition to a common daughter nuclide. The Penning-trap mass spectrometer SHIPTRAP has been used to determine the Q values of these transitions with an uncertainty of a few hundred eV. For the double-electron capture in ^{124}Xe, ^{130}Ba, and ^{136}Ce the degeneracy factors Δ have been determined to assess whether these transitions are suitable candidates for future experiments searching for neutrinoless double-electron capture. The mass differences of ^{130}Ba and ^{130}Xe, ^{124}Xe and ^{124}Te, and ^{124}Sn and ^{124}Te have been directly determined.

In the isobaric mass triplet at $A = 136$ our measurement of the mass difference of ^{136}Ce and ^{136}Ba has confirmed the value obtained by Penning-trap experiments [16].

It has been found that only the transition in ^{124}Xe for a capture of two K electrons to a nuclear excited state with an energy of 2790.41(9) keV, with Δ=1.86(15) keV, is partially resonantly enhanced. However, its half-life is of 10^{28} years and thus this nuclide is still a less favorable candidate than ^{152}Gd for a (potential) search for neutrinoless double-electron capture.

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