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Nuclear Data Evaluation for ^{217}Th

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Thorium-217 was produced by the reaction ^{170}Er (^{50}Ti, xn) $^{220-x}$Th. The nuclei were studied by Evaporation Residues gamma-alpha-gamma coincidence measurements (ER-γ-α-γ). The evaluated decay data for the ^{217}Th nuclide resulted from the above interaction is presented in this report. Three delayed γ-transitions (309, 673 and 1269 keV) have been measured from the ER-γ(-γ)-α correlations and γ-γ coincidences. They were assigned to ^{217}Th, based on the level systematics of the $N = 127$ isotones. The evaluated half-lives $T_{1/2}$ for these levels were assigned to be 64^{+64}_{-22}, 69^{+32}_{-17} and 66^{+27}_{-15} μs, respectively. In addition, an isomeric state $(2252 + x)$ keV is presented in the ^{217}Th decay scheme between the 2252 (21/2+) and 2362 (25/2+) keV. Q (α) has been updated based on the recent published work of the Atomic Mass Evaluation AME2012 as well. Moreover, the total conversion electrons as well as the K-Shell to L-Shell, L-Shell to M-Shell and L-Shell to N-Shell conversion electron ratios have been calculated using BrIcc code v2.3.

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1. Introduction

Valli and Hyde [1] have discovered ^{217}Th in 1968 using beams of ^{16}O of maximum energy of 166 MeV from the Berkeley HILAC. They reported that $^{213-217}$Th resulted from the bombardment of ^{206}Pb targets in (9–5n) fusion-evaporation reactions. Recoils were deposited on a metallic surface in front of a semiconductor detector with a helium gas jet. They reported that the half life $T_{1/2}$ of ^{217}Th is 240(5) μs.

The isotope ^{217}Th was produced by the ^{181}Ta (^{40}Ar, p3n) ^{217}Th reaction in the experiment that was performed at the velocity filter SHIP at GSI, Darmstadt, using a beam of ^{40}Ar of intensities $(1.2-1.5)\times10^{13}$ ions/s [2]. The incident beam energy was 182 MeV. The natural tantalum (99.988% ^{181}Ta) was used in the target, which was produced by sputtering the metal onto a carbon layer with thickness of 40 μg/cm^2. Eight targets were mounted on a target wheel that rotated synchronously with the beam macro structure [3]. The mean thickness of tantalum was 400 μg/cm^2. The evaporation residues, recoiling from the targets with energies of $\approx$ 25 MeV were separated from the primary beam by the velocity filter SHIP [4]. Behind SHIP authors have passed three transmission detectors [5], which were used to discriminate between incoming particles and α-decays (anticoincidence). Finally, the residues were implanted into a position-sensitive 16-strip PIPS detector ("stop detector") with an active area of 80 × 35 mm^2. The α-γ-coincidences analysis by Nishio et al. [6] has lead to a better estimation of the energy of the daughter levels populated by the α-decays. Three αs were measured with energies E_α of 9261, 8725 and 8455 keV. The measured half-lives $T_{1/2}$ were reported to be 0.247(3), 0.293(28) and 0.250(8) ms, respectively [7]. This resulted in an average half-life of 0.237(2) ms. The $Q(\alpha)$ was calculated to be 9435(5) keV from [8].

Heßberger et al. [9] produced ^{215,216,217}Th isotopes from heavy-ion fusion reactions ^{170}Er (^{50}Ti, 3n). The evaporation residues were investigated by α- and α-γ-spectroscopy after in-flight separation from the projectile beam by the velocity filter SHIP and implantation into a 16-strip position-sensitive Si-detector. Three αs were measured with energies E_α of 9268, 8731 and 8459 keV. The average half-life $T_{1/2}$ was 0.247(3) ms. In addition, Nichio et al. [6] has measured the three αs with energies of 9247, 8713 and 8429 keV for the ^{217}Th, that was produced from a ^{28}Si+^{198}Pt fusion reaction with 5αn. The ^{28}Si beam of 140–180 MeV was supplied from JAERI-tandem accelerator and used to bombard the rotating ^{198}Pt targets. The ^{198}Pt targets of 460 μg/cm^2 thickness were made by sputtering the enriched material of a ^{198}Pt isotope on a 0.8 μm aluminum foil. The evaporation residues (ER's) emitted to the beam direction were separated in flight from the beam by the recoil mass separator (JAERIRMS) [10]. The estimated average half-life $T_{1/2}$ was 0.261(+22-18) ms. Meanwhile, one α line was measured by Häusser et al. [11] of energy 9250 keV. The estimated average half-life $T_{1/2}$ was 0.252(7) ms. From the previous measurements, Alkovali [12] has reported an weighted average half-life $T_{1/2}$ to be 0.241(2) ms.

For the evaluated adopted gamma levels for ^{217}Th Akovali [12] has reported that only α-decay of 100% has been observed and J^π for the ground state is 9/2+. Akovali has also reported that there was an isomeric state with energy of 673.8 keV, half-life of 141(40) ns and with J^π of (15/2-), observed in the ^{204}Pb (^{16}O, 3nγ)

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reaction of pulsed 84 MeV from the Chalk River MP tandem accelerator [11, 13]. The beam-pulsing system was located between the injector and the low-energy end of the accelerator. This isomeric state was observed in analogy to the isomeric state that has been observed in the ^{213}Rn and ^{215}Ra. In that experiment, α-particles were observed between beam bursts in a 100 μm-thick annular surface barrier detector, shielded from charged particles coming directly from the target. A transverse magnetic field of 1 kG was applied between the catcher foil and the detector to reduce background from low-energy electrons. Most of the recoils from the (^{16}O, 3nγ) reactions were collected, while background from spontaneous fission and α-activities from heavy ion transfer reactions were strongly suppressed. Moreover, one possible gamma transition from that very weak isomeric state to the ground state was observed. Dracoulis et al. [13] reported that the multipolarity for this gamma transition is (E3) based on the measured internal conversion coefficients $\alpha(K)_{\rm exp} = 0.051(14)$, $\alpha(L)_{\rm exp} \leq 0.030(11)$, and $T_{1/2}(\gamma) \times B(E3)(\text{W.u.}) = 46(17)$. The decay scheme of ^{217}Th, based on the evaluation of Akovali [12] is shown in Fig. 1. However, there are three αs that were recorded in the NUDAT 2.6 hosted by BrookHaven National Laboratory (BNL) website www.nndc.bnl.gov with energies of 9261(4), 8726(4) and 8456(4) keV and with intensities of 94.7, 1.64 and 3.67%, measured by Basunia [14].

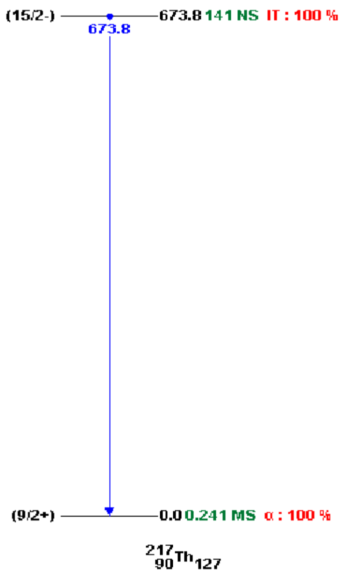

Fig. 1. The decay scheme of ^{217}Th, based on the evaluation by Akovali [12]. Gamma transition energy is shown in blue color, the black lines are for the level energies of ^{217}Th, whereas, the green color is for the half-lives.

This paper presents the results of the new evaluations for ^{217}Th, which have been performed in the framework of the KASCT Research Contract no. 11-MAT2037-03, using the procedures adopted by the DDEP working group. The references cut-off date was 2015, March 31. The calculated and adopted nuclear structure and decay data parameters are important to update the Evaluated Nuclear Structure and Decay Data Files (ENSDF) for the nuclide under consideration, which were appraised in 2003. The complete and updated datasets for ^{217}Th are of great importance for the development of different aspects of nuclear technologies.

2. Procedure for decay data evaluation

The most recently completed decay data for ^{217}Th is presented in the work of Kuusiniemi et al. [15]. In this work, authors have reported that ^{217}Th was produced from the evaporation residues-gamma-alpha-gamma ER γ-α-γ coincidence measurements. The nuclei were produced by the reaction ^{170}ER (^{50}TI, $3n\gamma$) ^{217}Th. ^{50}Ti beam of 4.35 MeV at an intensity of 200 nA was delivered from the UNILAC at GSI, Darmstadt. The target was made of ^{170}Er with thickness of 0.4 mg/cm^2, evaporated on 30 μg/cm^2 thick carbon foils which where mounted on a wheel that had rotated synchronously to the beam macro structure. The ER-recoiling out of the targets were separated from the primary beam by the velocity filter SHIP and implanted on a positive-sensitive 16-strip PIPS-detector, each with an active area of 80 $\times$ 35 mm^2. The ER γ-α-γ correlation/coincidence measurements were performed to identify γ-rays depopulating isomeric states. A Ge-Clover detector constituted of four individual crystals, each of 70 mm in diameter and 140 mm in length was used for measurement of γ-rays. The detector was placed behind the Si detector in close geometry. Coincidences between α and γ were recorded within a 5 μs interval [15]. The Si detector was cooled to a temperature of $\approx$258 K to achieve an energy resolution of $\approx$25 keV (FWHM) for 8 MeV α-particles.

The statistical analysis of γ-ray data and the deduced level schemes were calculated using the computer codes available at Brookhaven Lab's website: www.nndc.bnl.gov. From the gross beta decay theory calculations [11, 13], it has been reported that $T_{1/2}(\varepsilon + \beta^+) \approx$ 1000 s, which yields $\approx$ 0.000025% for the $\varepsilon + \beta^+$ decay branching and that $\text{T}_{1/2}(\beta^+)/T_{1/2}(\alpha) \geq 100$ s/0.019 ms. In addition, the theoretical conversion coefficients were deduced from BrIcc code: v2.3 (29–March–2013) [16] with "frozen orbitals" approximation, and with implicit uncertainty of 1.4%. The $Q(\alpha)$ was calculated using the Atomic Mass Evaluation AME2012 [17].

3. Results and discussion

Three energy levels were observed from the analysis of the ER γ-α-γ coincidence experiment in [15], in addition to a short-lived isomeric state. Moreover, three γ-transitions were measured, but no gamma transition was detected from the isomeric state. The energy levels with their uncertainties, their spin and parities J^π, their half-lives with the associated uncertainties are listed in Table I. Whereas, the gamma-transition energies, their intensities, their associated uncertainties, their assigned multipolarities are listed in Table II.

TABLE I

The energy levels with, their uncertainties, their spin and parities J^{π}, their half-lives $T_{1/2}$ with the associated uncertainties.

Energy levels [keV]	J^{π}	Half-lives ($T_{1/2}$) [μs]
0.0	9/2+	241(5000)
673.30(10)	15/2-	69(+32-17)
1924.16(14)	17/2+	66(+27-15)
2251.91(17)	21/2+	64(+64-22)
2251.9+x*	25/2+	67(+17-11)

*Uncertainties not given by the authors in [15].

TABLE II

Gamma-transition energies E_{γ}, their intensities I_{γ}, their associated uncertainties and their assigned multipolarities.

E_{γ} [keV]	I_{γ}	Multipolarities
673.30(1)	100(7)	(E3)
1269.3 (1)	84(10)	M1+E2
309.30(1)	18(3)	E2

The isomeric transition at $2251.90 + x$ was assumed to be between 2225 and 2362 keV, based on the small number of ^{217}Th K X-rays that were observed in γ-γ coincidences gated by the 309, 673 or 1269 keV γ-rays and that the K-electron binding energy is ≈ 110 keV [15].

The J^{π} were assigned based on the systematics of the lighter $N = 127$ isotones. The half-lives in Table I were extracted from the ER-γ-α correlations, gated by the ground state-to-ground state α-decays of ^{217}Th, within a time interval of 1 ms of α- and γ-decays. From the analyzed data, three transitions were observed with energies of 309, 673 and 1269 keV, respectively. The extracted half-lives were 64^{+64}_{-22}, 69^{+32}_{-17} and 66^{+27}_{-15} μs, respectively. The mean half-life for the isomeric state was estimated to be 67^{+17}_{-11} from the systematic levels in $N = 127$ [15].

GTOL code was used to determine the intensity balance using levels energies obtained from the measured values of the energies of transitions. In addition, the theoretical conversion coefficients were deduced from the BrIcc code: v2.3S (29–March–2011) [16] with "frozen orbitals" approximation and with an implicit uncertainty of 1.4% ($k = 2$ confidence level). The probabilities of internal conversion are represented as conversion coefficients by Eq. (1):

$$\alpha = \frac{\lambda_e}{\lambda_\gamma}. \tag{1}$$

Here, λ_e and λ_γ are the probabilities for emission of conversion electrons and γs, respectively [18]. The total conversion coefficient represents the sum of the probabilities of conversion electrons in different atomic shells as in Eq. (2):

$$\alpha_T = \alpha_K + \alpha_L + \alpha_M + \ldots, \tag{2}$$

where,

$$\alpha_K = \frac{\lambda_K}{\lambda_\gamma},\ \alpha_L = \frac{\lambda_L}{\lambda_\gamma} \text{ and } \alpha_M = \frac{\lambda_M}{\lambda_\gamma}. \tag{3}$$

The conversion coefficients for mixed transitions are given as a function of a mixed ratio δ, as in Eq. (4):

$$\alpha_K = \frac{\alpha_{Ml} + \delta^2 \alpha_{E(l+1)}}{1 + \delta^2}. \tag{4}$$

The calculated internal conversion coefficients $I_{\rm ce}(K)$ and the total internal conversion coefficients $I_{\rm cc}$ with their associated uncertainties for the gamma-transitions are listed in Table III, based on the assigned multipolarities listed in Table II. Moreover, the K-shell to L-shell and L-shell to M-shell and to N-shell conversion electrons ratios K/L, L/M and L/N have been calculated from the calculated results in Table III and are listed in Table IV. The complete decay scheme for ^{217}Th, based on the current evaluation, is shown in Fig. 2.

TABLE III

The internal conversion coefficients $I_{\rm ce}(K)$, the total internal conversion coefficients $I_{\rm cc}$ with their associated uncertainties, calculated using BrIcc.

E_{γ} [keV]	α (K)	α (L)	α (M)	α (N)	$I_{\rm cc}$
673.30	0.0365(7)	0.0211(3)	0.00561(8)	0.00192(22)	0.0654(10)
1269.3	0.010(5)	0.0018(8)	0.00044(19)	0.00012(5)	0.0120(6)
309.30	0.0686(10)	0.0627(9)	0.0168(24)	0.0045(7)	0.1540(22)

TABLE IV

The K-shell to L-shell, L-shell to M-shell and L-shell to N-shell conversion electron ratios for the 673.3, 1269.3 and 309.3 keV gamma lines in ^{217}Th using BrIcc V2.3.

E_{γ} [keV]	K/L	L/M	L/N
673.30(10)	1.74(4)	3.77(8)	14.0(3)
1269.3	5.0(4)	4.0(3)	16.0(10)
309.30	1.095(22)	3.73(8)	13.9(3)

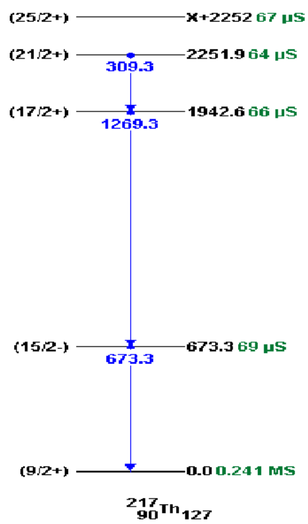

Fig. 2. The complete decay scheme of ^{217}Th, based on the current evaluation. Gamma transition energy is shown in blue color, the black lines are for the level energies of ^{217}Th, whereas, the green color is for the half-lives.

4. Conclusions

In the present paper, the nuclear structure and decay data parameters for ^{217}Th have been evaluated before the cut-off date of March 2015. The Q-values, the total internal conversion electrons as well as the K-shell to L-shell, L-shell to M-shell and L-shell to N-shell conversion electron ratios have been calculated using the codes available from the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory (BNL). Adopted values were recommended for those parameters in the present work. In addition, those recommended values were used to update the Evaluated Nuclear Structure Data Files (ENSDF) for the nuclide under consideration. Moreover, an updated skeleton decay scheme has been presented here. The presented completed ENSDF datasets for ^{217}Th have been sent to NNDC at BNL for updating the online publication of the previous datasets.

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