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α decay of a new isotope ^{209}Th

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The new neutron deficient isotope ^{209}Th has been produced in the reaction of ^{32}S on ^{182}W at beam energy of 171 MeV. Evaporation residues were separated in flight from beam by a JAERI recoil mass separator, and implanted in a position sensitive strip detector. The genetic correlation of α-decay events, their energies and half-lives has been used to identify isotopes. An α-decay energy and a half-life of ^{209}Th have been determined to be 8.080(50) MeV and $3.8^{+6.9}_{-1.5}$ ms, respectively. [S0556-2813(96)01310-6]

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The study of radioactive decay properties of nuclei near the neutron and proton drip lines has been of considerable interest. Extensive studies of their decay Q values have been used to improve the atomic mass formula. This paper presents results which concern the decay of a new isotope, ^{209}Th.

The production of ^{209}Th was achieved using the ^{182}W(^{32}S,5n) reactions with a bombarding energy of 171 MeV. Beams of ^{32}S supplied by the JAERI-tandem accelerator were used to bombard the ^{182}W target of thickness 270 μg/cm^2 evaporated on a carbon backing of 30 μg/cm^2. The evaporation residues (ER's) were separated in flight from the primary beam by the recoil mass separator (JAERI-RMS) [1], which disperses the ER's according to their mass-to-charge ratio m/q at the focal plane.

The ER were implanted in a double-sided position sensitive strip detector (PSSD, horizontal size of 73 mm and vertical size of 55 mm), which provided two-dimensional positions and energies associated with the implantation of the ER and subsequent decays. The PSSD had 15 strips in the front face and 128 strips in the back face. Each strip made on the front face was position sensitive in the horizontal (x) direction and the vertical (y) positions were obtained from the back side strips, where 128 strips were divided into eight groups of 120Ω interstrip to read out a vertical position within a group. The position resolutions Δx and Δy were 0.25 mm and 0.5 mm, respectively.

The PSSD was surrounded by other four single-sided strip detectors (60 mm $\times$ 60 mm, 12 strips). The solid angle of the present detector arrangement was almost 70% of the total solid angle for α particles decaying from implanted ER.

A large size microchannel plate detector (MCP) was positioned at about 30 cm upstream from the PSSD to obtain fast timing signals of the ER. Events associated with the ER coming through the JAERI-RMS were identified by a time-of-flight signal characterized by a coincidence between the MCP and the PSSD, and distinguished from decay events which were characterized by a signal in the PSSD in the absence of a MCP signal.

Energies, horizontal and vertical positions of implanted ER and decay α particles, and flight times of the ER between the MCP and the PSSD were recorded together with the times at which events occurred. The event rate of the ER implanted in the PSSD was very low (2–3 Hz) in the present experiment. This means that the probability of the chance coincidence between the ER and decay α particles detected in the same two-dimensional positions within the uncertainties of Δx and Δy and in relatively short time (for example, 500 ms) in the PSSD is extremely small (approximately 4×10^{-6}). Typical beam intensity was 60 pnA and the total data acquisition time was about 46 h. The time-ordered data were sorted to identify correlated decay events within the position resolution in the PSSD.

The events obtained with time gates of 500 ms for ER-

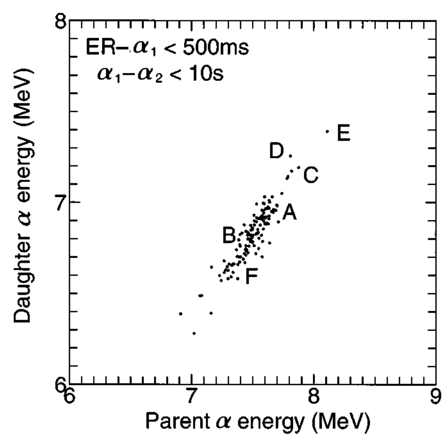

FIG. 1. A two-dimensional matrix showing the correlation between energies of parent and daughter α decays in the reaction of ^{32}S on ^{182}W. Maximum search times were 500 ms and 10 s for the correlations of the evaporation residue-α_1 and $\alpha_1-\alpha_2$, respectively. See text for the correlated events labeled by A, C, D, and E. The correlated events labeled by B and F correspond to the α-particle decays from ^{210,211}Ac and ^{212,213}Ac, respectively. The α-particle decays from ^{206}Ra are also included in the group labeled by F. Escaped events which did not deposit their full energies in the PSSD and the surrounding strip detectors are excluded.

TABLE I. α-particle energies and half-lives of parent activities measured in the present work and compared with earlier measurements if possible. Reduced width W_α is obtained by assuming s-wave α decay.

Nuclei	E_α (MeV) (Present work)	$T_{1/2}$ (ms) (Present work)	E_α (MeV) (Literature)	$T_{1/2}$ (ms) (Literature)	Ref.	W_α (keV)
^{209}Th	8.080(50)	$3.8^{+6.9}_{-1.5}$				76^{+100}_{-60}
^{210}Th	7.810(50)[a]	12.5[a]	7.899(17)	9^{+17}_{-4}	[9]	110^{+120}_{-80}
^{211,212}Th	7.820(50)	41^{+41}_{-14}	7.792(14)[b]	37^{+28b}_{-11}	[9]	56^{+30b}_{-30}
			7.802(10)[c]	30^{+20c}_{-10}	[10]	62^{+40c}_{-30}
^{208}Ac	7.620(40)	83^{+34}_{-19}	7.572(15)	95^{+24}_{-16}	[4]	
^{208m}Ac	7.720(50)	21^{+28}_{-8}	7.758(20)	25^{+9}_{-5}	[4]	
^{209}Ac	7.580(40)	82^{+18}_{-13}	7.581(15)	91^{+21}_{-14}	[4]	

[a]See text.
[b]For ^{211}Th.
[c]For ^{212}Th.

α_1 correlations and 10 s for subsequent $\alpha_1-\alpha_2$ correlations are shown in Fig. 1, where α_1 means an α decay from a parent nucleus (ER) and α_2 the one from a daughter nucleus. Escaped events which did not deposit their full energies in the PSSD and the surrounding strip detectors are excluded in the figure. An energy calibration was performed using the strong α lines observed in the present experiment. α particles from the decay of ^{206}Fr at 6.790(3) MeV, ^{207}Fr at 6.768(3) MeV, ^{208}Fr at 6.641(3) MeV, ^{209}Fr at 6.647(4) MeV and also ^{241}Am source at 5.485 56(12) MeV [2] were used. Actually, average values of 6.779 MeV for ^{206,207}Fr and 6.644 MeV for ^{208,209}Fr were used, because the two α-particle energies of ^{206}Fr and ^{207}Fr and also these of ^{208}Fr and ^{209}Fr could not be resolved by the PSSD. The energy resolution of the present detection system was 98 keV (FWHM) for 6.779 MeV α particles. The estimation of the statistical error for the half-life was made by the method reported in Ref. [3].

Correlated α particles labeled by A in Fig. 1 correspond to the α decays from ^{208,209}Ac. The present data for light Ac isotopes are shown in Table I together with the data reported by Leino *et al.* [4]. In this group, the 12 α_1-α_2 chains were identified to the α-decay chain from the parent nucleus ^{208}Ac, because the measured energy and half-life for the parent decay were consistent with the α decay from ^{208}Ac [4] and the measured energy of 6.980(40) MeV and half-life of $2.3^{+0.9}_{-0.5}$ s for the daughter decay were also consistent with the α decay from ^{204}Fr. Three α decaying states of ^{204}Fr are known, whose energies and half-lives are 7.028(5) MeV and 2.2(2) s [5], 6.973(5) MeV and 3.3(2) s [5], and 7.013 and $\sim$1 s [6].

In addition, three decay chains were observed at a parent decay energy of 7.720(50) MeV and half-life of 21^{+28}_{-8} ms correlated with a daughter decay energy of 6.980(50) MeV and half-life $2.6^{+3.5}_{-1.0}$ s. These decay chains are consistent with the α decay from the isomeric state of ^{208m}Ac [4] and the α decay from ^{204}Fr as quoted above.

The 30 decay chains in the group labeled by A had the average energy of 7.580(40) MeV and the average half-life of 82^{+18}_{-13} ms for the parent decays, and the average energy of 6.910(40) and the average half-life of $2.9^{+0.7}_{-0.5}$ s for the daughter decays. These decay chains were consistent with

TABLE II. Energies, two-dimensional positions, and time intervals of the measured evaporation residues and subsequent decay α particles for ^{209}Th. The events indicated by the time interval of zero represent the ER implanted in the PSSD.

Event no.	Type	Strip no. Front	Strip no. Back	Positions in strip Front (mm)	Positions in strip Back (mm)	E (MeV)	Time interval
1	ER	9	5	4.24	1.32	9.880	0
	α_1	9	5	4.20	1.14	8.109	2.4 ms
	α_2	9	5	4.32	1.76	7.392	87.5 ms
	α_3	9	5	3.07	-	0.074	3.0 s
	α_4	9	5	4.23	1.71	6.444	27.2 s
2	ER	8	5	3.92	1.47	10.44	0
	α_1	8	5	3.92	1.83	8.060	8.6 ms
	α_2	8	5	3.87	-	1.824	28.6 ms
	α_3	8	5	3.74	-	0.487	8.7 s
	α_4	8	5	3.84	1.40	6.397	64.2 s

the α decay from the parent nucleus ^{209}Ac [4] and the observed daughter decays were also consistent with the α decay from ^{205}Fr, where the energy of 6.917(3) MeV [2] and the half-lives of 3.96(4) s [7] and 3.7(1) s [8] were reported.

Four α_1-α_2 correlated chains labeled by C in Fig. 1 have an average energy of 7.820(50) MeV and an average half-life of 41^{+41}_{-14} ms for the parent decays and the average energy of 7.160(50) MeV and the average half-life of $1.9^{+1.9}_{-0.6}$ s for the daughter decays. The observed energy and half-life for the parent decay are consistent with the α decays from ^{211}Th [9] and ^{212}Th [10]. These two α particles decaying from ^{211}Th and ^{212}Th could not be resolved in energy and also in half-life in the present experiment. The observed daughter decay is also consistent with the α particles decaying from ^{207}Ra and ^{208}Ra, whose energies and half-lives are 7.133(5) MeV and 1.3(2) s for ^{207}Ra [11], and 7.133(5) MeV and 1.4(2) s for ^{208}Ra [11], respectively.

One α_1-α_2 chain labeled by D was observed at the parent energy of 7.810(50) MeV and the time interval 12.5 ms between the ER event and the subsequent decay event. The observed energy of the correlated daughter decay and the observed time interval between the α_1 and the α_2 are 7.260(50) MeV and 714 ms, respectively. The observed daughter decay is consistent with the known α-particle energy of 7.262(15) MeV and the known half-life of $0.4^{+0.7}_{-0.16}$ s for ^{206}Ra [9]. Although the observed energy of the parent decay is about 90 keV smaller than the known energy of 7.899(17) MeV for the α decay from ^{210}Th [9], the observed time interval is consistent with the half-life of 9^{+17}_{-4} ms for the α decay from ^{210}Th [9]. The energy difference of 90 keV is larger than the experimental error. Since the measured daughter decay is in good agreement with the α decay from ^{206}Ra, this energy difference 90 keV probably comes from the escape of the first α particle from the PSSD and this decay chain is probably originating from the decay of ^{210}Th, although firm conclusions cannot be reached without more statistics.

Two observed α_1-α_2 correlated chains, one of which is labeled by E, are listed in Table II together with the observed positions in the PSSD, energies, and also the time interval between the subsequent decay events. The third and the fourth columns represent the strip number of the front side strips and the group number of the back side strips of the PSSD. The fifth and the sixth columns represent the horizontal and vertical positions of these events within the specified front strip and back group numbers. The observed energies and the time interval are shown in the seventh and the eighth columns. As shown in Table II, five particle correlations including the ER were observed in each decay chain.

The first event shows that the observed α-particle energy of 7.390(50) MeV for a daughter decay (α_2) is consistent with the reported α energies of 7.360(20) MeV [12] and 7.355(10) MeV [13] for ^{205}Ra and the observed time interval 87.5 ms between the α_1 and the α_2 is also consistent with the reported half-lives of 220(60) ms [12] and 120^{+107}_{-49} ms [13] for ^{205}Ra. The event α_3 occurred 3.0 s after the daughter decay deposits only 74 keV in the PSSD and the observed horizontal position is shifted about 1.1 mm from the position where the parent ER was implanted. This correlated event α_3 probably originates from the ground daughter decay. The reason is that this small energy deposit, which is very close to an electric noise level of the detector, gives rise to a large position uncertainty and also no event except the event α_3 was detected in the strip number 9 during the time period between the daughter decay α_2 and the event α_4. In this case, the vertical position could not be measured because a signal from the back side strips of the PSSD was smaller than the one from the front side strips and also an electric noise level of the back side strips was even higher than the one of the front side strips. The observed time interval 3.0 s is consistent with the reported half-lives of 3.8(4) s [14] and $1.7^{+1.5}_{-0.7}$ s [13] for the α decay from the isomeric state of ^{201m}Rn. The half-life of 7.0(4) s [14] has also been reported for the α decay from the ground state of ^{201}Rn. The observed energy of 6.440(50) MeV for the event α_4 is consistent with the reported energy of 6.385(24) MeV [2] and 6.362(12) MeV [13] for the decay from the isomeric state of ^{197m}Po. The observed time interval 27.2 s between the α_3 and the α_4 is also consistent with the reported half-lives of 26(2) s [15] and 27(3) s [13] for ^{197m}Po. Therefore, it is concluded that this correlated chain originates from the α-particle decay from a new isotope ^{209}Th.

The other correlated decay chain listed in Table II shows that the events α_2 and α_3 escaped from the PSSD and only parts of their energies were detected. Measured horizontal positions for these events coincides with the position of the ER within the experimental error 0.25 mm. The time interval 28.6 ms between α_1 and α_2, and the time interval 8.7 s between α_2 and α_3 are consistent with the known half-lives for the α-decay states from ^{205}Ra and ^{201}Rn as quoted above, respectively. It is emphasized that the probability of the chance coincidence to find α_2 and α_3 at the implanted position x of the ER during the time interval about 8.7 s is approximately 3×10^{-4}. The observed energy 6.400(50) MeV and the observed time interval 64.2 s between α_3 and α_4 are also consistent with the α decay from ^{197m}Po as quoted above.

We conclude that the observed two decay chains listed in Table II correspond to the α decays from new isotope ^{209}Th. The obtained average energy and half-life for ^{209}Th are shown in Table I together with the other Th isotopes observed in the present experiment. The reduced width W_α obtained from the present data for ^{209}Th is shown in Table I together with the ones for the neighboring nuclei which were obtained from the data of [9,10]. The values of W_α were obtained by assuming s-wave α decay and using the formalism developed by Rasmussen [16]. The obtained reduced width for ^{209}Th is consistent with neighboring even-even nuclei within experimental error.

The production cross section for ^{209}Th was determined to be $\sim$1 nb. This is an approximate value since the estimation of the transmission of the ER in the JAERI-RMS suffers from lack of knowledge concerning the angular distribution of the ER.

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