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INVESTIGATION OF 0^+ STATES IN ^{228}Th VIA TWO-NEUTRON TRANSFER: EXPERIMENTAL DATA

The excitation spectra in the deformed nucleus ^{228}Th have been studied by means of the (p, t) reaction, using the Q3D spectrograph facility at the Munich Tandem accelerator. The angular distributions of tritons were measured for about 110 excitations seen in the triton spectra up to 2.5 MeV. Firm 0^+ assignments are made for 17 excited states by comparison of experimental angular distributions with the calculated ones using the CHUCK3 code. Assignments up to spin 6^+ are made for other states.

Keywords: 0^+ states, collective bands, moments of inertia, nuclear models.

Introduction

After the first observation of a large number of excitations with the $L = 0^+$ transfer in the (p, t) reaction seen in the odd nucleus ^{229}Pa [1], it was logical to investigate such excitations in the even-even nucleus ^{228}Th, since ^{229}Pa corresponds to ^{228}Th + p, as well as in other actinide nuclei. Such measurements were carried out for the nuclei ^{228}Th, ^{230}Th and ^{232}U, and the results of a limited analysis have been published in [2] (besides the earlier preliminary study of ^{228}Th and ^{232,234,236}U in [3]). The paper [2] concentrated only on the energies of the excited 0^+ states in these actinide nuclei and the (p, t) transfer strengths to these states. The (p, t) reaction, however, gives much more extensive information on specific excitations in these nuclei, which was not analyzed previously. Such information was obtained for ^{230}Th in our paper [4] after detailed analysis of the experimental data from the (p, t) reaction. For the 0^+ excitation, we were able to derive additional information on the moments of inertia, which can be useful in clarifying the structure of these excitations. In this paper we present the results of a careful and detailed analysis of the experimental data from the high-resolution study of the ^{230}Th(p, t)^{228}Th reaction carried out to obtain deeper insight into all excitations in ^{228}Th. The total picture for ^{228}Th has to differ from the one for ^{230}Th, since the first one is considered as an octupole soft and the latter as a vibration-like nucleus. It would be interesting to compare the 0^+ excitations in the even nucleus ^{228}Th and the odd nucleus ^{229}Pa, the data for which in the low-energy part of excitations are known from the publication [1].

Information on excited states of ^{228}Th prior to this study was obtained mainly from the α-decay of ^{232}U, the β- and EC-decay of ^{228}Ac and ^{228}Pa, as well as from the (α, xnγ)- reaction. The most complete information was obtained from the β-decay of ^{228}Ac reported by Dalmasso et al. [5] and from the EC-decay study of ^{228}Pa by Weber et al. [6]. The lowest collective bands in ^{228}Th were studied in the (α, xnγ)-reaction [7]. A total of 58 levels were reported in [5] and 80 levels were observed in [6] below 2.1 MeV, connected by more than 240 γ-rays.

Present results, derived from the ^{230}Th(p, t)^{228}Th reaction, lead to about 163 levels in the energy range up to 3.25 MeV. Unfortunately, during the experiment the radioactive target was destroyed and assignments were made only for 106 levels in the range up to 2.5 MeV. Energies and cross sections for one angle were obtained additionally for 57 levels. Besides 0^+ excitations, where the number of reliable assignments could be increased for five states in comparison with the preliminary analysis in publication [2], information on the spins for many other states was obtained. This information was essentially complementary to what was known from publications [5, 6]. Some levels are grouped into rotational bands, thus allowing to derive the moment of inertia for some 0^+, 2^+ and 0^-, 1^-, 2^-, 3^- bands [8].

Details of the experiment

A radioactive target of 100 μg/cm^2 ^{230}Th with half-life $T_{1/2} = 8 - 10^4$ years, evaporated on a 22 μg/cm^2 thick carbon backing, was bombarded with 25 MeV protons at an intensity of 1 - 2 μA from the Tandem accelerator of the Ludwig-Maximilians-Universitat and Technische Universitat Munchen. The isotopic purity of the target was about 99 %. The tritons were analyzed with the Q3D magnetic spectrograph and then detected in a focal plane detector. The focal plane detector is a multiwire proportional chamber with readout of a cathode foil structure for position determination and dE/E particle identification [9, 10]. The acceptance of the spectrograph was 11 msr, except for the most forward angle of 5° with an acceptance of 6 msr. The resulting triton spectra have a resolution of 4 - 7 keV (FWHM) and are background-free. The angular distributions of the cross sections were obtained from the triton spectra at ten laboratory angles from 5 to 40° for energies up to 1800 keV, but only at five angles from 7.5 to 30° for energies from 1800 to 2500 keV. The energies and cross sections for the states from 2500 to 3250 keV were measured only for 10°.

A triton energy spectrum measured at a detection angle of 10° is shown in Fig. 1. The analysis of the triton spectra was performed with the program GASPAN [11]. For the calibration of the energy scale, the triton spectra from the reactions $^{184}W(p, t)^{182}W$, $^{186}W(p, t)^{184}W$ and $^{234}U(p, t)^{232}U$ were measured at the same magnetic settings.

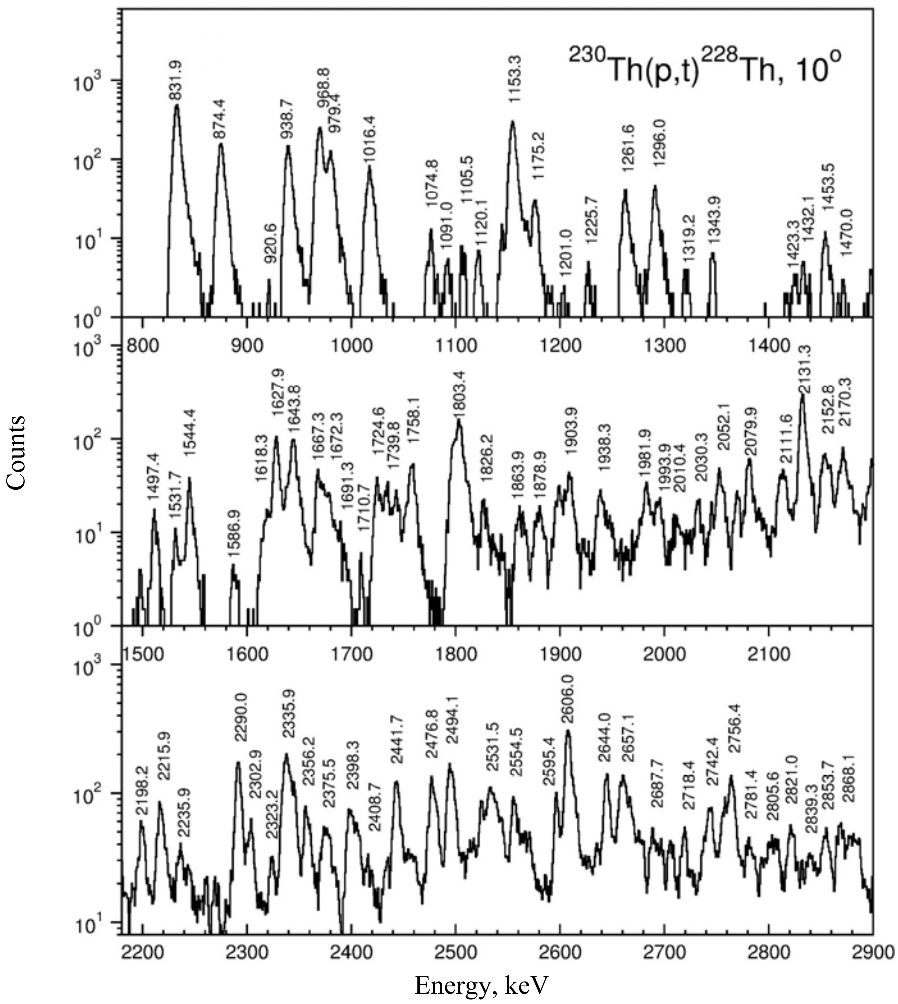

Fig. 1. Triton energy spectrum from the $^{230}Th(p, t)^{228}Th$ reaction (E_p = 25 MeV) in logarithmic scale for a detection angle of 10°. Some strong lines are labeled with their corresponding level energies in keV.

From 106 levels identified in the spectra, 60 levels were identified for all ten angles and 46 levels only for 5 angles. They are listed in Table 1. The energies and spins of the levels as derived from this study are compared to known energies and spins, mainly from the published data [5, 6]. They are given in the first four columns. The ratios of cross sections at angles 7.5 and 26° to the one at 16°, given in the next two columns, help to highlight the 0^+ excitations (large values). The column labelled $\sigma_{integ.}$ gives the cross section integrated in the region from 7.5 to 30°. The column titled $\sigma_{exp.}/\sigma_{calc.}$ gives the ratio of the integrated cross sections, from experimental values and calculations in the DWBA approximation. The last column lists the notations of the schemes used in the DWBA calculations: sw.jj means one-step direct transfer of the $(j)^2$ neutrons in the (p, t) reaction; notations of the multi-step transfers used in the DWBA calculations are displayed in Fig. 2. Additionally, energies of 57 levels seen only in the spectrum measured at 10° and corresponding cross sections are listed in Table 2.

Table 1. **Energies of levels in ^{228}Th, the level spin assignments from the CHUCK analysis, the (p, t) cross sections integrated over the measured values and the reference to the schemes used in the DWBA calculations (see text for more detailed explanations)**

Level energy, keV		I^π		Cross section ratios		$\sigma_{integ.}$, μb	Ratio $\sigma_{expt.}/\sigma_{calc.}$	Way of fitting
This work	[5, 6]	[5, 6]	This work	7.5°/16°	26°/16°			
0.0 *2*	0.00	0^+	0^+	5.83	5.61	165.56	6.20	sw.gg
57.8 *2*	57.76	2^+	2^+	1.59	0.68	37.07	8.30	m1a.gg
186.8 *2*	186.83	4^+	4^+	0.74	0.38	9.07	1.90	m1a.gg
328.0 *2*	328.00	1^-	1^-	0.45	0.66	0.82	0.50	m2a.gg
378.2 *2*	378.18	6^+	6^+	0.58	0.71	4.48	1.60	m2a.gg
396.9 *2*	396.08	3^-	3^-	0.54	0.33	2.89	0.56	m3a.gg
519.2 *3*	519.20	5^-	(5^-)	1.23	1.33	0.43	0.90	sw.gg
622.5 *4*	622.50	8^+	(8^+)	0.20	0.94	0.26		
695.6 *3*	695.50	7^-	(7^-)	0.15	0.41	0.37		
831.9 *2*	831.83	0^+	0^+	12.06	7.50	39.10	360	sw.ii
874.4 *2*	874.42	2^+	2^+	1.22	0.58	9.57	160	m1a.ii
911.6 *5*	911.80	10^+						
920.6 *5*	920.80	9^-						
938.7 *2*	938.55	0^+	0^+	18.38	7.21	6.83	8.20	sw.ii
943.8 *4*	944.18	1^-	1^-	0.12	0.67	0.37	1.00	sw.gg
	968.33	2^-						
	968.43	4^+						
968.8 *2*	968.97	2^+	2^+	0.67	0.47	20.0	132	sw.ig
979.4 *2*	979.51	2^+	2^+	0.78	0.59	9.25	55.6	sw.ig
1016.4 *2*	1016.43	$2^+, 3^-$	3^-	0.80	0.47	5.37	1.10	m3a.gg
	1022.53	3^+						
	1059.93	$3^-, 4^-, 4^+$	(4^-)					
1074.8 *3*	1074.8	4^+	4^+	0.74	1.32	1.62	0.26	m1a.gg
1091.0 *3*	1091.01	4^+	4^+	0.74	0.44	0.42	0.10	m1a.gg
1105.5 *3*			6^+	0.61	0.56	0.77	21.0	sw.ii
1120.1 3	1120.1	0^+	0^+	2.63	3.71	1.24	0.03	sw.gg
	1122.95	2^-						
1142.8 *3*	1143.2	5^-	5^-	0.80	0.98	1.10	26.0	sw.jj
1153.3 *3*	1153.48	2^+	2^+	0.65	0.49	23.89	140	sw.ig
1168.0 *4*	1168.37	3^-	3^-	0.36	0.58	0.68	1.00	sw.gg
	1174.52	5^+						
1175.2 *4*	1175.41	2^+	2^+	1.05	0.91	2.09	13.0	sw.ig
1201.0 9	1200.54	3^+	3^+	0.31	1.10	0.40	0.56	m2a.gg
1225.7 *6*			4^+	1.00	0.64	0.25	1.75	sw.jj
	1226.55	4^-						
1261.6 *3*	1261.5	4^+	4^+	1.33	1.12	3.64	67.0	sw.ii
1270.2 *6*	1270.0		6^+	0.40	0.97	0.31	0.15	sw.gg
1290.4 *3*	1290.2	4^+	4^+	1.14	0.88	3.59	67.0	sw.ii
1296.0 5	1297.34	5^-	(5^-)	1.33	1.23	0.50	1.00	sw.gg
1319.2 *4*			(2^+)	0.74	1.08	0.24	1.50	sw.ig
1343.9 *5*	1344.03	3^-	3^-	0.77	0.33	0.31	0.08	m3a.gg
	1393.4	$1^+, 2, 3^-$						
1415.8 *6*	1415.92	$2^+, 3^-$	(3^-)	1.15	1.20	0.05	2.80	sw.jj
1423.8 *5*			(2^+)	2.20	1.33	0.16	0.03	m1a.gg
1432.1 *5*	1431.98	$3^+, 4^+$	4^+	1.61	1.17	0.21	6.80	sw.ii
	1448.80	$3, 4^-$						
	1450.29	$3^-, 4^-$						
1453.5 *5*			(3^-)	0.61	0.63	1.34	1.80	sw.jj
1470.0 *5*			(6^+)	0.94	1.81	0.19	0.01	m3a.gg
1497.4 *4*	1497.7	$4^+, 5^-$	(5^-)	1.07	0.91	0.37	0.56	sw.gg
1511.2 *3*			0^+	7.96	6.96	2.13	1.10	sw.ig
1531.7 *3*			0^+	2.21	0.83	0.47	2.60	sw.ii
plus	1531.48	3^+	3^+				0.02	m2a.gg

Continuation of Table 1

Level energy, keV		I^{π}		Cross section ratios		$\sigma_{integ.}$, μb	Ratio $\sigma_{expt.}/\sigma_{calc.}$	Way of fitting
This work	[5, 6]	[5, 6]	This work	7.5°/16°	26°/16°			
	1539.13	(2, 3)						
1544.4 *3*			2^+	1.27	0.65	1.61	1.53	m1a.gg
	1581.0	(2^-)						
1586.9 *4*			2^+	0.98	0.71	0.31	1.00	sw.jj
	1588.33	4^-						
1613.0 *5*			4^+	1.06	1.26	0.54	12.0	sw.ii
1618.3 *5*	1617.74	$(3, 4)^+$	4^+	0.88	0.76	1.22	0.16	m2a.ii
1627.9 *3*			0^+	7.44	5.21	9.66	10.0	sw.ig
1638.4 *4*	1638.25	2^+	2^+	0.59	0.37	1.45	23.5	sw.ii
	1643.18	$(2, 3)^-$						
1643.8 *3*	1643.8	$(2, 3, 4)^+$	4^+	1.58	1.08	8.54	160	sw.ii
	1645.89	3^+						
1651.4 *3*			(3^-)	0.08	0.79	0.86	1.20	sw.gg
1667.3 *5*	1667.3		2^+	0.71	0.61	3.17	46.0	sw.ii
1672.3 *5*			2^+	0.91	0.53	1.85	3.80	sw.jj
1678.4 *5*	1678.4	$2, 3, 4^+$	2^+	0.88	0.75	1.48	19.5	sw.ii
	1682.70	$(3, 4)^+$						
	1683.74	(4^-)						
	1688.39	3^+						
1691.3 *4*			0^+	2.66	2.06	1.26	0.75	sw.ig
	1707.2	$2, 3^-$						
1710.7 *6*			0^+	1.38	1.86	0.54	0.01	sw.gg
1724.6 *4*	1724.29	2^+	2^+	1.06	0.66	2.73	5.50	sw.ii
1733.8 *4*	1735.62	4^+	4^+	1.13	0.86	2.28	3.50	sw.ij
1742.8 *4*	1743.86	$3, 4^+$	4^+	0.81	0.56	1.36	0.16	m2a.gg
1750.7 *3*			0^+	1.27	1.84	1.75	0.70	sw.jj
1758.1 *3*	1757.9	$1^-, 2, 3^-$	2^+	0.85	0.75	4.35	26.0	sw.ig
	1758.24	$(3, 4)^+$						
	1760.25	$(2, 3,4)^+$						
	1795.9	$3^-, 4^+$						
1796.8 *3*	1796.4	$3^+, 4, 5^+$	4^+	1.40	0.83	6.47	89.0	sw.ig
	1797.65	$(2^+, 1^-)$						
1803.0 *4*	1802.9	$1^-, 2, 3^-$	2^+	0.65	0.49	15.34	90.0	sw.ig
	1804.60	(4^+)						
	1811.5	$1^-, 2, 3^-$						
1812.7 *4*			(6^+)	1.35	1.63	0.62	0.04	sw.ig
	1817.43	4^-						
	1823.4	$3^-, 4, 5$						
1826.2 *4*			(4^+)	1.16	0.83	1.91	7.50	sw.ij
1840.3 *8*	1842.2	$2^+, 3^-$		1.41	0.33	0.21		
1858.6 5			(6^+)	0.65	1.19	1.28	0.06	sw.ig
1863.9 *5*	1864.8	$1^-, 2, 3^-$	(2^+)	0.75	0.79	1.47	8.10	sw.ig
	1876.5	$3^-, 4, 5^-$						
1878.9 *5*	1879.0	$3^-,4, 5^-$	(3^-)	1.05	0.91	1.93	110	sw.ii
	1892.98	3^+						
1898.2 *4*	1899.98	2^+	(2^+)	0.84	0.81	2.55	140	sw.ii
	1901.90	4^+						
1903.9 *4*			(6^+)	0.69	1.58	1.54	0.07	sw.gg
	1906.78	$(2^+,1^-)$						
	1908.4	3^-						
1908.9 7			0^+	2.17	1.91	4.56	1.30	sw.jj
	1924.1	$2^-, 3, 4$						
	1924.6	$(4, 5^+)$						
1925.4 *4*	1925.20	4^+	$4^+, 5^-$	0.61	1.73	0.54	21.0	sw.ii
	1928.54	3^+						
	1937.16	$(3, 4)^+$						
1938.3 *4*	1938.9	4^+	(4^+)	1.06	0.76	1.99	0.67	m2a.gg
	1944.85	3^+						
	1945.8	$4^+, 5^-$						

Continuation of Table 1

Level energy, keV		I^π		Cross section ratios		σ_{integ},. µb	Ratio $\sigma_{expt.}/\sigma_{calc.}$	Way of fitting
This work	[5, 6]	[5, 6]	This work	7.5°/16°	26°/16°			
1947.8 *7*			(2^+)	1.02	0.75	0.77	3.50	sw.ig
	1949.7	1^+, 2, 3^+						
1959.7 *6*	1958.5	2^+	(2^+)	0.10	1.69	0.43	1.50	sw.ig
	1964.90	(2^+)						
1971.7 *4*			$(2^+, 3^-)$	0.66	0.81	0.79	3.10	sw.ig
	1974.20	4^+						
1981.9 *4*	1981.97 1987.46	3, 4^+ 4^+	(3^-)	1.68	0.77	1.70	2.60	sw.gg
1993.9 *5*			(3^-)	0.97	0.72	1.80	2.80	sw.gg
2010.4 *6*	2010.15	2^+, 3, 4^+	(2^+)	0.46	0.43	0.76	13.0	sw.ig
	2013.6	$(3, 4)^+$						
	2016.75	4^+, 5^-						
	2022.73	2^+						
2030.3 *4*	2029.6	(2^+)	2^+	0.54	0.23	0.84	16.0	sw.ig
	2037.0	$(3, 4)^+$						
2044.7 *5*			0^+	9.22	4.56	0.57	0.26	sw.gg
2052.1 *4*			(6^+)	0.72	1.30	3.70	180	sw.ii
2069.6 *5*			2^+	0.76	0.56	1.38	6.10	sw.ig
2079.9 *5*			0^+	17.08	13.13	4.62	25.9	sw.ii
2091.2 *7*			(6^+)	0.62	0.82	1.20	35.0	sw.ii
2111.6 *5*			(2^+)	0.70	0.71	2.57	11.0	sw.ig
	2123.1	$(3, 4)^+$						
2131.3 *6*			0^+	6.84	4.53	24.80	120	sw.ii
2152.8 *4*			(4^+)	1.30	0.90	4.13	98.0	sw.ii
2159.4 *6*			(0^+)	3.78	1.54	1.18	8.10	sw.ii
2170.3 *4*			(2^+)	1.00	0.85	5.61	26.0	sw.ig
2198,2 *4*			2^+	0.59	0.62	3.81	19.5	sw.ig
2215.9 *4*			(4^+)	1.40	1.15	6.00	130	sw.ii
2235.2 *7*			(4^+)	0.98	0.86	2.82	61.0	sw.ii
2290.0 *7*			0^+	9.96	5.75	11.00	61.0	sw.ii
2302.9 *5*			(4^+)	1.09	0.84	2.75	62.0	sw.ii
2323.2 *5*			2^+	0.41	0.62	2.24	16.0	sw.ig
2335.9 *5*			(4^+)	2.13	1.65	17.10	0.50	sw.gg
		or	(0^+)			4.50[a]	25.0	sw.gg+14
2344.2 *5*			(3^-)	0.77	0.58	6.65	10.0	sw.gg
2356.2 *5*			(2^+)	0.63	0.61	4.61	21.5	sw.ig
2375.5 *8*			(2^+)	0.78	0.60	4.87	22.0	sw.ig
2398.3 *9*			(3^-)	0.76	0.75	7.36	11.0	sw.gg
2408.8 9			(4^+)	1.87	1.28	2.34	60.0	sw.ii
2441.7 *5*			(2^+)	0.71	0.51	10.32	47.0	sw.ig
2456.8 *5*			(0^+)	16.18	1.27	0.53	52.0	sw.ii
2476.7 *5*			(2^+)	0.62	0.52	10.38	48.0	sw.ig
2375.5 *8*			(2^+)	0.78	0.60	4.87	22.0	sw.ig
2494.1 *5*			(2^+)	0.65	0.47	12.74	63.5	sw.ig

a - The value after subtracting a constant of 14 µb (see text below).

DWBA analysis

The spins of the excited states in the final nucleus ^{228}Th were assigned via an analysis of the angular distributions of tritons from the (p, t) reaction. The angular distributions for 0^+ excitations have a steeply rising cross section at very small reaction angles, and a sharp minimum at a detection angle of about 14°. This pronounced feature helped to identify most of these states in complicated and dense spectra, even without fitting experimental angular distributions. No complication of the angular distributions was expected, since the excitation of 0^+ states predominantly proceeds via a one-step process. This is not the case for the excitation of states with other spins, where multi-step processes could play a very important role.

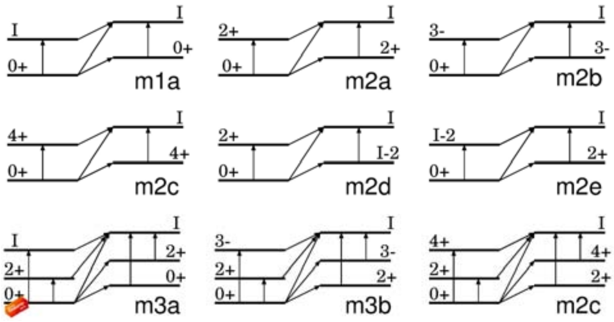

Fig. 2. Schemes of the CHUCK3 multi-step calculations tested with spin assignments of excited states in ^{230}Th (see Table 1).

Table 2. **Energies and cross sections of the ^{230}Th(p, t)^{228}Th reaction for the states for which measurements were carried out only at 10°**

E, keV	$d\sigma/d\Omega$, μb/sr	E, keV	$d\sigma/d\Omega$, μb/sr	E, keV	$d\sigma/d\Omega$, μb/sr
2513.5 *7*	2.00	2742.3 *4*	5.50	3035.6 *9*	0.95
2531.5 *7*	6.60	2763.7 *4*	8.60	3046.4 6	2.10
2536.8 *9*	3.20	2781.4 *5*	1.75	3059.2 *5*	2.15
2542.4 *9*	1.85	2798.6 8	1.55	3075.2 *5*	2.20
2554.5 *5*	6.00	2805.6 *7*	2.00	3085.2 8	1.25
2566.3 6	2.20	2821.0 *5*	2.90	3097.0 6	3.10
2595.4 *5*	5.40	2839.3 6	1.30	3104.7 6	3.40
2606.1 *5*	23.5	2853.7 *5*	2.75	3112.7 *11*	1.70
2615.1 *9*	0.15	2868.1 *5*	3.20	3119.9 *9*	2.30
2634.8 *5*	1.60	2877.5 8	1.80	3128.2 *10*	1.25
2644.0 *3*	9.20	2883.7 *9*	1.60	3158.8 8	1.50
2657.1 *4*	5.20	2918.8 6	1.85	3165.7 6	2.00
2660.1 *5*	6.00	2927.4 *5*	3.25	3186.0 6	2.00
2667.1 *5*	3.30	2936.8 *9*	1.40	3195.2 6	2.60
2676.0 6	67.2	2945.3 *9*	1.35	3209.6 *12*	1.40
2688.4 *4*	2.10	2955.1 8	1.25	3214.8 *9*	2.20
2695.6 *7*	1.10	2993.1 *12*	1.00	3225.0 *20*	0.50
2705.5 *5*	1.35	2999.5 *10*	1.50	3232.9 *13*	1.20
2718.4 *5*	2.10	3014.3 *11*	0.80	3239.9 8	3.40

The identification of these states is possible by fitting the experimental angular distributions with those calculated in the distorted-wave Born approximation (DWBA). The potential parameters suggested by Becchetti and Greenlees [12] for protons and by Flynn *et al.* [13] for tritons were used in the calculations. These parameters have been tested via their description of angular distributions for the ground states of ^{228}Th, ^{230}Th and ^{232}U [2]. Minor changes of the parameters for tritons were needed only for some 3^- states [14]. For each state the binding energies of the two neutrons are calculated to match the outgoing triton energies. The corrections to the reaction energy are introduced depending on the excitation energy. For more details see [4].

A problem arising in such calculations is the lack of prior knowledge of the microscopic structure of these states. We can assume, however, that the overall shape of the angular distribution of the cross section is rather independent of the specific structure of the individual states, since the wave function of the outgoing tritons is restricted to the nuclear exterior and therefore to the tails of the triton form factors. To verify this assumption, DWBA calculations of angular distributions for different $(j)^2$ transfer configurations to states with different spins were carried out in our previous paper [4]. The coupled-channel approximation (CHUCK3 code of Kunz [15]) was used in these calculations. Indeed, the calculated angular distributions are very similar. Nevertheless, they depend to some degree on the transfer configuration, the most pronounced being found for the 0^+ states, what is confirmed by the experimental angular distributions. The best reproduction of the angular distribution for the ground state was obtained for the transfer of the $(2g_{9/2})^2$ configuration in the one-step process. This orbital is close to the Fermi surface and was considered as the most probable one in the transfer process. Other transfer configurations that might be of importance are $(1i_{11/2})^2$ and $(1j_{15/2})^2$, also near the Fermi surface. Better reproduction of the angular distribution for some 0^+ states is obtained just for these configurations. The main features of the angular distribution shapes for 2^+ and 4^+ states are even more weakly dependent on the transfer configurations. Nevertheless the $(2g_{9/2})^2$, $(1i_{11/2})^2$ and $(1j_{15/2})^2$ configuration, alone or in combination, were used in the calculations for these states too.

Results of fitting the angular distributions for the states assigned as 0^+ excitations are shown in Fig. 3. The agreement between the fit and the data is excellent for most of the levels. Remarks are needed only for the levels at 1531.7 and 2335.9 keV. The spin 3^+ was assigned to the level at 1531.47 keV in [5, 6]. A level at the close-lying energy of 1531.7 keV has been observed also in the (p, t) reaction, but the angular distribution of tritons cannot be fitted by calculations for transition to the 3^+ state. The maximum cross section for forward angles suggests the presence of a 0^+ excitation, though the angular distribution fitted by a calculation for transfer of the $(1i_{11/2})^2$ configuration to the 0^+ state is not perfect. A satisfactory fit of the experimental angular distribution was obtained assuming overlapping states with spins 0^+ and 3^+ (see Fig. 3), thus confirming the assignment for both states. An ambiguous picture is observed for the 2335.9 keV state, where the angular distribution is measured for a limited range of angles. The fitting agreement is perfect for a transition to the 4^+ state, but the cross section is surprisingly large for a 4^+ state, twice larger than for the 4^+ member of the g.s. band. Therefore, the possibility of a 0^+ excitation can

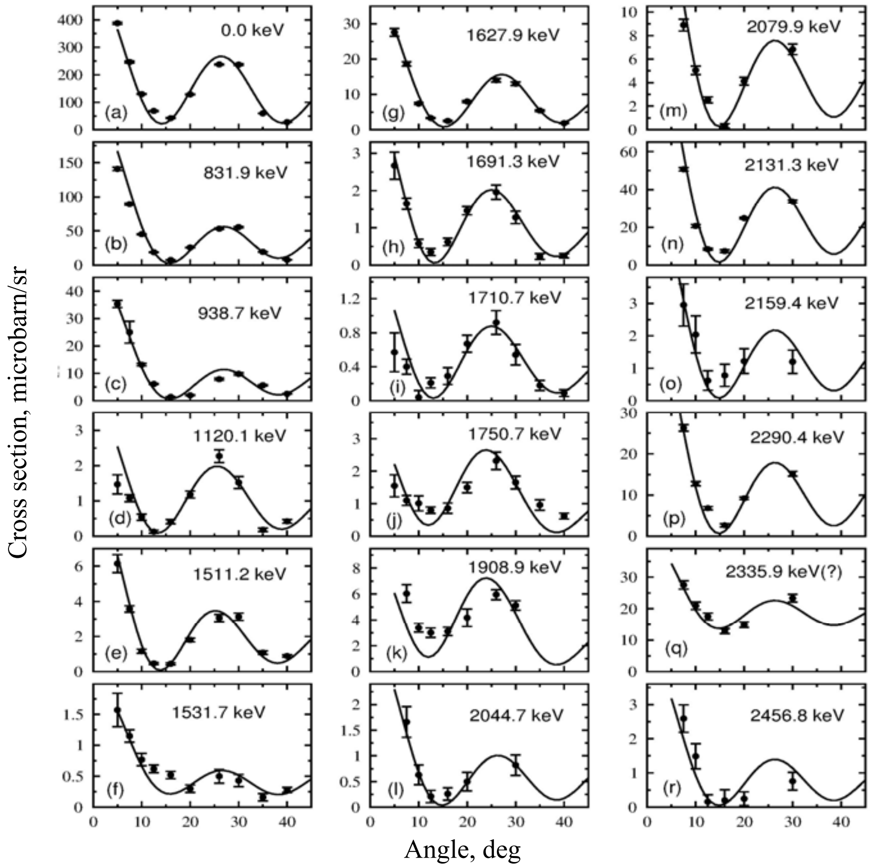

Fig. 3. Angular distributions of assigned 0^+ states in ^{228}Th and their fit with CHUCK3 one-step calculations. The (ij) transfer configurations used in the calculations for the best fit are given in Table 1. See text for further information.

not be excluded, but the experimental angular distribution is fitted for a 0^+ state only with adding a constant of 14 μb. This ambiguity can be resolved by measurements in wider angular regions.

Thus we can make firm 0^+ assignments for 17 states for energies excitations below 2.5 MeV, in comparison with 12 states found in the preliminary analysis of the experimental data [2]. Of course, some higher lying 0^+ levels are lost because of the cutoff of the investigated energy region. But as follows from a similar study for ^{230}Th, only a few 0^+ states are observed above 2500 keV, where the density of 0^+ excitations decreases for higher energies (or else that the cross section of such excitations is very low and they are hidden in very dense and complicated spectra). Therefore, we can compare 24 0^+ states in ^{230}Th with only 17 0^+ states in ^{228}Th in the same energy region.

Similar to 0^+ excitations, the one-step transfer calculations give a satisfactory fit of angular distributions for about 80 % of the states with spins different from 0^+, but about 20 % of these states need the inclusion of multi-step excitations. Multi-step excitations have to be included to fit the angular distributions already for the 2^+, 4^+ and 6^+ states of the g.s. band. Fig. 2 shows the schemes of the multi-step excitations, tested for every state in those cases, where one-step transfer did not provide a successful fit. Fig. 4 demonstrates the quality of the fit of some different-shaped angular distributions for the excitation of states with spin 2^+ by calculations assuming one-step and one-step plus two-step excitations, respectively. Results of similar fits for the states assigned as 4^+, 6^+ and 1^-, 3^-, 5^- excitations are shown in Fig. 5.

The assignments of the spins resulting from such fits are presented in Table 1, together with other experimental data. Special comments are needed for the column displaying the ratio $\sigma_{exp}/\sigma_{cal}$. Calculated cross sections for the specific transfer configurations differ very strongly. Since we have no a priori knowledge of the microscopic structure of the excited states, and thus do not know the relative contributions of the specific $(j)^2$ transfer configurations to each of these states, these ratios cannot be considered as spectroscopic factors. Nevertheless, a very large ratio, such as in the case of the $(1i_{11/2})^2$ transfer configurations used in the calculation for some 0^+ and even 2^+ and 4^+ states, is unexpected. Surprisingly, the shape just for this neutron configuration gives the best agreement with experiment.

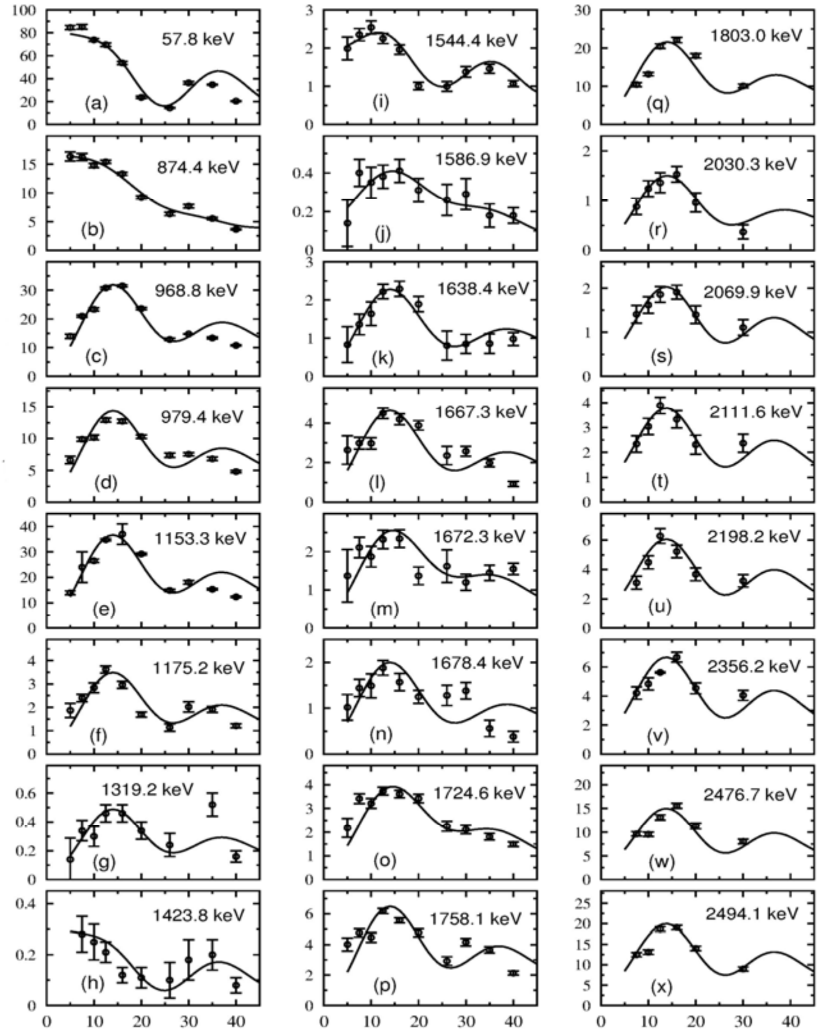

Fig. 4. Angular distributions of assigned 2^+ states in ^{228}Th and their fit with CHUCK3 calculations. The (ij) transfer configurations and schemes used in the calculations for the best fit are given in Table 1.

Some additional comments on Table 1 are needed. In all cases, where the firm assignment were known from the previous studies [5, 6], they are confirmed by the (p, t) angular distribution analysis. In those cases, where two or three possible spin assignments were proposed earlier, the (p, t) angular distribution analysis allows to select only one assignment almost in all cases. For the energies above 2030 keV only the assignments from the (p, t) reaction are possible at present. The following remarks are needed in those cases, where the assignments from different publications are in contradiction, which can be removed using the data from the (p, t) reaction.

938.7 keV. Spin 2^- was assigned for this level in [5]. Our fit of the angular distribution gives reliably spin 0^+ in agreement with [6].

943.8 keV. Spin 2^+ was assigned for this level in [5]. The angular distribution rejects this value and agrees with the assignment of spin 1^- accepted in [6].

968 - 969 keV. Three levels around 968 keV with spins 2^+, 4^+, 2^- were identified in [6] and two levels with spins 2^+, 3^- in [5]. There is a discrepancy in assignment for the 968.33 keV level as 3^- in [5] and as 2^- in [6]. This line is masked in the (p, t) spectrum by a strong line from the transition to the 969 keV level. But since the angular distribution is very well described by a calculation leading to a 2^+ state and is not disturbed by a transition to spin 3^-, the assignment 2^- is preferable (transition is weak).

1016.4 keV. The discrepancy in assignment for the 1016.4 keV level as 2^+ in [5] and as 3^- in [6] can not be removed by the (p, t) angular distribution, since it can be fitted by a transition sw.ig to 2^+ and m3a.gg to 3^-, respectively. However, transitions seen in the decay of ^{228}Pa [6] from this state to the 5^- and 4^+ states leads to the assignment of 3^-. We accepted this spin also due to strong arguments in [6], including the assignment of spins 2^- and 1^- to the levels at 968.3 and 943.8 keV as members of the $K^\pi = 1^-$ band.

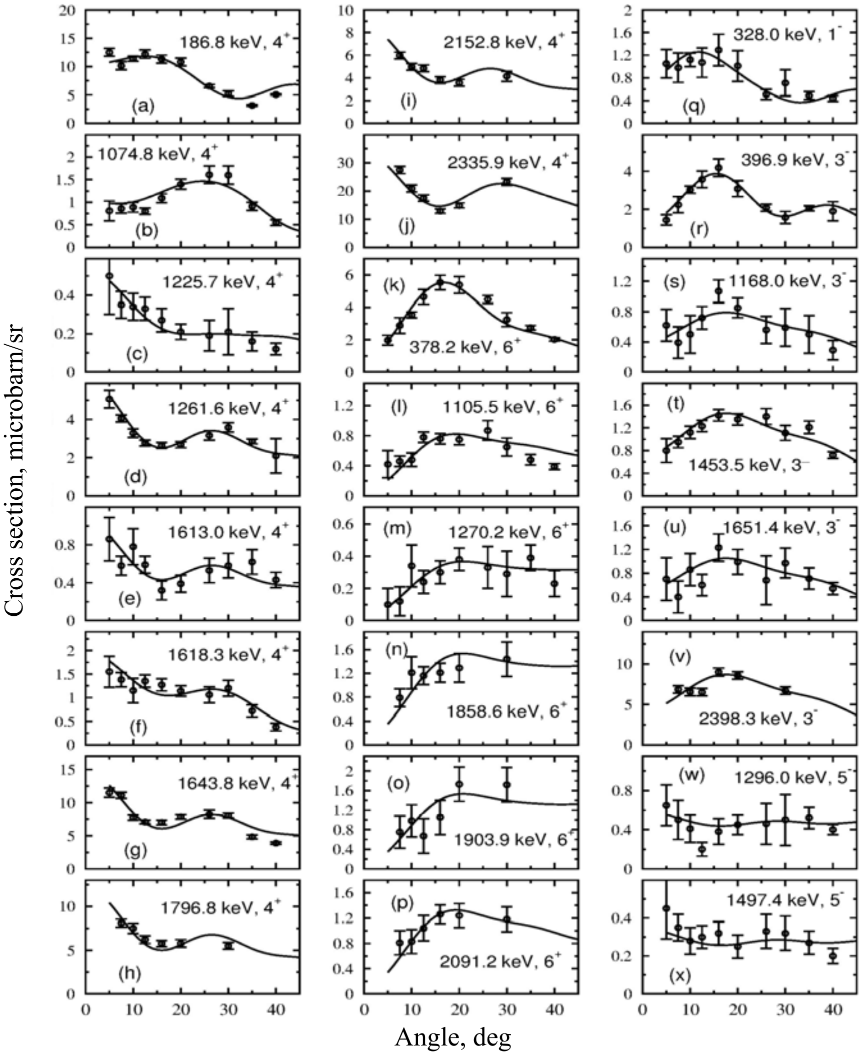

Fig. 5. Angular distributions of some assigned states in ^{228}Th and their fit with CHUCK3 calculations: 4^+ and 6^+ with positive parity and 1^-, 2^- and 3^- with negative parity.
The (ij) transfer configurations and schemes used in the calculations for the best fit are given in Table 1.

1059.9 keV. From the tentative assignments (4^+, 3^-) in [5] and the firm assignment 4^- in [6] for this level, the latter has to be additionally supported by the fact, that the corresponding line in the (p, t) spectrum was not seen (transition to the state of unnatural parity).

1225.7 and 1226.56 keV. Spin 4^- was assigned for the level 1226.56 keV in both [5] and [6]. The level with the close energy 1225.7 keV is seen in the (p, t) reaction, but the angular distribution agrees with the assignment of spin 4^+. Therefore both levels are present in Table 1.

1393.4 keV. This level was observed in the decay of ^{228}Pa with restriction of the spin-parity to 1^+, 2 and 3^- by its population and depopulation [6]. Additional restriction from the $W(90°)/W(180°)$ angular distribution ratio indicates that this level has most likely $I^\pi = 1^+$ and that the 2^+ and 3^- assignments are nearly excluded. This level was not observed in the (p, t) reaction, thus supporting such conclusion.

1415 keV. Spin 2^+ was assigned to this level in [5] and spins 2^+ or 3^- were allowed in [6]. The angular distribution of tritons gives preference to spin 3^-.

1432.1 keV. The discrepancy between 3^+ in [5] and 4^+ in [6] for the 1432.1 keV level is removed already by the fact of the excitation of this state in the (p, t) reaction, and additionally by the angular distribution leading to the 4^+ assignment. Also additional lines observed in the decay of ^{228}Pa [6], leading to the 6^+ level, confirm this assignment.

1450.29 keV. Spin 3^- was assigned to this level in [5] and spin 4^- in [6]. The fact that this level is not observed in the (p, t) reaction gives preference for an assignment of spin 4^- not excluding spin 3^-.

1531.7 keV. Spin 3^+ was assigned for the level at 1531.47 keV both in [5] and [6]. However, the angular distribution of tritons for the level with the close-lying energy 1531.7 keV indicates another spin value. It has a steeply rising cross section at small angles as for a 0^+ excitation; however, the minimum at a detection angle about 14° is not sharp. Therefore we assumed an overlapping of peaks of two levels, one of which is a 0^+ level.

1643.8 keV. There are two close-lying levels at 1643.18 keV with spin 2^- or 3^- identified both in [5] and [6] and 1643.8 keV, respectively, as identified in [6] with an assignment of possible spins $(2, 3, 4)^+$. Only the level at 1643.8 keV is observed in the (p, t) reaction with clear assignment of spin 4^+.

1733 keV. We assumed that the level at 1735.6 keV, identified as a 4^+ state in [5] and as $2^+, 3, 4^+$ state in [6], and the level at 1733.8 keV seen in the (p, t) reaction with an assignment of spin 4^+ are identical, though the energy difference is larger than the energy error.

1742.8 keV. Spin 3 was assigned to the level at 1743.86 keV in [5] and spin 4^+ in [6]. The angular distribution from the (p, t) reaction prefers the assignment of spin 4^+.

1758 - 1760 keV. Several close-lying levels were identified at 1757.9 keV with spin 1^-, 2, 3^- [6], at 1758.24 keV with spin $(3, 4)^+$ [5], at 1760.25 keV with spin 4^+ [5] and with spin $(2, 3)^+$ [6]. Different γ-lines were used in the identification of the levels at 1757.9 and 1758.24 keV: 741.9, 1361.4, 1430.0 keV for the first one and 1571.52 and 1700.59 keV for the latter. At the same time, in [5] the line at 1430.0 keV was used for the identification of another level at 1617.74 keV, and the important line at 1758.24 keV was used for the identification of the level at 1944.85 keV. The line at 1758.11 keV can be attributed to the decay of the level at 1758.24 keV, then the spin of this state distinctly has to be 2^+. The ambiguity cannot be solved with the (p, t) data. Therefore we put the level at 1758.1 keV with an assignment of spin 2^+ from the (p, t) study in correspondence with the level at 1757.9 keV in [6], but for the level at 1758.24 keV in [5] we do not exclude the spin 2^+, too. As far as the level at 1760.25 keV is concerned, a spin 2^+ can be nearly excluded, since this line is not observed in the (p, t) reaction.

1796.8 keV. Two close-lying levels were identified: 1795.9 keV with an assignment $(4^+, 3^-)$ in [5] and 1796.4 keV with an assignment as 3^+, 4, 5^+ in [6]. The level at 1796.8 keV with spin 4^+ is observed in the (p, t) reaction. It is problematic to put this level in correspondence with one of the observed ones in decay, considering the assignments. Therefore only energetic proximity was taken into account.

1908.9 keV. The level at 1908.4 keV, (3^-) was identified in [6], however, a level with almost the same energy of 1908.9 keV as observed in the (p, t) reaction was clearly identified as a 0^+ state, they must be considered as a different levels.

2010.4 keV. There is discrepancy in the assignment of spin to the level at 2010.15 keV: 2^+, 3 in [6] and 4^+ in [5]. The angular distribution from the (p, t) reaction prefers spin (2^+).

Conclusions

Excited states in ^{228}Th have been studied in (p, t) transfer reactions. 106 levels were assigned; using a DWBA fit procedure, additionally only the energies are determined for 57 states. Among them, 17 excited 0^+ states have been found in this nucleus up to an energy 2.5 MeV, most of them have not been experimentally observed before. Their accumulated strength makes up for more than 70 % of the ground-state strength. Firm assignments have been made for most of the 2^+ and 4^+ states and for some of the 6^+ states.

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ДОСЛІДЖЕННЯ 0^+ СТАНІВ У ^{228}Th ШЛЯХОМ ДВОНЕЙТРОННИХ ПЕРЕДАЧ: ЕКСПЕРИМЕНТАЛЬНІ РЕЗУЛЬТАТИ

Спектри збуджень у деформованому ядрі ^{228}Th вивчались за допомогою (p, t)-реакції, використовуючи Q3D-спектрограф на Мюнхенському тандемному прискорювачі. Кутові розподіли тритонів були виміряні для 110 збуджень, що спостерігались у тритонних спектрах до 2,5 МеВ. Для 17 станів були надійно присвоєні спіни 0^+ шляхом порівняння експериментальних кутових розподілів з розрахованими з використанням програми CHUCK3. Спіни до 6^+ включно були присвоєні для решти станів.

Ключові слова: 0^+ стани, колективні смуги, моменти інерції, ядерні моделі.

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ИССЛЕДОВАНИЕ 0^+ СОСТОЯНИЙ В ^{228}Th ПУТЕМ ДВУХНЕЙТРОННЫХ ПЕРЕДАЧ: ЭКСПЕРИМЕНТАЛЬНЫЕ РЕЗУЛЬТАТЫ

Спектры возбуждений в деформированном ядре ^{228}Th были изучены с помощью (p, t)-реакции, используя Q3D-спектрограф на Мюнхенском тандемном ускорителе. Угловые распределения тритонов были измерены для 110 возбуждений, наблюдаемых в спектрах тритонов до 2,5 МэВ. Для 17 возбужденных состояний присвоены спины 0^+ путем сравнения экспериментальных угловых распределений с расчетными с использованием программы CHUCK3. Спины до 6^+ включительно были присвоены для остальных состояний.

Ключевые слова: 0^+ состояния, коллективные полосы, моменты инерции, ядерные модели.

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