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SPECTROSCOPY OF ^{232}U IN THE (p, t) REACTION: EXPERIMENTAL DATA

The excitation spectra in the deformed nucleus ^{232}U 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 162 excitations seen in the triton spectra up to 3.25 MeV. 0^+ assignments are made for 13 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, (p, t) reaction, coupled-channel approximation analysis.

1. Introduction

The first observation of multiple excitations with zero angular momentum transfer in the (p, t) reaction seen in the odd nucleus ^{229}Pa [1] initiated an extensive campaign to study 0^+ excitations in even-even nuclei. During the last two decades, many of such investigations have been performed using the Q3D magnetic spectrograph at the Maier - Leibnitz - Laboratory (MLL) Tandem accelerator in Garching. Because of its very high energy resolution, this spectrograph is a unique tool in particular for the identification of 0^+ states by measuring the state-selective angular distributions of triton ejectiles. Subsequent analysis is performed within the distorted-wave Born approximation (DWBA). In addition to our studies on the actinide nuclei ^{230}Th, ^{228}Th, ^{232}U, the neighboring odd nucleus ^{229}Pa [2], and most recently on ^{240}Pu [3], the majority of studies on 0^+ excitations was carried out in the regions of rare earth, transitional and spherical nuclei [4 - 9]. Most of these studies were limited to measuring the energies and excitation cross sections of 0^+ states. Therefore they provided only the trend of changes in the nuclei contributing to such excitations in a wide range of deformations: from transitional nuclei (Gd region) to well-deformed (Yb region), gamma-soft (Pt region) and spherical nuclei (Pb region). The main result of these studies is the observation of the dependence of the number of 0^+ states as a function of valence nucleon numbers. A particularly large number of low-lying states was interpreted as a signature of a shape phase transition (Gd region), and the sharp drop of the number of low-lying 0^+ states was interpreted as a result of proximity to the shell closure. More information from the (p, t) experiments, as well as on the 0^+ excitations in even nuclei, was given in Refs. [10, 11]. They report data on spins and cross sections for all states observed in the (p, t) reaction. This allowed to extract information about the moments of inertia for the bands built on

the 0^+ states. These experimental studies contributed to the development of theoretical calculations, which explain some of the features of the 0^+ excitation spectra. Some publications have dealt with the microscopic approach [12, 13], but the majority of studies used the phenomenological model of interacting bosons (IBM) [14, 15]. Nevertheless, the nature of multiple 0^+ excitations in even nuclei is still far from being understood [16].

In this paper, we present the results of a careful and detailed analysis of the experimental data from the high-resolution study of the ^{234}U(p,t)^{232}U reaction. A short report on this topic was presented in Ref. [2]. The nucleus ^{232}U is located in the region of strong quadrupole deformation, where stable reflection-asymmetric octupole deformations occur. Information on excited states of ^{232}U is rather scarce [17]: they have been studied via ^{232}Pa β$^-$ decay, ^{232}Np electron capture decay, ^{236}Pu α decay and via the ^{230}Th(α, 2nγ) and ^{232}Th(α, 4nγ) reactions. The study of the (p, t) reaction adds to this information considerably: data are obtained for 162 levels in the energy range up to 3.25 MeV. Besides 0^+ states, where the number of reliable assignments could be increased from 9 to 13 states in comparison to the preliminary analysis in Ref. [2], information on the spins up to 6^+ for many other states was obtained. 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.

2. Details of the experiment

The (p, t) experiment has been performed at the Tandem accelerator of the Maier - Leibnitz - Laboratory of Munich Universities. A radioactive target of 100 μg/cm^2 ^{234}U with half-life $T_{1/2} = 2.45 \cdot 10^5$ years, evaporated on a 22 μg/cm^2 thick carbon backing, was bombarded with 25 MeV protons at an intensity of 1 - 2 μA on the target. The isotopic purity of the target was about 99 %. The reaction products have

been 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 [18, 19]. The acceptance of the spectrograph was 11 msr. The resulting triton spectra have a resolution of 4 - 7 keV (FWHM) and are background-free. The experimental runs were normalized to the integrated beam current measured in a Faraday cup behind the target. The angular distributions of the cross sections were obtained from the triton spectra at twelve different laboratory angles from 5 to 50° in two sets:

the first one with higher accuracy for energies up to 2350 keV and the second one with somewhat lower accuracy for energies from 2200 to 3250 keV.

A triton energy spectrum measured at a detection angle of 5° is shown in Fig. 1. The analysis of the triton spectra was performed using the program GASPAN [20]. For the calibration of the energy scale, the triton spectra from the reactions $^{184}W(p, t)^{182}W$ and $^{186}W(p, t)^{184}W$ were measured at the same magnetic settings. The known levels in ^{232}U [17] were also included in the calibration.
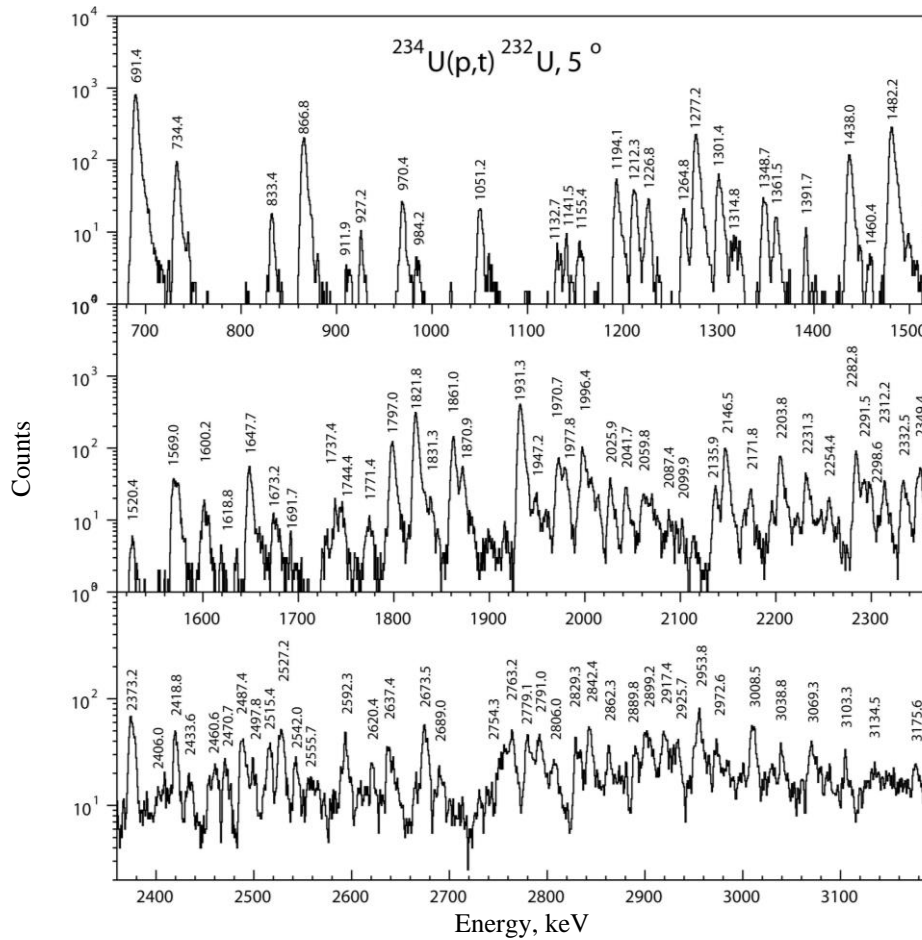

Fig. 1. Triton energy spectrum from the $^{234}U(p, t)^{232}U$ reaction ($E_p = 25$ MeV) in logarithmic scale for a detection angle of 5°. Some strong lines are labeled with their corresponding level energies in keV.

The peaks in the energy spectra for all twelve angles were identified for 162 levels. The information obtained for these levels is summarized in the Table. The energies and spins of the levels as derived from this study are compared to known energies and spins from [17]. They are given in the first four columns. The column labeled σ_{integ} gives the cross section integrated in the region from 5 to 50°. The column

entitled $\sigma_{exp}/\sigma_{calc}$ gives the ratio of the integrated cross sections, obtained from experimental values and from calculations in the DWBA approximation (see Sec. 3). 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.

**Energies of levels in ²³²U, the level spin assignments from the CHUCK3 analysis,
the (p, t) cross sections integrated over the measured values (i.e. 5 to 50°)
and the reference to the schemes used in the DWBA calculations
(see text for more detailed explanations)**

Level energy, keV			I^π			Ratio		Way of fitting
This work		NDS[17]	This work	NDS[17]	σ_{integ}, μb	$\sigma_{exp}/\sigma_{calc}$		
0	*1*	0	0^+	0^+	183.9	*58*	8.95	sw.gg
47.6	*1*	47.573(8)	2^+	2^+	43.4	*35*	50.5	m1a.gg
156.6	*1*	156.566(9)	4^+	4^+	8.11	*35*	1.2	m1a.gi
322.6	*2*	322.69(7)	6^+	6^+	5.55	*40*	178	m2d.gg
541.1	*4*	541.1(1)	(8^+)	8^+	0.42	*20*	0.75	m2c.gg
563.2	*4*	563.194(7)	1^-	1^-	0.9	*25*	0.12	m1a.gg
628.8	*4*	628.965(8)	3^-	3^-	2.7	*33*	0.24	m3a.gg
691.4	*2*	691.42(9)	0^+	0^+	35	*70*	194	sw.ii
734.4	*2*	734.57(5)	2^+	2^+	21.68	*65*	2.85	m1a.gi
746.5	*5*	746.8(1)		(5^-)	0.35	*18*		
833.4	*2*	833.07(20)	4^+	4^+	3.21	*23*	0.55	m1a.gg
866.8	*2*	866.790(8)	2^+	2^+	64.05	*90*	8.15	m1a.gi
911.9	*4*	911.49(4)	3^+	(3^+)	1.08	*15*	6.75	m2a.gg
914.5	*9*	915.2(4)		7^-	0.1	*6*		
927.2	*4*	927.3(1)	0^++2^+	(0^+)	0.35	*10*	1.45	sw.ii
967.1	*9*	967.6(1)		(2^+)	0.65	*35*		
970.4	*3*	970.71(7)	4^+	(4^+)	4.65	*32*	69	m1a.ij
984.2	*9*	984.9(2)	6^+	6^+	0.4	*12*	13	m2d.gg
1015.9	*9*	1016.850(8)	(2^-)	2^-	0.12	*7*	0.2	m2f.gg
1051.2	*3*	1050.90(1)	3^-	3^-	3.45	*25*	0.24	m1a.gg
1060.8	*8*		(3^-)		0.32	*12*	0.14	m2a.gg
1097.6	*8*	1098.2(4)	(4^-)	(4^-)	0.1	*6*	3.15	m2a.gg
1132.7	*3*	1132.97(10)	2^+	(2^+)	1.52	*18*	0.15	sw.gg
1141.5	*4*		(1^-)		1.02	*15*	0.13	m1a.gg
1155.4	*4*		5^-		1.38	*35*	0.78	m2e.gg
			or 3^+				6.4	m2a.gg
1173	*6*	1173.06(17)	2^-	$(2)^-$	0.52	*12*	6.12	m2a.gg
1194.1	*3*	1194.0(2)	4^+	$(3^+,4^+)$	3.18	*53*	1.65	m2a.gg
1212.3	*3*	1211.3(3)	3^-	3^-	6.6	*55*	0.46	m1a.gg
1226.8	*4*		4^+		2.64	*26*	0.33	m1a.gj
1264.8	*3*		3^-		2.42	*22*	1	m2a.gg
1277.2	*3*		0^+		16.12	*60*	0.45	sw.gg
1301.4	*3*		2^+		3	*25*	3.95	m1a.gg
1314.8	*4*		6^+		3.57	*28*	13.3	m2e.gg
1321.8	*5*		2^+		0.57	*20*	2.9	sw.jj
			or 3^-				0.12	m3a.gg
1348.7	*3*		(2^+)		3.25	*25*	14.5	sw.jj
1361.5	*4*		4^+		1	*16*	0.45	m2a.gg
			or 3^-				0.16	m3a.gg
1372	*6*		2^+		0.3	*12*	0.03	m1a.ig
			or 6^+				0.33	m2d.gg
1391.7	*4*		4^+		0.85	*15*	0.12	m1a.gg
			or 5^-				12	sw.ji
1438	*3*		4^+		12.72	*55*	205	m1a.ij
1460.4	*6*		6^+		0.85	*15*	0.27	m2d.gg
1482.2	*3*		0^+		14.15	*55*	27.25	sw.ig
1489.2	*4*		2^+		4.18	*50*	0.45	sw.gg
1501.4	*7*		3^-		0.68	*15*	41.8	sw.jj
1520.4	*4*		2^+		6.85	*33*	150	m1a.ii
1552.8	*8*		(3^+)		0.83	*15*	4.6	m2a.gg
1569	*4*		0^+		3.72	*36*	8.15	sw.ig

Level energy, keV			I^π			Ratio	Way of fitting
This work		NDS[17]	This work	NDS[17]	σ_{integ}, μb	$\sigma_{exp}/\sigma_{calc}$	
1572.9	6		4^+		3.45	36	31.5	sw.jj
1600.2	6		2^+		1.4	25	1.5	m1a.gg
1605.4	8		4^+		0.72	22	6.15	m1a.ij
1618.8	7		2^+		0.62	15	0.08	m1a.ig
1633.8	6		3^+		1.35	25	5.05	m2a.gg
			or 6^+				16	sw.jj
1647.7	5		2^+		24.88	50	3.15	m1a.gg
1673.2	5		4^+		1.72	25	0.35	sw.gg
1679.8	6		1^-		1.25	22	0.04	m1a.gg
			or 3^-				0.06	m3a.gg
1691.7	6		(6^+)		1.05	18	4.2	m2e.gg
1700.5	8		6^+		0.85	18	0.2	sw.gg
1728.5	6		(4^+)		1.08	22	0.2	m1a.gg
1737.4	5		(6^+)		3.25	33	0.35	m3a.gg
1744.4	5		4^+		4.86	40	0.85	m1a.gg
			or 5^-				2.7	m2e.gg
1758.9	9		(5^-)		0.69	15	19	sw.ii
1771.4	8				2.96	26		
1790.8	7		6^+		2.05	28	7.5	m2e.gg
1797	5		0^+		10.15	65	11	sw.ii
1802.5	9		(4^+)		0.88	45	9.8	sw.ij
1821.8	5		0^+		20.65	70	27.2	sw.ii
1831.7	5		(2^+)		1.38	30	0.22	m1a.gg
1838.6	6		2^+		1.16	26	1.4	m1a.gg
1861	5		0^+		9.63	50	11.2	sw.ig
1870.9	5		2^+		14.18	65	1.7	m1a.gi
1880.8	5		6^+		2.08	35	0.18	m3a.gg
1900	6				1.25	25		
1915.2	8		6^+		1.85	30	7.4	m2d.gg
1931.3	5		0^+		29.55	75	140	sw.ig
1947.2	8		(0^+)		1.52	30	7.6	sw.ig
1957.4	8		6^+		3.05	35	11.9	m2d.gg
1970.7	5		2^+		25.65	95	2.7	sw.ig
1977.8	5		2^+		20.05	90	2.25	m1a.gg
1996.4	5		4^+		15.2	65	108	sw.ij
2004.9	6		4^+		4.7	50	46	sw.ij
2011.6	6				2.3	65		
2025.9	6		0^+		2.96	35	19	sw.ii
2041.7	5		2^+		10.85	55	1.2	m1a.gg
2059.8	5		2^+		10.65	55	1.2	m1a.gg
2068.6	5		4^+		3.4	45	0.42	sw.gg
2073.4	9				1.3	40		
2087.4	6		5^-				1.95	m2e.gg
			or 6^+				53	sw.jj
2094.2	8				1.2	40		
2099.9	6		6^+		1.62	35	21.3	sw.jj
2135.9	5		4^+		4.22	55	32.4	m1a.ij
2146.5	5		2^+		39.8	98	4.6	m1a.gg
2171.8	5		2^+		8.81	55	1	sw.gg
2194.6	5		2^+		4.08	55	0.45	sw.gg
2203.8	5		2^+		29.2	95	3.15	sw.gg
2221.3	9				1.22	45		
2231.3	5		4^+		10.38	58	67	m1a.ij
2235.9	5				2	60		
2246.2	5				1.55	55		

Level energy, keV		I^π			Ratio		Way of fitting
This work	NDS[17]	This work	NDS[17]	σ_{integ}, μb	$\sigma_{exp}/\sigma_{calc}$		
2254.4	5	6$^+$		5.35	45	19.2	m2d.gg
2282.8	5	2$^+$		29.3	70	3.3	m1a.gg
2291.5	5	2$^+$		11.23	90	1.28	m1a.gg
2298.6	5	2$^+$		4.73	85	1.35	sw.gg
2312.2	6	4$^+$		3.95	75	28.5	m1a.ij
2332.5	6	2$^+$		8.98	65	1.1	m1a.gg
2349.4	6	2$^+$		17.27	86	2.05	m1a.gg
2373.2	6	2$^+$		19.15	90	2.25	m1a.gg
2397.7	6	2$^+$		2.48	48	0.21	sw.gg
2406	6	6$^+$		2.8	68	12.8	m2e.gg
		or 5$^-$				110	sw.ij
2412.4	6	2$^+$		3.67	90	0.35	m1a.gg
2418.8	5	2$^+$		11.88	92	1.45	m1a.gg
2433.6	5	3$^-$		2.61	47	3.8	m2a.gg
2454.2	5	(3$^-$)		1.67	96	2.6	m2a.gg
2460.6	5	3$^-$		4.14	98	5.2	m2a.gg
		or 6$^+$				0.45	m3a.gg
2470.7	6	(3$^-$)		3.32	63	4.9	m2a.gg
2487.4	5	3$^-$		5.96	68	8.9	sw.gg
2497.8	6	(4$^+$)		2.82	58	21.4	m1a.ij
2515.4	6	(3$^-$)		8.21	74	10.8	m2a.gg
2527.2	6	4$^+$		7.69	73	46	m1a.ij
2542	7	2$^+$		5.88	69	0.67	m1a.gg
2555.7	8	(4$^+$)		1.98	62	11.2	m1a.ij
2564.7	8	(3$^-$)		1.82	62	2.6	m2a.gg
2582.9	8			1.85	66		
2592.3	7	4$^+$		5.78	71	32.9	m1a.ij
2598.7	9			1.2	40		
2608	9	2$^+$		2.15	53	0.32	m1a.gg
2620.4	6			2.75	62		
2637.4	6	6$^+$		6.84	87	0.65	m3a.gg
		or 5$^-$				180	sw.ij
2642	7			1.78	80		
2664.6	7	4$^+$		1.75	45	11.5	m1a.ij
2673.5	7	2$^+$		9.11	76	1.08	m1a.gg
2689	8	2$^+$		3.45	58	0.38	m1a.gg
2754.3	7	4$^+$		4.89	68	29.5	m1a.ij
2763.2	6	(3$^-$)		6.08	70	8.95	sw.gg
2779.1	6	2$^+$		7.21	70	0.92	m1a.gg
2791	7	2$^+$		8.9	75	1.18	m1a.gg
2806	7	2$^+$		4.5	62	0.66	m1a.gg
2829.3	7	4$^+$		5.98	65	34.5	m1a.ij
2842.4	7	4$^+$		7.12	75	38	m1a.ij
2850.6	7	6$^+$		2.63	63	11.9	m2d.gg
2862.3	7	3$^-$		4.58	63	6.75	sw.gg
2878.3	7	(6$^+$)		4.45	63	345	sw.ig
2889.8	6	4$^+$		4.6	72	26	m1a.ij
2899.2	7	(4$^+$)		5.1	15	0.75	sw.gg
2905.8	7			3.5	16		
2917.4	7	0$^+$		5.58	92	8.95	sw.ji
2925.7	8	(6$^+$)		3.4	18	14.5	m2d.gg
2931.5	7	(5$^-$)		5.8	20	61	sw.ij
2953.5	8	4$^+$		9.6	80	58.5	m1a.ij
2959.7	7	(2$^+$)		3.05	60	8.9	sw.ig
2972.6	8	2$^+$		4.7	65	0.48	m1a.gg

Continuation of the Table

Level energy, keV		NDS[17]	I$^\pi$				Ratio	Way of fitting
This work		NDS[17]	This work	NDS[17]	σ$_{integ}$, μb		σ$_{exp}$/σ$_{calc}$	
2984.2	*8*				1.09	*50*		
2998.7	*8*		(2$^+$)		2.4	*54*	7.4	sw.ig
3008.5	*8*		(3$^-$)		2.8	*65*	0.52	m3a.gg
3028.8	*8*		4$^+$		2.05	*55*	12	m1a.ij
3038.8	*8*		(5$^-$)		4.4	*63*	145	sw.ij
3058.3	*9*		(6$^+$)		1	*50*	91	sw.ig
3069.3	*8*		3$^-$		5.04	*75*	6.75	m2a.gg
3075.7	*9*		(5$^-$)		1.88	*65*	61.5	sw.ij
3087.5	*9*		2$^+$		1.7	*65*	0.2	m1a.gg
3103.3	*9*		(4$^+$)		1.95	*55*	10.2	m1a.ij
3134.5	*9*		(4$^+$)		1.68	*55*	9.9	m1a.ij
3149.1	*9*		2$^+$		1.85	*55*	41.8	sw.ij
			or 3$^-$				2.6	m2a.gg
3175.6	*8*		(2$^+$)		1.96	*55*	42	sw.ij
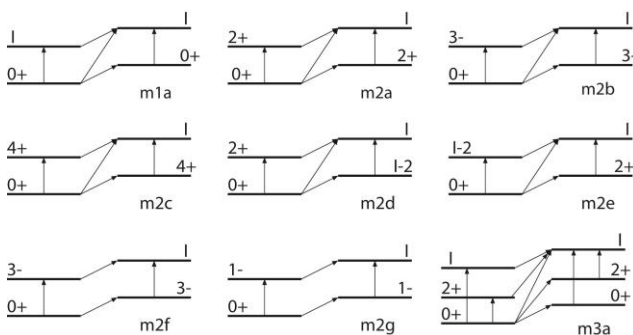
Fig. 2. Schemes of the CHUCK3 multi-step calculations tested with spin assignments of excited states in ^{232}U (see the Table).

3. DWBA analysis

We assume that a (lj) pair transferred in the (p, t) reaction is coupled to spin zero, and 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. At the same time, cross sections for different orbits have to differ strongly in magnitude. 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 [10]. Indeed, the magnitude of the cross sections differs strongly for different orbits, but the shapes of 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, which is confirmed by the experimental angular distributions. This is true for most of the (lj) pairs and only for the case of a one-step transfer. No complication of the angular distributions is expected for the excitation of 0$^+$ states, which proceeds predominantly via a one-step process. This is not the case for the excitation of states with other spins, where the angular distribution may be altered due to inelastic scattering (coupled channel effect), treated here as multi-step processes. Taking into account these circumstances allows for a reliable assignment of spins for most of the excited states in the final nucleus ^{232}U by fitting the angular distributions obtained in the DWBA calculations to the experimental ones. The assignment of a single spin has not been possible only in a few cases, for which two or even three spin values are allowed.

The magnitude and shape of the DWBA cross section angular distributions depends on the chosen potential parameters. We used the optical potential parameters suggested by Becchetti and Greenlees [21] for protons and by Flynn et al. [22] for tritons. These parameters have been tested in fitting with their aid the 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, particularly for the states at 628.8, 1051.2 and 1212.3 keV. For these states, the triton potential parameters suggested by Becchetti and Greenlees [23] have been used. 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 of the calculations and used parameters see [10].

The coupled-channel approximation (CHUCK3 code of Kunz [24]) was used in previous [10, 11] and present calculations. The best reproduction of the angular distribution for the ground state and for the 1277.2 keV 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 in previous studies [10, 11] as the most probable one in the transfer process. But for ^{232}U, a better reproduction of the angular distributions for other 0^+ states is obtained for the configuration $(1i_{11/2})^2$, also near the Fermi surface, alone or in combination with the $(2g_{9/2})^2$ configuration. The only exception is the state at 2917.4 keV, for which the experimental angular distribution can be fitted only by the calculated one for the transfer of the $(1j_{15/2})^2$ neutron configuration.
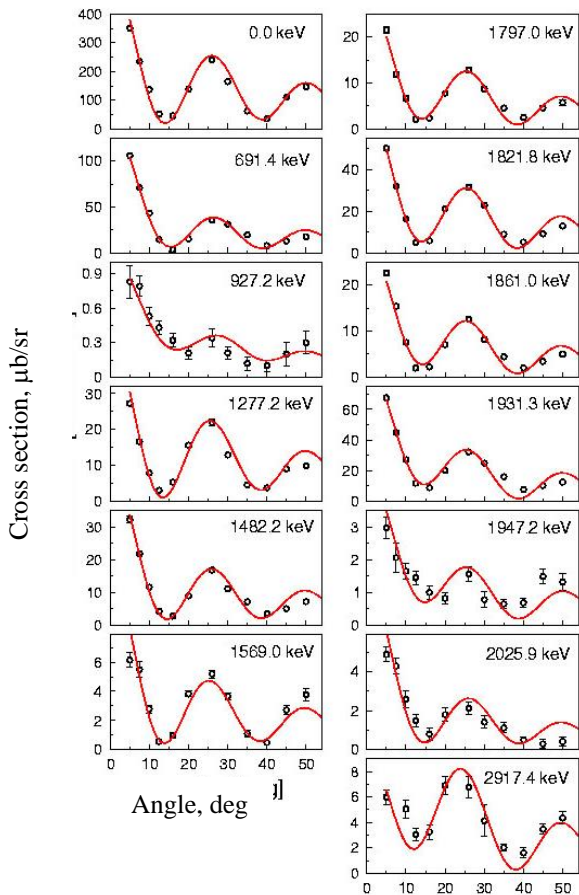

Fig. 3. Angular distributions of assigned 0^+ states in ^{232}U and their fit with CHUCK3 one-step calculations. The transfer configurations used in the calculations for the best fit are given in the Table. See text for further information.

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 level at 927.2 keV. The existence of this state and the state at the energy of 967.7 keV was established by the γ energies and the coincident results at the α decay of ^{236}Pu [25]. Strong evidence has been obtained that these states have spins 0^+ and 2^+ and are the members of a $K^\pi = 0^+$ band. At the same time, it was noted that the occurrence of a 927.7 keV γ ray is in contradiction with the 0^+ assignment

for this state if this γ ray corresponds to a ground-state transition from the 927.7 keV state. Alternatively, this transition should be placed in another location. The measured (p, t) angular distribution for the 927.7 keV state strongly peaks in the forward direction, which is typical for the L = 0 transfer but the lack of a deep minimum at about 14 degrees contradicts the 0^+ assignment. The assumption that a doublet with spins 0^+ and 2^+ occurs at the energy of 927.7 keV seems to be a unique explanation of the experimental data. The angular distribution in this case is fitted by the calculated one satisfactorily as one can see in Fig. 3. In order to obtain a satisfactory fit one has to assume a population of the 2^+ state at about 1/3 of the population of the 0^+ state. Thus we can make firm 0^+ assignments for 12 states for energy excitations below 3.25 MeV, in comparison with 9 states found in the preliminary analysis of the experimental data [2]. The assignment for the 1947.2 keV level is tentative. We can compare 24 0^+ states in ^{230}Th and 18 0^+ states in ^{228}Th with only 13 0^+ states in ^{232}U in the same energy region.

The main goal of many studies using two-neutron transfer in the regions of rare earth, transitional and spherical nuclei [4 - 9] was to collect information only about the 0^+ states, their energies and excitation cross sections. At the same time the states with non-zero spin are intensively excited in the (p,t) reaction and information about them can be obtained from the analysis of the angular distributions. The main features of the angular distribution shapes for 2^+, 4^+ and 6^+ states are even more weakly dependent on the transfer configurations only in the case of one-step transfer. Therefore the $(2g_{9/2})^2$, $(1i_{11/2})^2$, and $(1j_{15/2})^2$ configurations alone or in combination, were used in the calculations for these states. The one-step transfer calculations give a satisfactory fit of angular distributions for about 30 % of the states with spins different from 0^+ and the inclusion of multi-step excitations for about 70 % of the states is needed. As in the Th isotopes [10, 11], 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. At least a small admixture of multi-step transfer for most of the other states is required to get a good agreement with experiment. 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 different-shaped angular distributions at the excitation of states with spin 2^+ by calculations assuming one-step and one-step plus two-step excitations. Results of similar fits for the states assigned as 4^+, 6^+ and 1^-, 3^-, 5^- excitations
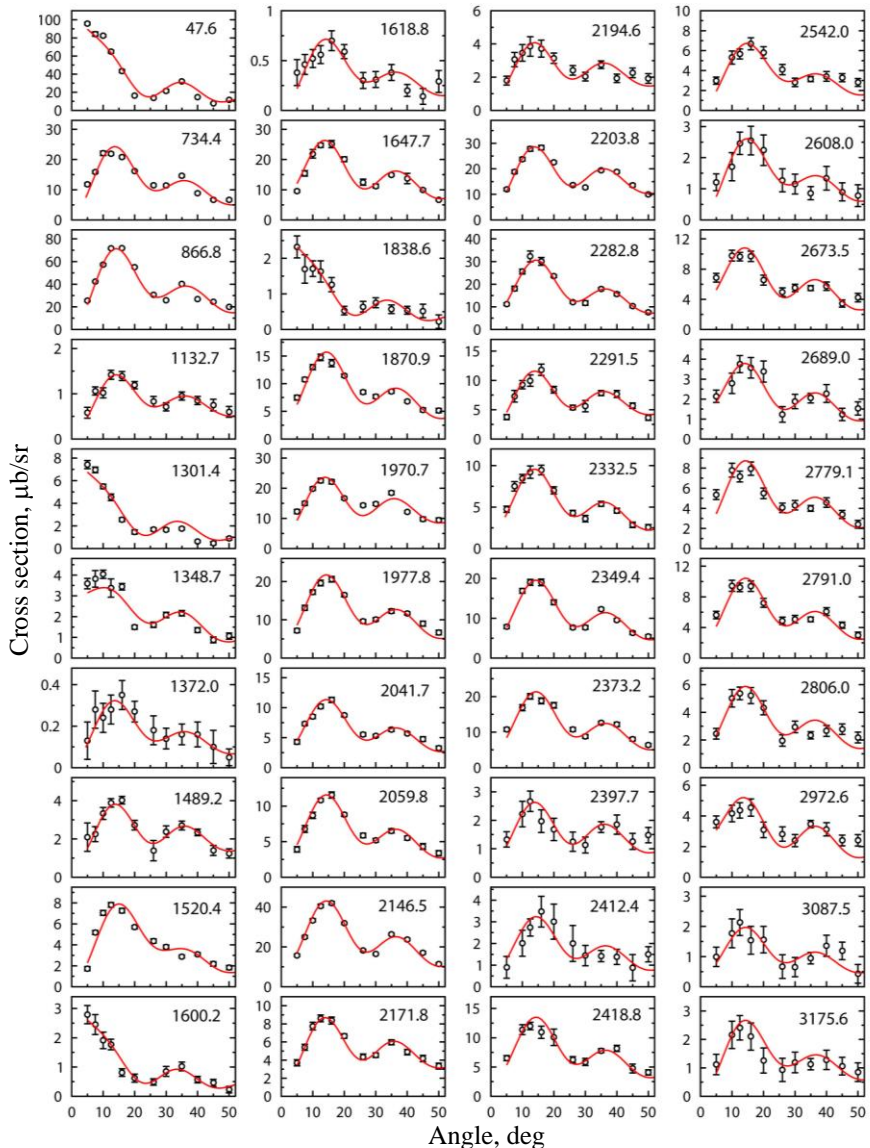
Fig. 4. Angular distributions of assigned 2^+ states in ^{232}U and their fit with CHUCK3 calculations.
The (ij) transfer configurations and schemes used in the calculations for the best fit are given in the Table.

are shown in Fig. 5. At the same time, for a number of states, possibly due to a lack of statistical accuracy, a good fit of the calculated angular distributions to the experimental ones cannot be achieved for a unique spin of the final state and therefore uncertainties remain in the spin assignment for such states. Some of them are demonstrated in Fig. 6.

The spins and parities resulting from such fits are presented in the Table, together with other experimental data. Fig. 7 summarizes the (p, t) strengths integrated over the angle region 5 - 50° for positive parity states. The sixth column in the Table displays the ratio $\sigma_{exp} / \sigma_{cal}$. Calculated cross sections for the specific transfer configurations differ very strongly. If the microscopic structure of the excited states is known, and thus the relative contribution of the specific $(j)^2$ transfer

configurations to each of these states, these relationships are considered as spectroscopic factors. A perfect fit of the experimental angular distributions may mean that the assumed configurations in the calculations correspond to the major components of the real configurations. Therefore, at least the order of magnitude for the ratio $\sigma_{exp} / \sigma_{cal}$ corresponds to the actual spectroscopic factors with the exception of too large values, 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. Surprisingly, the shape just for this neutron configuration gives the best agreement with experiment for the mentioned states.

A few additional comments have to be added for the region where data about the spins and parities are known from the analysis of γ spectra [17]. The angular distributions for some states are very different
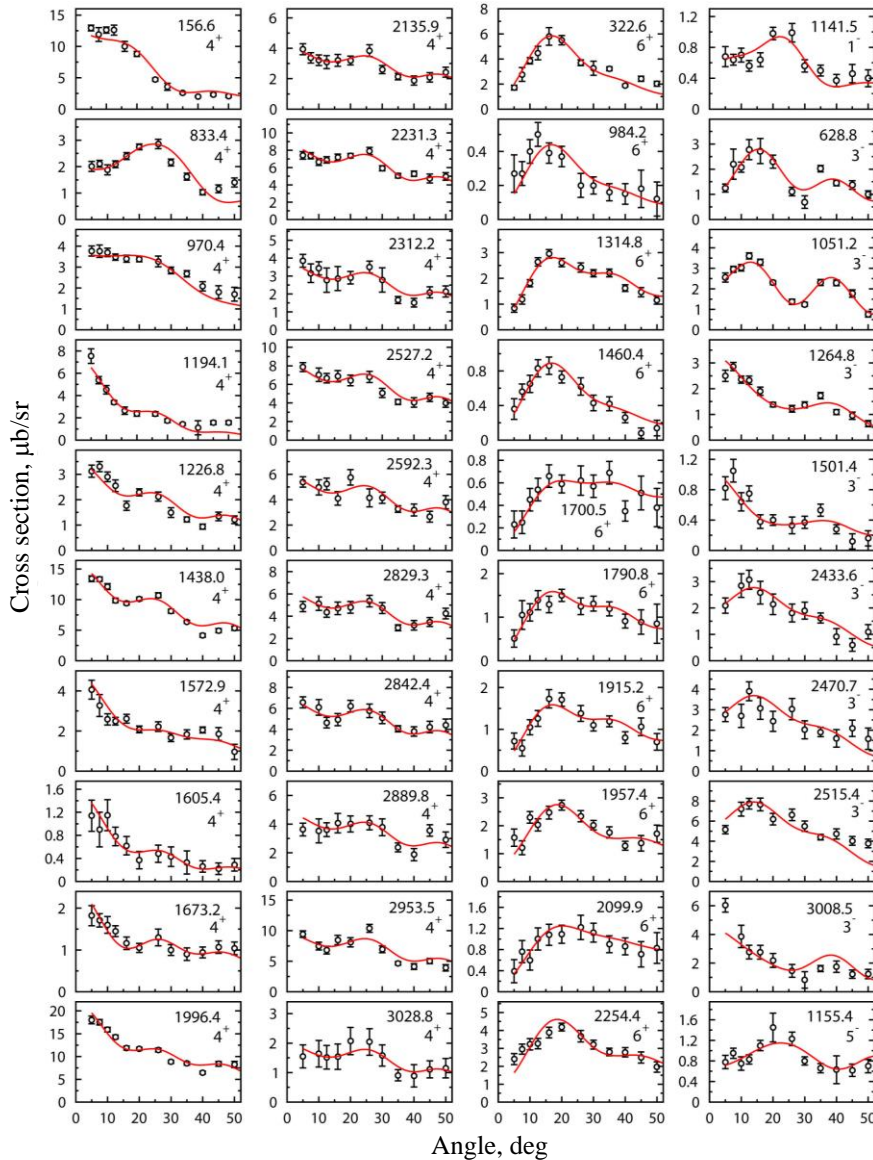
Fig. 5. Angular distributions of some assigned states in ^{232}U and their fit with CHUCK3 calculations: 4^+ and 6^+ with positive parity and 1^-, 3^- and 5^- with negative parity. The (*ij*) transfer configurations and schemes used in the calculations for the best fit are given in the Table.

from those calculated for the one-step transfer. Therefore, they were used as examples for other states at higher energies in the analysis of the angular distributions. As already noted the difference is significant already for the 2^+ and 4^+ states of the g.s. band. For example, the angular distribution for the 2^+ state at 47.6 keV can be used as an example for the states at 1301.4, 1600.2 and 1838.6 keV. From the two spins 3^+ and 4^+ proposed for the state at 1194.1 keV in the analysis of the γ spectra [17], our data clearly confirm the spin 4^+. Then the angular distribution for this state can serve as an example for the states at 1361.5 keV and 1604.9 keV. Importantly, the angular distributions for some 2^+ and 4^+ states have a feature typical for the excitation of 0^+ states, namely a strong peak at small angles.

The angular distribution for the 4^+ state at 833.4 keV, which is known from the γ spectroscopy, is very different from the one for the one-step transfer. It was used as an example for the assignment of spins of the states at 1728.5 keV and 1744.4 keV with similar angular distributions. Similarly, the angular distribution for the 1^- state at 563.2 keV can serve as an example for the state at 1141.3 keV. The angular distribution for the state 3^- at 628.8 keV not only differs from the one calculated for one-step transfer and can be described by the scheme m3a.gg, but it is very similar to the angular distribution for the 2^+ state at one-step transfer. Therefore, for all states with similar experimental distributions, the calculated angular distributions for the spin 2^+ and 3^- were tested during fitting procedure, using the scheme m3a.gg.
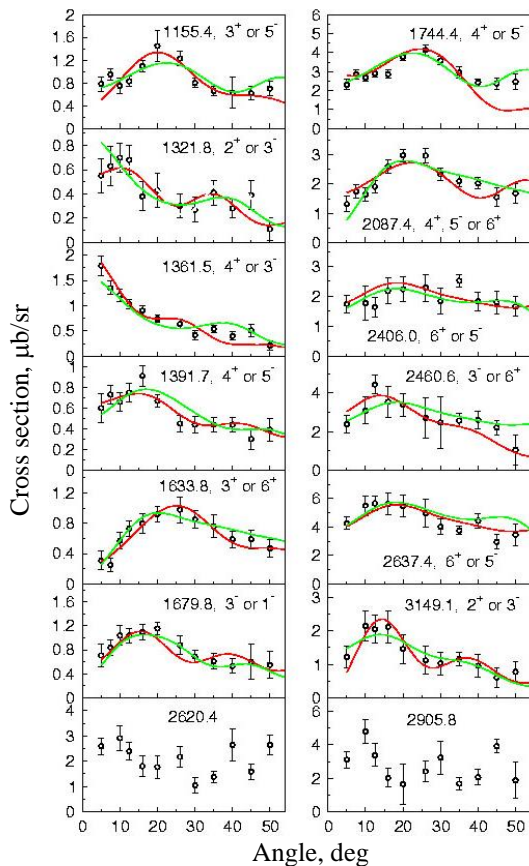
Fig. 6. Angular distributions for some states in ^{232}U for which fitting of the calculated distributions for a unique spin is doubtful or not possible. The first spin is indicated by red color. (See color Figure on journal website.)

Fig. 7. Experimental distribution of the (p, t) strength integrated in the angle region 5 - 50° for 0^+, 2^+, 4^+ and 6^+ states in ^{232}U. Green lines represent tentative assignments. (See color Figure on journal website.)

The states with unnatural parity populated via two step transfer, such as 3^+ at 911.9 keV and 2^- at 1173.0 keV, represent a special case. Assignments based on the γ-spectra analysis are tentative. These spins and parities are confirmed by fitting the angular distributions. Spin 3^+ for the states at 1552.8 and 1633.8 keV is attributed taking into account also the similarity of their angular distributions with those for the state at 911.9 keV. The state at 1015.9 keV is excited weakly, but the angular distribution measured with small statistics does not contradict the assignment of spin 2^-. The same is true for the state at 1097.6 keV with spin 4^-.
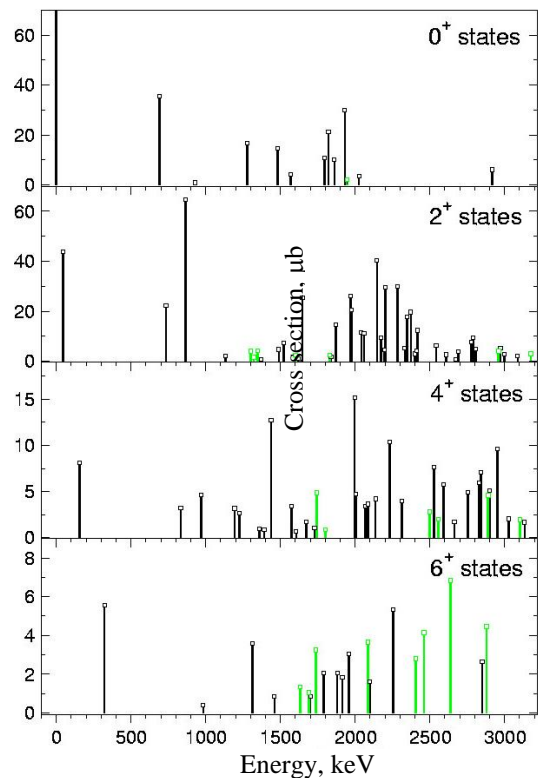
4. Conclusion

To summarize, in a high-resolution experiment the excited states of ^{232}U have been studied in the (p, t) transfer reaction. 162 levels were assigned, using a DWBA fit procedure. Among them, 13 excited 0^+ states have been found in this nucleus up to an energy of 3.2 MeV, most of them have not been experimentally observed before. Their accumulated strength makes up 84 % of the ground-state strength. Firm assignments have been made for most of the 2^+, 4^+ and for about half of the 6^+ states.

Discussion of the experimental results is presented in the forthcoming paper [26].

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СПЕКТРОСКОПІЯ ЯДРА ^{232}U В (p, t)-РЕАКЦІЇ: ЕКСПЕРИМЕНТАЛЬНІ ДАНІ

Спектри збудження в деформованому ядрі ^{232}U було досліджено в (p, t)-реакції з використанням Q3D спектрографа на мюнхенському тандемі. Кутові розподіли тритонів виміряно для 162 збуджень, що спостерігались у тритонних спектрах включно до 3,25 MeB. Ідентифіковано 13 0^+ збуджених станів шляхом порівняння експериментальних кутових розподілів із розрахованими з використанням програми CHUCK3. Визначено спіни включно до 6^+ для інших станів.

Ключові слова: 0^+-стани, (p, t)-реакція, аналіз наближення пов'язаних каналів.

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СПЕКТРОСКОПИЯ ЯДРА ^{232}U В (p, t)-РЕАКЦИИ: ЭКСПЕРИМЕНТАЛЬНЫЕ ДАННЫЕ

Спектры возбуждения в деформированном ядре ^{232}U были изучены в (p, t)-реакции с использованием Q3D спектрографа на мюнхенском тандеме. Угловые распределения тритонов измерены для 162 возбуждений, наблюдаемых в тритонных спектрах вплоть до 3,25 МэВ. Идентифицированы 13 0^+ возбужденных состояний при сравнении экспериментальных угловых распределений с вычисленными с использованием программы CHUCK3. Определены спины вплоть до 6^+ для остальных состояний.

Ключевые слова: 0^+-состояния, (p, t)-реакция, анализ приближения связанных каналов.