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States in ^{233}U excited by the ^{234}U(d, t) and ^{234}U(^{3}He, α) reactions

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The low-lying level structure of ^{233}U has been studied with the ^{234}U(d,t) and the ^{234}U(^{3}He,α) reactions, induced by 14-MeV deuterons and 30-MeV ^{3}He particles, respectively. Levels below 1 MeV of excitation energy are identified and their cross sections are compared with theoretical values, calculated including both Coriolis and $\Delta N = 2$ mixing. Nilsson band assignments are made and discussed.

[NUCLEAR REACTIONS ^{234}U(d,t), $E_{\rm lab}=14$ MeV; ^{234}U(^{3}He, α), $E_{\rm lab}=30$ MeV; measured $\sigma(\theta)$, deduced l values, Nilsson configurations, and level scheme of ^{233}U.]

I. INTRODUCTION

In recent years the level scheme of ^{233}U has been studied by a variety of techniques, including β-decay spectroscopy,[1,2] inelastic deuteron scattering,[3] and two-nucleon transfer from ^{235}U.[4] Furthermore, the hole states of ^{231}Th, the isotone of ^{233}U, are well known,[5,6] and since both ^{231}Th and ^{233}U are expected to have ground state configurations of $\frac{5}{2}^{+}[633\downarrow]$, their low-energy level schemes should be similar. That the ground state of ^{233}U is indeed represented by the $\frac{5}{2}[633\downarrow]$ assignment is known from Coulomb excitation experiments.[7]

The present work examines hole states in ^{233}U populated through the ^{234}U(d, t) and ^{234}U(^{3}He, α) reactions. As the (d, t) reaction excites predominantly low-spin states and the (^{3}He, α) reaction excites mainly high-spin states, members of low-lying hole state rotational bands with $J \leq \frac{15}{2}$ should be accessible with one or both reactions.

II. THEORY

If one makes the assumption that the oscillator quantum number N is a good quantum number for deformed wave functions in the Nilsson model, one may write the differential cross section for a one-nucleon pickup from an even target as

$$\left(\frac{d\sigma}{d\Omega}\right)_{0^+\to J=j} = 2N_0\left[\sum_i a_i c^i_{jl} V_i\right]^2 \sigma_l(\theta, Q)\,, \quad (1)$$

where $\sigma_l(\theta, Q)$ is the single-particle distorted-wave Born-approximation (DWBA) cross section for pickup of a nucleon of angular momentum l, N_0 is a normalization factor characteristic of the incident and outgoing particles, and the quantity in brackets times 2 is the spectroscopic factor S for the excitation of the rotational level in question. There the sum is carried out over all single-particle configurations i contributing to the rotational level having occupation probability $V_i{}^2$, mixing amplitude a_i, and amplitude c^i_{jl}, which is the coefficient of expansion of the deformed wave function in a spherical basis.

For realistic Nilsson states this form proves to be inadequate. The DWBA cross section $\sigma_{l\rm DW}(\theta, Q)$ is a function of the radial oscillator quantum number N which may vary by as much as two orders of magnitude as N goes from 1 to 7, holding θ and Q fixed. As the single-particle configurations may include significant contributions from spherical basis functions having differing values of N, it is necessary to replace Eq. (1) by the more general form

$$\left(\frac{d\sigma}{d\Omega}\right)_{0^+\to J=j} = 2N_0 \sum_N \left[\sigma^N_l(\theta, Q)\left(\sum_i a_i c^{i,N}_{jl} V_i\right)^2\right], \quad (2)$$

where the first sum is carried out over all contributing radial quantum numbers. This form is particularly meaningful in the actinide region when applied to negative-parity states for which asymptotic values for N both of 5 and 7 are observed.

The pairing factors V_i are determined from a blocked, BCS calculation which uses the 25 configurations nearest the Fermi surface of ^{233}U. The strength of the pairing interaction is obtained by fitting to the experimental pairing gap of the adjacent even-even nuclei.

The expansion coefficients c^i_{jl} are strongly dependent on the parameters κ and μ in the Hamiltonian of Nilsson.[8] It has been shown[6] that the values of κ and μ given in the literature[8] inadequately reproduce the observed band energies and intensity patterns in odd-neutron deformed nuclei of $230 \leq A \leq 240$; therefore, values[6] of $K=0.05$ and $\mu=0.448$ were used for intensity and energy calculations to be mentioned in Sec. IV.

III. EXPERIMENTAL TECHNIQUE

Beams from the University of Rochester MP tandem Van de Graaff accelerator impinged on a line-shaped target of ^{234}U with dimensions of approximately 1×5 mm^2 and a thickness of ~ 25 μg/cm^2, deposition on a doubled 20 μg/cm^2 carbon backing. The (d, t) experiments were performed with a beam energy of 14 MeV (lab) and the $(^3\mathrm{He}, \alpha)$ experiments with a beam energy of 30 MeV (lab).

The outgoing particles were analyzed at various angles using an Enge split-pole magnetic spectrograph[9] and detected using nuclear emulsion plates (Kodak NTB-50 for tritons and Ilford K-0 for α particles), which for the $(^3\mathrm{He}, \alpha)$ exposures were covered with thin aluminum absorbers to enhance track densities. Typical exposure times were 6 hours for the (d, t) experiments and 18 hours for the $(^3\mathrm{He}, \alpha)$ experiments. The plates were developed and scanned with calibrated microscopes in $\frac{1}{4}$-mm strips.

A NaI detector mounted at 45° in the scattering chamber was used to monitor the beam exposure. Short elastic runs at 20° and 45° provided the standard by which absolute cross sections could be extracted for the reactions.

IV. EXPERIMENTAL RESULTS

A spectrum of the ^{231}U$(d, t)^{233}$U reaction in the energy range up to 1 MeV is shown in Fig. 1. The (d, t) spectra have an energy resolution of approximately 9-keV full width at half maximum (FWHM); the $(^3\mathrm{He}, \alpha)$ spectra show a resolution of about 34 keV FWHM. In Table I and II are summarized experimental data taken at several angles.

Calculation of theoretical cross sections was performed using the computer code DWUCK[10] at excitation energies of 0 and 1 MeV. The optical-model parameters[11,12] used in these calculations are given in Table III. Cross sections at intermediate energies were obtained by linear interpolation between the 0- and 1-MeV values.

The Nilsson band assignments based on the above data are summarized in Table IV. Theoretical cross sections were calculated using a computer code which included Coriolis coupling of the 25 configurations nearest the Fermi surface as well as $\Delta N = 2$ mixing; a comparison of theoretical values with those derived from experimental data is shown in Table V. A partial level scheme for ^{233}U appears in Fig. 2. All levels observed in this work are included, as are selected levels observed in other experiments. Only Nilsson bands

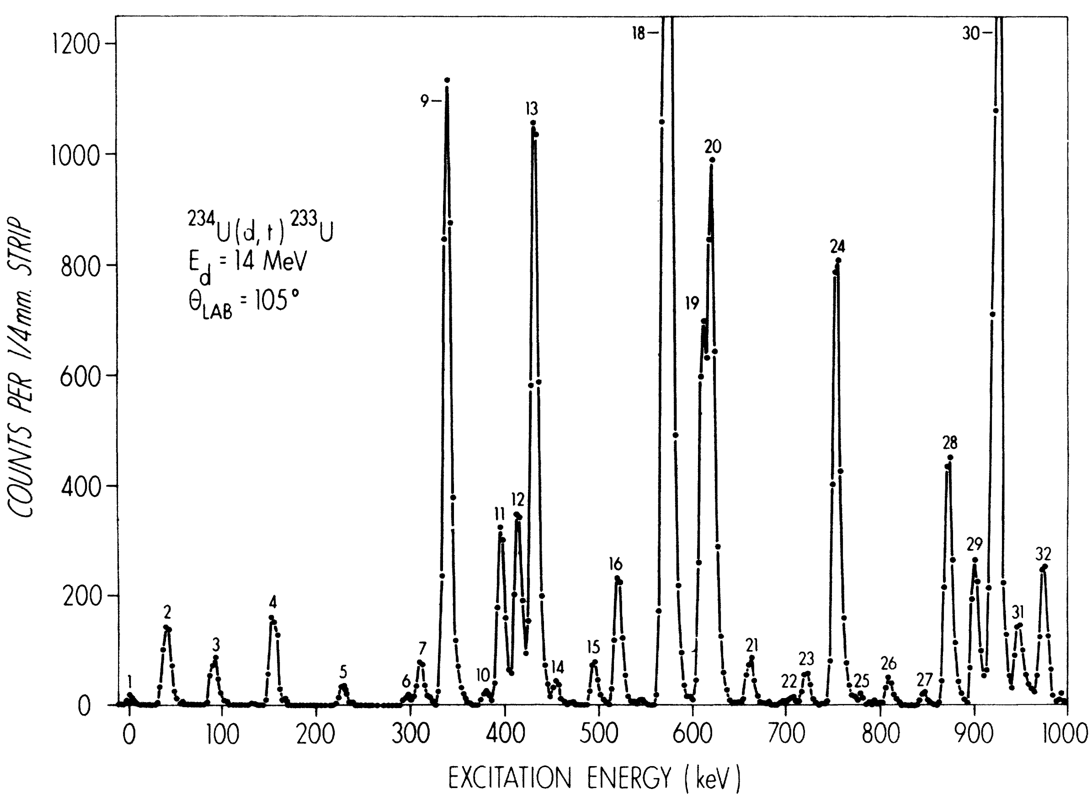

FIG. 1. Triton spectrum from the ^{234}U$(d,t)^{233}$U reaction.

TABLE I. Energy levels excited in the ^{234}U(d,t)^{233}U reaction.

Level	Energy (keV)	Cross section in μb/sr (±μb/sr) 50°	60°	90°	105°	120°
1	0	···	6(1)	4(1)	4(1)	3(1)
2	40 ± 1	40(10)[a]	29(2)	41(2)	33(2)	24(2)
3	94 ± 2	24(6)[a]	15(2)	22(2)	19(1)	16(1)
4	156 ± 2	15(4)[a]	14(2)	29(2)	35(2)	29(2)
5	228 ± 3	···	2(1)	4(1)	8(1)	6(1)
6	300 ± 3	···	3(2)	4(1)	4(1)	2(1)
7	312 ± 2	20(3)	24(2)	26(2)	17(2)	12(1)
8	(319 ± 4)	···	···	···	···	4(1)
9	341 ± 1	236(11)	330(13)	326(14)	234(6)	161(5)
10	379 ± 2	···	6(2)	5(1)	5(2)	4(2)
11	398 ± 2	56(4)	82(6)	99(26)	68(5)	56(23)
12	415 ± 2	121(7)	111(42)	78(4)	52(22)	···
13	432 ± 1	112(6)	186(9)	279(19)	231(5)	175(8)
14	456 ± 2	11(2)	17(3)	14(1)	11(2)	6(1)
15	497 ± 2	10(2)	11(2)	14(1)	17(2)	16(6)
16	522 ± 2	9(2)	14(2)	45(9)	50(3)	45(3)
17	(546 ± 3)	···	···	2(2)	···	2(2)
18	572 ± 1	696(31)	1300(130)	1256(62)	982(50)	808(32)
19	610 ± 3[b]	38(13)	58(19)	144(10)	140(9)	131(9)
20	620 ± 3[b]	103(18)	176(27)	214(12)	188(9)	149(10)
21	660 ± 2	···	26(6)	21(3)	19(2)	16(2)
22	(700 ± 3)	···	···	3(1)	3(1)	6(1)
23	717 ± 3	···	···	12(1)	12(1)	12(9)
24	749 ± 2	56(5)	117(15)	180(9)	176(6)	147(5)
25	774 ± 3	10(3)	···	8(2)	4(1)	2(1)
26	802 ± 3	···	···	10(2)	10(1)	9(2)
27	(839 ± 4)	···	···	3(1)	5(1)	24(21)
28	865 ± 2	60(5)	102(10)	119(17)	103(8)	73(14)
29	894 ± 2	18(3)	45(7)	61(30)	61(6)	48(24)
30	916 ± 1	71(6)	156(13)	279(25)	316(13)	278(22)
31	938 ± 2	31(4)	52(8)	36(6)	40(4)	23(8)
32	964 ± 3	61(15)	94(9)	76(6)	58(6)	40(7)
33	1003 ± 3	72(7)	98(15)	120(60)	84(9)	66(32)
34	1016 ± 1	246(13)	439(6)	525(34)	568(29)	454(24)
35	1053 ± 2	13(2)	40(8)	54(5)	55(4)	48(6)
36	(1079 ± 4)	···	···	4(1)	3(1)	···
37	(1090 ± 4)	···	···	4(1)	4(1)	···
38	1103 ± 3	···	6(2)	26(5)	27(3)	26(5)
39	(1114 ± 4)	···	7(2)	···	4(2)	···
40	1125 ± 3	···	6(2)	8(1)	7(2)	6(2)
41	(1155 ± 4)	···	···	4(1)	5(1)	···
42	1169 ± 4	···	···	6(3)	6(2)	···
43	1193 ± 3	18(6)	27(4)	26(11)	18(3)	15(8)
44	1216 ± 3	47(9)	79(6)	87(7)	75(6)	60(13)
45	(1227 ± 4)	···	···	21(5)	24(5)	···
46	1236 ± 3	35(7)	45(5)	56(6)	46(5)	40(14)
47	1263 ± 3	41(6)	68(6)	113(13)	106(8)	86(12)
48	(1276 ± 4)	···	···	20(2)	14(4)	···

[a] The low-energy portion of the 50° plate displays a high background which renders cross sections unreliable.

[b] Possible multiplet.

with one or more members observed in the present experiment are shown.

V. DISCUSSION

Owing to the relatively structureless angular distributions encountered at the bombarding energies used, it is difficult to extract unambiguous l-transfer information from the ^{234}U(d, t) reaction alone. However, some indications of the size of the l transfer can be obtained from the ratio $d\sigma(d, t)/d\sigma(^3\text{He}, \alpha)$. The usefulness of this ratio has been pointed out elsewhere,[13] and has been used in the following analysis.

TABLE II. Some of the energy levels excited in the $^{234}U(^3He,\alpha)^{233}U$ reaction.

Level[a]	Energy (keV)	Cross section in μb/sr (±μb/sr) 40°	60°
2	41 ± 5	2(1)	2(1)
3	94 ± 5	1(1)	2(1)
4	156 ± 4	27(2)	15(1)
5	228 ± 5	4(1)	3(1)
7	(312 ± 6)	2(1)	···
8	(324 ± 6)	···	4(1)
11	395 ± 5	5(1)	6(1)
13	432 ± 4	26(2)	30(8)
16	521 ± 3	89(6)	54(6)
24	748 ± 4	5(1)	10(1)
30	916 ± 3	10(1)	15(3)
33	1007 ± 4	6(1)	17(3)
35	1057 ± 5	14(2)	8(2)

[a] The number of the level is assigned to agree with a corresponding level listed in Table I.

A. $\frac{5}{2}^+$ [633↓] band

Previous workers[7,14] have observed the existence of a rotational band built on the ground state with members having energies of 41, 94, 157, 234, 320, and 415 keV, and have suggested that these levels are the members of the $\frac{5}{2}^+$[633↓] Nilsson band. The present work supports this assignment and confirms the placement of the first four excited states. In addition, it is possible that the 320-keV, $J=\frac{15}{2}$ level is populated weakly in the (^{3}He, α) experiment, though the predicted cross section is small. The $J=\frac{9}{2}$ level at 94 keV is found to have a smaller cross section that that calculated from theory with Nilsson wave functions. The same effect has been noted in other actinides.[5,15] Eigenfunctions of a Woods-Saxon potential, as suggested by Gareev *et al.*,[16] also fail to reproduce the experimentally observed signature.

The level at 749 keV has been assigned previously in a (d,d') experiment[3] as the $J=\frac{5}{2}$ member of the $\frac{5}{2}^-$[633↓⊗$K^\pi=0^-$] band. This band is formed by coupling of the ground state to the $K^\pi=0^-$ octupole band. The relatively large (d,t) and (^{3}He, α) cross sections for transfer to the 749-keV level may result from a significant admixture of the nearby [503↓] band (given a tentative assignment in Sec. V F). The [503↓] band has almost all of its single-particle strength in the $\frac{5}{2}^-$ band-head level which is only 167 keV away from the $\frac{5}{2}^-$ [633↓⊗$K^\pi=0^-$] level.

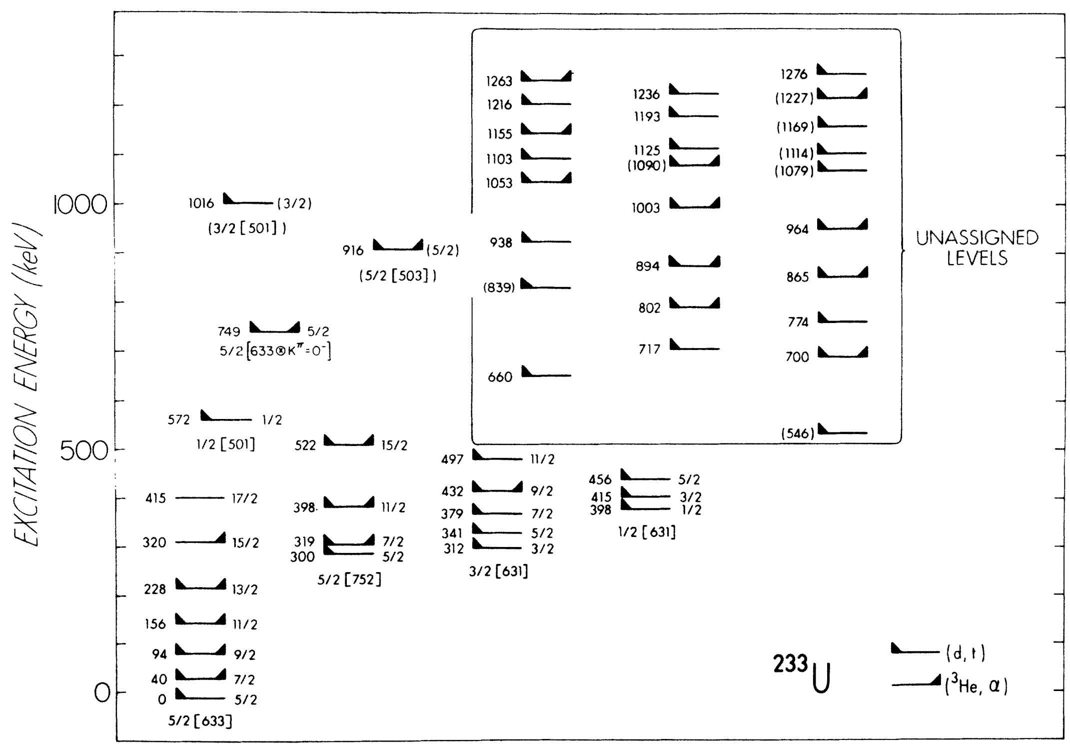

FIG. 2. Partial level scheme for ^{233}U. Only levels observed in this work are shown. Observations of the levels in the (d,t) and (^{3}He, α) reactions are designated by flags placed at the left- and right-hand sides of the lines, respectively. Assignments in parentheses are uncertain.

TABLE III. Optical-model parameters used in the DWBA analysis.

	V_R	r_{0R}	c_R	V_I	r_{0I}	c_I	r_c	Ref.
Bound state	−50	1.225	0.7					
d (volume)	−100	1.14	0.89				1.30	a
(surface)				−55.2	1.33	0.75		a
t	−168	1.14	0.723	−17	1.52	0.77	1.4	a
^{3}He	−175	1.14	0.723	−17.5	1.6	0.81	1.4	b
α	−206	1.41	0.519	−25.8	1.41	0.519	1.3	b

[a]Reference 12.
[b]Reference 11.

TABLE IV. Rotational band assignments.

Nilsson band	Level	Spin Assignments	State energies (keV)	Confidence level[a]
$\frac{5}{2}^+[633\downarrow]$				A
	1	$\frac{5}{2}$	0	A
	2	$\frac{7}{2}$	40	A
	3	$\frac{9}{2}$	94	A
	4	$\frac{11}{2}$	156	A
	5	$\frac{13}{2}$	228	A
	8	$\frac{15}{2}$	319	C
$\frac{3}{2}^+[631\uparrow]$				A
	7	$\frac{3}{2}$	312	B
	9	$\frac{5}{2}$	341	A
	10	$\frac{7}{2}$	379	A
	13	$\frac{9}{2}$	432	A
	15	$\frac{11}{2}$	497	B
$\frac{1}{2}^+[631\downarrow]$				A
	11	$\frac{1}{2}$	398	B
	12	$\frac{3}{2}$	415	A
	14	$\frac{5}{2}$	456	C
$\frac{5}{2}^-[752\uparrow]$				A
	6	$\frac{5}{2}$	300	B
	8	$\frac{7}{2}$	319	C
	11	$\frac{11}{2}$	398	B
	16	$\frac{15}{2}$	522	A
$\frac{1}{2}^-[501\downarrow]$				A
	18	$\frac{1}{2}$	572	A
	19,20	$\frac{3}{2},\frac{5}{2}$	~615	C
$\frac{5}{2}^-[503\downarrow]$				C
	30	$\frac{5}{2}$	916	C
$\frac{3}{2}^-[501\uparrow]$				C
	34	$\frac{3}{2}$	1016	C

[a]A—high confidence assignments, B—intermediate confidence assignments, and C—low confidence assignments.

TABLE V. Theoretical and experimental cross sections for the (d,t) reaction at $\theta=90°$.

Band	J^{π}	Cross section (μb/sr) Experiment	Theory
[633↓]	$\frac{5}{2}+$	4	8
	$\frac{7}{2}+$	41	20
	$\frac{9}{2}+$	22	57
	$\frac{11}{2}+$	29	30
	$\frac{13}{2}+$	4	4
	$\frac{15}{2}+$	(<3)	<1
[631↑]	$\frac{3}{2}+$	26	1
	$\frac{5}{2}+$	326	90
	$\frac{7}{2}+$	5	4
	$\frac{9}{2}+$	279	168
	$\frac{11}{2}+$	14	13
[631↓]	$\frac{1}{2}+$	53 [a]	25
	$\frac{3}{2}+$	111	43
	$\frac{5}{2}+$	14	7
[752↑] [b]	$\frac{5}{2}-$	4	4
	$\frac{7}{2}-$	~3	22
	$\frac{9}{2}-$	<3	<3
	$\frac{11}{2}-$	46 [a]	22
	$\frac{13}{2}-$	<5	<1
	$\frac{15}{2}-$	44	15
[501↓]	$\frac{1}{2}-$	1256	1048
	$\frac{3}{2}-$	{358} [c]	146
	$\frac{5}{2}-$		66
[501↑]	$\frac{3}{2}-$	525	572
[503↓]	$\frac{5}{2}-$	279	482

[a] Members of doublets were assumed to make contributions to the experimental cross sections proportional to the cross sections predicted from theory.

[b] This band is strongly Coriolis coupled to several unobserved $N=7$ bands leading to significant uncertainties in the theoretical cross sections.

[c] Total strength of lines 19 and 20.

B. $\frac{3}{2}$[631↑] band

The $\frac{3}{2}$ and $\frac{5}{2}$ members of this band have been assigned by Bisgaard *et al.*[14] at energies of 312 and 341 keV, respectively, and these assignments are confirmed here. Further members at 379, 432, and 497 keV are also observed. The experimental cross sections of the band members exhibit the same trends as the theoretically predicted cross sections. However, the theoretical cross sections of the $J=\frac{3}{2}$ and $\frac{5}{2}$ levels are smaller than the experimental values. Some improvement in the agreement between theory and experiment for the $\frac{5}{2}$ level may be obtained by including Coriolis coupling with the unobserved $\frac{5}{2}$[622↑] particle configuration which is expected to be near in energy.

C. $\frac{1}{2}$[631↓] band

This band is expected to be a particle configuration in ^{233}U and should be only weakly excited in the pickup reactions considered here. However, the $J=\frac{1}{2}$ and $J=\frac{3}{2}$ members of this band have been assigned in previous work[14] at 399 and 416 keV, respectively. These levels are populated in the (d,t) reaction with cross sections which support the above assignments. The presence of a weak line at 395 keV in the (^{3}He, α) spectrum suggests a higher-spin component, so that the 398-keV line in the (d,t) spectrum is proposed to be a doublet composed of the $J=\frac{1}{2}$, $\frac{1}{2}$[631↓] and $J=\frac{11}{2}$, $\frac{5}{2}$[752↑] states. The $\frac{5}{2}$ member of the [631↓] band is tentatively placed at 456 keV.

D. $\frac{5}{2}$ [752↑] band

This band is assigned on the basis of levels observed at 300, 398, 522, and possibly 319 keV, and on the unambiguous observation in (p,t) experiments[4] of the $J=\frac{7}{2}$ and $J=\frac{9}{2}$ members of this band at 318 and 352 keV, respectively. The $J=\frac{15}{2}$ member of the $\frac{5}{2}$[633↓] band is also expected to fall near 319 keV. However, its spectroscopic factor is expected to be very small, so that an assignment of $J=\frac{7}{2}$, $\frac{5}{2}$[752] is more reasonable. The decay study of Weiss-Reuter *et al.*[1] suggests that this is instead the $\frac{7}{2}$[743↑] band; however, the (p,t) study[4] gives an unambiguous placement of the [743↑] band at a considerably higher energy, and also supports our assignment.

E. $\frac{1}{2}$ [501↓] band

As in the case of the isotone ^{231}Th, the $J=\frac{1}{2}$ member of this band is the most strongly populated level in the (d,t) reaction and occurs here at an energy of 572 keV. The complex of lines in the vicinity of levels 19 and 20 is poorly resolved in the (d,t) reaction but is expected to include both the $\frac{3}{2}$ and $\frac{5}{2}$ members of this band. The absence of significant strength in the (^{3}He, α) spectrum in the energy region near 615 keV suggests that the components of levels 19 and 20 have moderately low spin.

F. Other assignments

A level at 1016 keV of excitation is found to be populated very strongly in the (d,t) reaction while showing no measurable cross section in the (^{3}He, α) reaction. This is consistent with an angular momentum transfer of $\Delta l = 0$ or 1; the level is therefore tentatively assigned as the $J=\frac{3}{2}$ member of the $\frac{3}{2}^-$ [501↑] band. The cross section is consistent with theoretical predictions. Calculations suggest that this band should fall at a somewhat higher excitation energy; however, the observed energy is still reasonable in view of uncertainties in the model. The ^{231}Th level at 809 keV which has a large cross section and appears to be analogous to the 1016-keV level in ^{233}U has also been interpreted by Grotdal *et al.*[6] as the $J=\frac{3}{2}$ band head of the [501↑] band.

The level at 916 keV is strongly populated in the (d, t) reaction and observed also in the (^{3}He, α) reaction. This level is very tentatively assigned to the $J=\frac{5}{2}$ member of the $\frac{5}{2}$ [503↓] band. The discrepancy in the experimental and theoretical cross sections for this level shown in Table V may be explained by this band being admixed into the [633↓$\otimes K^\pi = 0^-$] band which was discussed in Sec. V A. This 916-keV level was seen at 914 ± 3 keV in the (d, d') reaction,[3] indicating some collective components in its structure. However, the large cross section observed for transfer indicates that its dominant component is single-particle in nature.

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