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TWO-QUASIPARTICLE STATES IN ^{168}Er

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Abstract: The level structure of ^{168}Er and the de-excitation mechanism in this nucleus have been studied by radiative capture of thermal neutrons in samples of natural erbium which give a cross-section contribution of 89.8 ± 2.3 % for ^{167}Er. Interference from the 9.1 ∓ 2.1 % capture contribution of ^{166}Er was well known from a separate study with enriched ^{166}Er samples. High-resolution measurements of the γ-ray spectrum have been performed using the Karlsruhe Ge(Li) anti-Compton spectrometer below 2 MeV and a Ge(Li) double-escape spectrometer above 5.16 MeV. The high accuracy of the data allows the construction of a considerably extended transition diagram up to 2 MeV excitation energy. A large number of new levels has been assigned to specific configurations and their superimposed rotational bands. Conclusive evidence is given that the previously known states at 1094 keV and 1542 keV are the two-quasiparticle neutron levels $[633\uparrow+521\downarrow]_{nn}$ and $[633\uparrow-521\downarrow]_{nn}$, respectively. Some aspects of the corresponding $\log ft$ values are discussed in detail. Rotational bands at 1354 keV, 1569 keV and 1542 keV have to be identified with the $K^\pi = 1^-$, 2^- and 3^- octupole vibrational bands. The properties of the $K^\pi = 1^-$ state are presumably close to those of the neutron level $[512\uparrow-633\uparrow]_{nn}$. The 3^- rotational member of the $K^\pi = 0^-$ octupole band probably occurs at 1914 keV. The simple model of pairing plus state-independent octupole force provides a surprisingly good microscopic description of the octupole excitation energies. The first $K^\pi = 0^+$ band has been well established to occur at 1217 keV. Within the model of pairing plus quadrupole and spin-quadrupole force one obtains the interaction constants $\kappa_q = 5.3$ and $\kappa_t = 8.8$ (in units of $A^{-\frac{4}{3}}\hbar\omega_0$). The neutron level $[521\downarrow+642\uparrow]_{nn}$ has been tentatively assigned to a rotational band at 1893 keV. The properties of some other more or less collective states are discussed. No positive evidence has been found for the occurrence of two-quasiparticle proton levels below 1820 keV excitation energy. The neutron separation energy was determined to be 7771.24 ± 0.48 keV.

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NUCLEAR REACTIONS ^{167}Er(n, γ), E = th; measured E_γ, I_γ; deduced Q. ^{168}Er deduced levels, J, K, π. Er, Sm, Gd(n, γ), E = th; measured E_γ, I_γ. ^{150}Sm, ^{156,158}Gd, ^{167}Er deduced transitions. Natural target, Ge(Li) detectors.

1. Introduction

The characteristics of the nuclear level schemes in the mass region $150 < A < 190$ suggest that these nuclei have permanent deformations. Many properties of the energy levels follow the systematics of the collective model [1,2]). The nucleus ^{168}Er provides a typical example for a strongly deformed even nucleus in this mass region. The level scheme is expected to involve a ground state rotational band, a $K^\pi = 2^+$ γ-vibrational band near 1 MeV of excitation and at somewhat higher energies $K^\pi = 0^+$ bands having β-vibrational and pairing-vibrational character. Beginning at about 1 MeV one expects in addition two-quasiparticle states involving both proton-proton and neutron-neutron excitations [3]). Microscopic calculations on the structure of octupole vibrations [4]) have shown that only few two-quasiparticle configurations contribute to these states, the properties of the $K^\pi = 1^-$ and $K^\pi = 3^-$ bands being rather close to those of two-quasiparticle states. The excitation energies as calculated by various methods [4-8]) are predicted for all octupole states ($K^\pi = 0^-, 1^-, 2^-, 3^-$) between 1.3 and 2.2 MeV. Considerable Coriolis interaction is expected between these bands [9]).

Similar to most of the neighbouring nuclei the experimental information on the higher-lying configurations is still very poor. It is the purpose of the present investigation to extend the data on the ^{168}Er level structure with particular emphasis on excitation energies above 1 MeV.

The excited states of ^{168}Er have been studied by a variety of techniques. The most recent investigations comprise Coulomb excitation with oxygen ions [10]), neutron-capture experiments [11]), (d, p) reactions [12]), inelastic scattering of deuterons [13]) and studies of the decay [14]) of ^{168}Tm. The earlier works have been summarized in refs. [10-14]). The level scheme which results from the previous investigations includes several well established bands: the ground state rotational band, the $K^\pi = 2^+$ γ-vibrational band at 821 keV and two neutron-neutron excitations with $K^\pi = 4^-$ and 3^- at 1094 and 1542 keV, respectively.

A considerable amount of the information on the de-excitation mechanism has come from thermal-neutron capture experiments with a bent crystal diffraction instrument [11]). The investigation of the low-energy capture spectrum has been extended to higher energies by means of a combined flat crystal and Ge(Li) spectrometer [15]). However, no additional information on the ^{168}Er level structure has been deduced from these data. The excellent performance of the Karlsruhe Ge(Li) anti-Compton spectrometer with respect to energy resolution and Compton suppression efficiency suggested the possibility to improve considerably the quality of the data in the energy range from 500 to 2000 keV. Therefore, it was felt useful to reinvestigate with this instrument the low-energy capture spectrum. Although level information may be obtained in a more direct manner from other nuclear reactions, the neutron capture process permits a more detailed study of the level decay without restriction to any particular mode of excitation.

The spectrum of primary transitions leaving the neutron capture state has been studied both with a magnetic Compton spectrometer [16]) and a Ge(Li) detector [17]). The results disagree in several details. Since the high-energy γ-rays provide a quite direct information on the level structure, it is also intended by the present research to eliminate these discrepancies, to further reduce the uncertainty in the energies of the primary γ-rays and thereby reduce the uncertainties in the deduced level energies.

Another class of experiments has been performed in ref. [18]) in which the random fluctuations in intensity for the primary γ-rays were averaged out by measuring the spectra that result from the capture of neutrons in an energy band containing many resonances. Such measurements reveal the parity of low-lying nuclear states and also restrict the spin assignment for each of these levels to two possible values (3 or 4 and 2 or 5). The data have been a great aid to our analysis and quite good agreement has been found with the high-energy data obtained in the present study. The results of our high-precision measurements with the anti-Compton spectrometer provide the missing link to arrive at definite conclusions on the spectroscopic interpretation of the excited states below 2 MeV.

2. Experimental procedure

Thermal neutron beams from the reactor FR2 were used to irradiate samples of chemically pure natural erbium in external target geometry. The abundances of the isotopes and the relative cross-section contributions are summarized in table 1. Due

TABLE 1

Isotopic composition of the target and relative cross-section contributions

Isotope	Atomic %	Capture cross section [a]) for thermal neutrons (b)	Relative cross-section contribution (%)
^{162}Er	0.14	2.0 ± 0.2	< 0.01
^{164}Er	1.56	1.65 ± 0.17	< 0.02
^{166}Er	33.41	45 ± 9	9.1 ± 2.1
^{167}Er	22.94	650 ± 30	89.8 ± 2.3
^{168}Er	27.07	2.03 ± 0.41	0.33 ± 0.09
^{170}Er	14.88	9 ± 2	0.81 ± 0.23

a) Ref. [19]).

to the high capture cross section of ^{167}Er interference from most of the other isotopes was negligible. The γ-ray spectrum from capture in ^{166}Er was well known from our recent study [20]) of the reaction ^{166}Er(n, γ)^{167}Er. The data were also carefully examined for the possibility of contributions from likely chemical contaminants and, in fact, several lines were identified as arising from Sm and Gd isotopes.

High-resolution measurements of the low-energy capture γ-ray spectrum have been performed with the Karlsruhe Ge(Li) anti-Compton spectrometer †). The energy resolution including long-term instabilities was 1.62 keV FWHM for the 662 keV ^{137}Cs γ-ray. The following standards were used for energy calibration:

^{192}Ir	295.938 ± 0.009 keV [ref. [21])],
	316.486 ± 0.010 keV [ref. [21])],
^{137}Cs	661.595 ± 0.076 keV [ref. [22])],
^{60}Co	1173.226 ± 0.040 keV [ref. [21])],
	1332.483 ± 0.046 keV [ref. [21])],
^{88}Y	898.01 ± 0.07 keV [ref. [22])],
	1836.08 ± 0.07 keV [ref. [22])],
H(n, γ)	2223.29 ± 0.07 keV [ref. [23])].

† See ref. [20]) and the literature cited there.

The response function of the spectrometer was determined with a set of absolutely calibrated γ-ray sources.

The high-energy capture spectrum has been investigated with a 5.3 $cm^2 \times 0.6$ cm Ge(Li) detector. The energy resolution was 6.6 keV FWHM at 6 MeV γ-ray energy. The calibration is based on the following standards:

$^{14}N(n, \gamma)$	5269.2 ± 0.35 keV	
	5297.8 ± 0.35 keV	
	5533.2 ± 0.35 keV	
	5562.2 ± 0.35 keV	[ref. [24])]
	6322.0 ± 0.4 keV	
	7299.0 ± 0.5 keV	
	8310.2 ± 0.7 keV	

The response function was measured using the well-known intensities [25]) from the reaction $^{14}N(n, \gamma)^{15}N$.

Details on the experimental arrangements and the procedures applied in spectrum stabilization, spectrum analysis, energy and intensity calibration and nonlinearity correction may be found in ref. [20]) and the literature given there.

3. Experimental results

3.1. NEUTRON CAPTURE γ-RAY SPECTRUM IN THE ENERGY RANGE 80 keV TO 2000 keV

Using the anti-Compton spectrometer the low-energy capture spectrum has been investigated between 80 keV and 2000 keV. Below 525 keV excellent agreement was found with previously reported data for the (n, γ) reaction [11]). No additional information has been obtained in this energy region. It is worth mentioning that the energy of the $6^+ \rightarrow 4^+$ transition within the ground state rotational band (cf. subsect. 3.3) was observed to be 284.653 ± 0.065 keV which agrees very well with the value 284.646 ± 0.010 keV given in ref. [11]). The energy value of 284.11 ± 0.11 keV which very recently has been reported from precision spectroscopy on the ^{168}Tm decay [14]) could not be confirmed.

Above 525 keV the present research has brought about a considerable improvement in the quality and detail of the experimental data. The results are summarized in table 2. For comparison the data from bent crystal [11]) and flat crystal Ge(Li) detector [15]) measurements have also been included in the table.

Due to the high line density in the spectrum many of the γ-rays listed in table 2 may represent closely spaced doublets or complex structures. If a peak which is now assumed to correspond to a single γ-ray turns out to be a multiplet, the energy given in the table refers to the centroid and the intensity is the total intensity of the components. For determining the quoted uncertainties in the energy values consideration was given to: (i) the statistical fluctuations in the spectrum, (ii) the goodness of fit obtained in the spectrum analysis, (iii) possible errors in the nonlinearity correction function and (iv) the uncertainties associated with the energy standards.

The γ-ray intensities listed in table 2 are relative intensities. They were normalized to a value of 6.6 for the 631.77 keV line. This value was adopted from ref. [11]). The deviation from the absolute intensity in photons per 100 captures is stated in ref. [11]) to be not more than about 15 %. The errors quoted for the intensities in table 2 include uncertainties arising from the statistics, the fitting procedure and the spectrometer response function.

In order to facilitate the survey of the data, column 5 in table 2 gives the assignment of the lines in the γ-ray transition diagram (cf. subsect. 3.3). Gamma rays not belonging to ^{168}Er are labelled with the emitting isotope. When no assignment is given, the transition is attributed to ^{168}Er, but has not been fitted into the diagram.

Fig. 1 shows a typical sectional display of the γ-ray spectrum. The example clearly demonstrates both the high resolution and the effective suppression of Compton events. The inset illustrates the analysis of a group of γ-ray lines as obtained by means of a computer programme.

3.2. NEUTRON CAPTURE γ-RAY SPECTRUM IN THE ENERGY RANGE 5160 keV TO 7700 keV

Table 3 summarizes the γ-ray energies and intensities which have been measured with the Ge(Li) detector in the present research together with the previously reported data on the high-energy spectrum. The intensities quoted are relative values normalized to 100 for the 6677 keV transition. The above remarks (subsect. 3.1) on the error evaluation and the possible occurrence of unresolved complex structures also apply to the energy interval discussed here. It is assumed in table 3 that the high-energy transitions above 5670 keV proceed from the neutron capture state. For some weak lines between 5670 keV and 5740 keV this assumption is not quite ensured. The level assignment is therefore given in brackets. When no assignment is specified (below 5670 keV), the corresponding γ-ray is certainly attributed to ^{168}Er, but the possibility cannot be ruled out that the transition proceeds from an intermediate state.

As can be seen from table 3, the quality and detail of the data has been improved considerably by the present research. Our results suggest that 44 levels with excitation energies below 2100 keV are directly populated from the capture state which has spin and parity 3^+ or 4^+. Since the primary transitions are essentially dipole transitions, the associated levels should be characterized by the spin values 2, 3, 4 or 5. Large radiation widths in general point to E1 multipolarity and thus negative parity of the populated states. The only obvious exception from these simple rules is provided by the level at 549 keV which is known to have spin and parity 6^+. The weak transition feeding this state has probably E2 character. An alternative, but unlikely explanation is the presence of some p-wave capture.

The resonance work in ref. [18]) covers the excitation region up to 1914 keV. For twenty levels which have been observed both in thermal and resonance neutron cap-

TABLE 2

Gamma rays in the energy range 525 keV to 1950 keV observed with the anti-Compton spectrometer

This work [a]) Ge(Li) anti-Compton spectrometer					Koch [c]) Bent crystal spectrometer				Broman *et al.* [d]) Flat crystal with Ge(Li) detector			
E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)	remarks [b]); assignment	E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)	E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)
528.03	90	0.68	5		527.93	50	0.73	10				
531.61	120	0.70	8	^{167}Er								
533.29	200	0.29	15	1354 → 821	533.5	350	0.32	20	531	1000		
539.67	400	0.06	40	1634 → 1094								
543.75	80	1.69	3	(1820 → 1277)	543.66	60	1.67	10	543.9	500		
547.10	90	0.83	5	pd; 1542 → 995	547.11	100	0.88	15				
					(547.60)	250	0.06		548.6	500		
556.72	250	0.37	10	1820 → 1264	556.16	250	0.14	40				
				821 → 264	557.00	250	0.07					
559.60	80	1.91	3	1654 → 1094	559.53	40	1.82	10	559.5	500		
563.46	400	0.07	30	1828 → 1264	564.0	600	0.07					
568.93	90	1.01	3	1118 → 549	568.81	80	0.85	15	570.0	1000		
573.59	180	0.27	10	^{167}Er								
					577.9	500	0.07					
580.37	180	0.45	8		580.09	70	0.46	30	581.8	820		
582.83	180	0.43	10	1404 → 821	582.62	70	0.46	30	583.4	500		
584.67	250	0.24	15		584.5	500	0.19	30	(585.2)	1000		
590.97	450	0.086	20	1708 → 1118	590.8	400	0.075	30	590.9	500		
593.42	350	0.13	15	^{167}Er								
601.75	140	0.57	8	1719 → 1118	601.70	70	0.58	20	602.5	1500	1.2	65
604.2	550	0.09	40	^{167}Er								
607.9	500	0.09	40									
613.57	250	0.23	50	partially ^{167}Er								
616.65	400	0.25	50	1893 → 1277	615.6	800	0.08	40	615.6	300	0.36	70
620.07	180	0.36	10	1738 → 1118	620.24	100	0.22	30	620.4	700	0.33	40
631.77	80	6.6	—	896 → 264	631.75	40	6.6	10	631.7	—	6.60	15
638.84	200	0.71	8	1634 → 995	638.59	60	0.82	15	638.4	600	0.96	15
644.28	400	0.29	30	1193 → 549								
646.10	280	0.66	15	1542 → 896	645.80	70	0.71	15	645.5	800	0.94	15
654.8	1000	0.034	70									
658.8	800	0.043	50	1654 → 995					658.4	1100	0.23	20
662.2	1000	0.035	70	1657 → 995					664.2	1000	0.10	45
669.77	280	0.10	30		(671.9)	700	0.26		669.8	300	0.06	40

				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
675.6	600	0.10	40						(677.3)	330	0.12	30
679.28	180	0.29	10		679.7	500	0.31	20	680.2	300	0.12	30
686.63	380	0.13	20		685.5	600	0.11		686.2	300	0.05	40
					687.8	600	0.25	40				
689.07	400	0.15	20	1617 → 928	(690.8)	600	0.14		689.5	300	0.08	30
692.02	160	0.33	10	impurities possible								
696.2	1200	0.03	80	uncertain								
699.9	500	0.08	30	1893 → 1193	701.4	600	0.15		701.0	1000	0.11	30
702.84	250	0.22	15	1820 → 1118	703.3	600	0.29	40	704.0	700	0.13	40
									(708.6)	300	0.10	40
713.15	250	0.66	12	1708 → 995	712.8	500	0.6	40				
715.22	150	1.55	6	1264 → 549	714.9	350	1.6	20	714.1	500	1.7	15
					716.3	500	0.6	40				
720.11	90	2.31	3	pd; 1542 → 821	720.16	70	2.2	10	719.8	600	1.8	15
724.10	320	0.29	20	1719 → 995	724.1	500	0.32	40				
730.72	70	10.4	3	995 → 264	730.69	50	12.4	10	730.7	300	7.0	15
					(736.2)	700	0.5					
737.79	180	1.14	5	1634 → 896	738.4	350	1.4	30				
741.43	70	6.04	3	821 → 80	741.42	50	6.6	20	740.3	300	5.0	15
745.0	1000	< 0.2			743.7	700	0.5					
748.30	100	1.23	5	1569 → 821	748.10	160	1.4	20	747.2	600	1.2	15
									(751.7)	900	0.33	40
									756.1	900	0.175	40
									764.6	900	0.14	40
768.46	250	0.14	15						(768.4)	700	0.17	80
773.1	800	0.10	50		770.9	800	0.6	40	772.2	600	0.18	40
776.7	500	0.10	40						776.2	700	0.45	40
779.78	150	0.49	10		779.4	800	0.39		780.1	800	0.16	40
790.05	150	0.56	8	1983 → 1193	789.3	700	0.8	35	789.3	600	0.58	30
798.92	80	1.93	5	1893 → 1094	799.8	400	2.1	25	797.9	600	3.2	30
									(803.5)	700		
808.58	350	0.91	30						(807.1)	700		
811.19	450	2.1	25									
813.3	800	1.4	50	1634 → 821								
816.08	70	41.4	3	896 → 80	815.95	80	36	10	815.9		36	
821.18	80	6.55	5	821 → 0	821.14	90	4.8	15	822.4	600	3.4	30
823.46	180	1.52	10	1719 → 896								
825.78	200	0.87	10	1820 → 995								
830.06	120	3.84	5	1094 → 264	829.98	100	3.2	20	829.9	700	4.63	25

TABLE 2 (continued)

This work [a]) Ge(Li) anti-Compton spectrometer					Koch [c]) Bent crystal spectrometer				Broman *et al.* [d]) Flat crystal with Ge(Li) detector			
E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)	remarks [b]) assignment	E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)	E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)
832.86	180	0.79	8	1828 → 995								
841.3	500	0.13	30	small ^{167}Er; 1738 → 896					(838.9)	500	0.71	40
853.54	80	7.22	5	1118 → 264	853.53	90	6.2	15	852.9	1000	7.42	25
857.3	500	0.15	25									
862.47	120	1.11	5	1411 → 549	862.7	700	0.9	25	862.7	1000	1.84	40
866.3	600	0.09	40						866.9	1000	0.23	30
870.1	800	0.08	50	^{167}Er contributes								
878.2	600	0.05	60	at least partially ^{167}Er					877.6	1000	0.09	40
									880.0	1000	0.13	30
884.38	150	0.40	10	1433 → 549	883.6	1000	0.5		884.2	1000	0.16	30
									(886.1)	1000	0.10	30
889.32	400	0.08	35	1983 → 1094					(888.5)	1000	0.12	30
897.68	150	0.65	10	impurities possibly contribute; 2091 → 1193	897.6	1300	0.27		896.5	1000	0.10	30
899.54	300	0.20	20						(899.4)	1500	0.26	30
									905.5	1500	0.26	30
915.01	70	6.80	8	995 → 80	914.97	100	6.0	20	914.9		6.0	
919.25	480	0.17	30	1914 → 995					(920.2)	1000		
									926.5	1200	0.5	40
929.03	120	1.43	10	1193 → 264	929.0	800	1.0	40	928.3	1500	0.8	30
932.32	180	0.67	10		931.0	800	1.0	40	932.0	1000	0.82	30
940.3	1000	0.09	80	partially ^{167}Er+^{158}Gd								
944.31	160	1.00	10	impurities contribute								
952.45	280	0.23	20	(1848 → 896)								
955.36	180	0.45	10		955.0	1200	0.43	30	954.2	1500	0.2	30
960.2	500	0.18	35									
962.22	150	0.97	10		964.0	1200	0.8	25	963.7	1000	0.38	30
966.11	120	0.85	10						966.7	1000	0.90	30
				971.0 ^{167}Er					(972.0)	1000	0.1	40
976.81	180	0.47	10		978.4	1500	0.32	40	978.6	1000	0.24	40
980.06	220	0.33	15									
[illegible]	[illegible]	[illegible]	[illegible]						(986.4)	1000	0.15	40

									(988.5)	1000	0.15	40
996.3	500	0.14	30	2091 → 1094					(994.7)	1000	0.15	40
999.70	160	0.95	10						1000.2	1200	0.65	30
1007.2	500	0.15	30						1008.0	1200	0.42	30
1010.31	320	0.44	20	impurities contribute								
1012.47	150	1.17	10	1277 → 264	1012.0	400	1.3	30	1012.0		1.26	
1019.5	1500	0.04	60	^{167}Er								
									1023.1	1200	0.2	30
1025.58	140	0.85	10	1574 → 549	1026.2	1000	0.8	30	1025.8	1000	0.65	30
1037.74	350	0.14	25	^{167}Er								
1042.0	750	0.07	50									
(1052.4)	1900	0.02										
1061.1	500	0.15	25									
1065.2	600	0.11	35									
1068.15	250	0.36	15	1617 → 549	1067	3500	0.3					
1075.2	900	0.09	50									
1077.6	900	0.09	50	1627 → 549					1081.0	2000	0.6	45
1094.11	320	0.25	15									
1097.32	400	0.18	25									
1105.0	500	0.26	30	1654 → 549					1104	2000	0.37	45
1107.5	300	1.04	10	1657 → 549					1107	2000	0.32	40
					1111.1	2500	0.6	40	1111	1000	0.62	30
1118.2	500	0.31	40	pd								
1128.4	700	0.10	50									
1137.2	600	0.16	25	1217 → 80					1135	1000	0.3	30
1141.6	500	0.30	30									
1144.02	350	0.60	20						1144	1000	0.5	30
1146.91	300	0.85	10	1411 → 264	1146	3000	1.1	40	1147	1500	0.9	40
1152.7	700	0.12	50									
1159.29	350	0.30	25	1708 → 549					1164	1500	0.25	40
1167.37	120	1.66	8	1431 → 264	1169.0	500	1.3	30	1168	1500	0.92	40
1173.87	180	0.71	10						1174.5	1000	0.44	40
1181.2	700	0.14	40	impurities contribute								
1186.00	180	0.97	10	complex; Gd contributes								
1196.55	180	0.74	15	1277 → 80					1198	2000	0.40	45
1201.54	250	0.45	20		1200.5	2000	0.41	40	1202	2000	0.38	45
1205.2	1000	0.09	60									
1211.93	280	0.38	20						1212	2000	0.52	45
1220.16	300	0.28	20									
1223.96	450	0.17	30									

TABLE 2 (continued)

This work [a]) Ge(Li) anti-Compton spectrometer					Koch [c]) Bent crystal spectrometer				Broman *et al.* [d]) Flat crystal with Ge(Li) detector			
E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)	remarks [b]) assignment	E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)	E_γ (keV)	ΔE_γ (eV)	I_γ	ΔI_γ (%)
1229.48	180	0.63	10	1493 → 264	1231.0	2000	0.46	40	1231	2000	0.30	40
1234.56	280	0.39	15									
1242.86	380	0.21	20									
1246.91	480	0.17	30									
1259.87	400	0.32	20						1258	3000	0.14	45
1263.5	700	0.19	30									
1271.5	500	0.34	25	1820 → 549								
1275.6	800	1.04	30									
1277.77	250	2.77	20	1542 → 264; complex	1277.5	500	2.3	40	1277.5		2.3	
1279.7	600	0.61	40									
1293.87	350	0.35	20									
1298.04	380	0.32	20									
									1309	3000	0.5	45
1310.10	120	1.48	10	1574 → 264	(1311.0)	2500	0.38		1312	3000	0.9	30
1323.95	120	1.83	10	1404 → 80	1327.0	2500	0.5		1327	3000	2.0	50
1331.19	120	1.44	10	1411 → 80					1334	3000	1.4	50
1342.32	320	0.33	20									
1351.81	150	1.93	10	d; { 1615 → 264 1431 → 80								
1354.48	300	0.56	15	1354 → 0	1354.2	2000	1.4	40	1354	4000	3.2	60
1358.80	250	0.50	15									
1366.93	400	0.26	25						1365	5000	0.5	75
1371.82	450	0.22	25									
1379.3	1000	0.19	30									
1392.43	150	1.26	10	1657 → 264								
1396.89	450	0.23	25		1396	5000	0.5		1396	5000	2.4	80
1408.08	350	0.33	20						1402	5000		
1413.51	220	0.61	15	1493 → 80					1416	8000		
1433.5	600	0.16	35									
1441.74	320	0.38	20						1440	10000		
1452.5	800	0.13	50						1450	10000		
1457.4	700	0.16	40									
1473.6	800	0.11	50	1738 → 264								
1484.20	400	0.30	30						1488	15000		

1492.3	900	0.10	60				
1507.18	480	0.25	30			(1502)	15000
1516.57	300	0.55	20			(1514)	15000
1523.5	700	0.16	35			1528	15000
1534.9	800	0.15	40				
1556.2	700	0.24	30		1820 → 264		
1559.9	500	0.36	25				
1570.4	600	0.23	30				
1576.9	700	0.20	35		1657 → 80		
1581.34	400	0.46	20				
1588.6	700	0.20	40				
1618.7	700	0.19	40			1615	18000
1636.7	700	0.18	40			(1638)	20000
1645.7	800	0.15	40				
1650.23	280	0.69	20		1914 → 264		
1657.7	800	0.17	40		1738 → 80	(1660)	20000
1673.6	600	0.28	30				
1677.0	1000	0.16	40				
1682.1	600	0.22	35			1686	20000
1698.5	800	0.14	50			(1700)	20000
1703.3	1000	0.11	50				
1707.6	600	0.20	35				
1732.0	600	0.28	30				
1738.54	400	0.44	20				
1749.9	800	0.21	35				
1757.8	900	0.17	45				
1767.3	500	0.68	20	pd		1773	20000
1814.14	300	0.57	20				
1834.70	180	1.52	15		1914 → 80	1834	20000
1845.9	500	0.41	25			(1845)	20000
1850.7	800	0.23	35			(1852)	20000
1864.78	350	0.57	20			(1869)	20000
1891.63	420	0.38	25				
1915.0	700	0.28	40				
1922.4	600	0.36	25				
1943.07	350	0.53	20				

[a]) The intensities are normalized to a value of 6.6 for the 631.77 keV γ-ray. This value refers to 100±15 captures in ^{167}Er (cf. text).
[b]) The following abbreviations are used: pd = possible doublet, d = doublet. [c]) Ref. [11]). [d]) Ref. [15]).

TABLE 3

Gamma rays observed in the energy range [a]) 5160 keV to 7700 keV

E (keV)	ΔE (keV)	I_γ	ΔI_γ	Remarks; assignment [b])	Ref. [16]) E (keV)	Ref. [16]) ΔE (keV)	Ref. [17]) E (keV)
7691.29	0.70	2.8	0.4	C → 80	7684	8	
7507.34	0.50	7.3	0.8	C → 264	7503	7	
7381.0	1.6	0.8	0.4	^{156}Gd			
7288.5	1.3	1.0	0.3	^{156}Gd			
7222.82	0.70	3.3	0.6	C → 549			
7213.1	1.2	1.4	0.5	^{150}Sm			
6949.83	0.60	7.3	1.1	C → 821	6946	7	
6912.5	1.2	1.8	0.6	^{158}Gd			
6875.8	1.2	3.6	0.6	C → 896	6868	8	
6775.8	1.2	2.0	0.7	C → 995	6772	8	
6758.6	0.8	4.3	1.2	^{156}Gd			
6749.63	0.50	28.5	3.0	^{158}Gd			
6677.02	0.50	100		C → 1094	6671	5	6676.8
6650.8	2.1	2.4	1.2	50 % se. 6137.8+50 % 6653.4; C → 1118			
6577.93	0.50	34.8	3.5	C → 1193	6577	5	6577.7
6494.57	0.60	12.8	1.4	C → 1277	6485	5	6495.0
6464.5	1.4	1.7	0.4	^{156}Gd			
6425.2	1.8	2.1	0.7	^{156}Gd			6422.2
6417.6	1.0	4.7	0.8	^{158}Gd			
6366.96	0.50	25.4	3.0	C → 1404	6361	5	6366.8
6358.8	1.2	3.6	0.8	C → 1411			
6340.1	0.9	5.0	1.0	40 % ^{156}Gd; C → 1431	6346	6	
6278.73	0.80	4.1	0.6	C → 1493			
6228.83	0.50	153.0	15.0	^{167}Er+C → 1542	6224	5	6229.0
6201.7	1.6	15.7	3.1	C → 1569			
6196.9	1.2	21.0	3.5	C → 1574	6192	6	6199.9
6171.46	0.60	19.5	2.0	^{167}Er	6168	6	6171.9
6154.5	2.0	< 3		C → 1615			
6137.27	0.50	57.0	6.0	C → 1634	6134	5	6137.0
6115.0	0.9	8.5	1.2	C → 1657			6113.4
6078.0	1.9	1.6	1.0	C → 1693			
6062.45	0.50	21.7	1.9	C → 1708			
6051.73	0.50	42.0	3.5	C → 1719	6047		6051.7
6043.44	0.70	3.7	0.8	C → 1728			
6034.6	1.2	9.6	1.5	≈ 20 % ^{156}Gd+C → 1738			
5950.12	0.70	19.5	1.8	C → 1820			
5942.55	0.60	22.5	2.0	C → 1828	5944	5	
5934.1	0.9	5.3	0.8	C → 1837			
5903.16	0.70	13.3	1.4	^{158}Gd			
5884.8	1.0	6.7	0.8	C → 1886			
5878.04	0.40	79.0	6.0	C → 1893	5879	6	5877.8
5868.9	1.9	6.9	3.5	C → 1902			
5865.1	1.0	14.9	5.5	C → 1906			
5857.05	0.50	29.6	2.5	C → 1914	5860	6	5856.6
5786.85	0.80	7.2	0.8	C → 1983			
5773.03	0.80	22.3	5.0	C → 1998	5770	5	5771.3

TABLE 3 (continued)

E (keV)	ΔE (keV)	I_γ	ΔI_γ	Remarks; assignment [b]	Ref. [16] E (keV)	Ref. [16] ΔE (keV)	Ref. [17] E (keV)
5769.7	0.9	19.8	4.5	C → 2002			
5748.21	0.60	16.0	1.8	C → 2023			5748.3
5740.7	1.9	2.3	1.2	(C → 2030)			
5717.6	1.2	3.8	1.0	(C → 2054)			
5711.31	0.60	16.3	1.7	C → 2060	5711	7	5711.9
5697.0	1.3	3.3	1.1	(C → 2074)			
5689.2	1.0	5.4	0.9	(C → 2082)			
5681.16	0.60	16.7	1.5	C → 2090			
5673.56	0.40	39.0	2.8	C → 2098	5672	6	5673.4
5662.7	1.0	3.7	0.9	^{158}Gd			
5641.72	0.50	15.2	1.6				5641.2
5622.57	0.50	15.3	1.5				5620.8
5583.81	0.70	9.2	1.0	^{158}Gd			
5570.76	0.50	18.3	1.8		5572		5570.4
5532.90	0.70	7.5	0.9				5531.2
5509.09	0.70	12.8	1.3				
5503.75	0.70	13.1	1.3		5502		5506.4
5468.31	0.50	15.2	1.4		5463	7	5468.0
5459.52	0.70	7.1	0.8				
5433.98	0.50	24.8	2.2		5428	7	5433.3
5426.4	1.1	3.9	0.9				
5405.39	0.50	18.3	1.6		5403	7	5406.5
5397.6	1.1	3.8	0.9	^{158}Gd			
5375.84	0.60	22.6	2.0				
5369.09	0.50	36.2	3.2		5363		5371.9
5359.16	0.40	69.0	5.0				5358.9
5349.2	1.2	12.3	2.4				
5344.7	1.8	6.0	2.5				
5318.8	0.9	6.0	0.9				5317.8
5297.58	0.80	12.2	1.4				
5292.44	0.40	63.0	5.5		5293	6	5292.9
5285.49	0.70	12.2	1.4				
5277.21	0.70	16.9	1.8				5277.8
5272.1	2.0	3.6	1.2				
5258.40	0.50	24.2	2.1				5256.9
5252.6	1.0	6.6	1.3	≈ 40 % ^{158}Gd			
5242.32	0.50	19.3	1.6				5240.9
5234.4	1.0	5.2	1.4				
5216.62	0.70	15.2	1.5				
5210.52	0.40	37.6	3.5	^{167}Er+^{168}Er	5207		5211.6
5200.59	0.70	11.6	1.2				
5169.67	0.40	50.6	4.5		5169	7	5169.2

[a]) The intensities are relative values. They are normalized to a value of 100 for the 6677 keV γ-ray.
[b]) C → E_a denotes primary transition from compound state in ^{168}Er to level with excitation energy E_a.

ture, the precise level energies, as deduced from column 1 of table 3, agree within ±0.5 keV with the excitation energies reported from resonance capture. Only for

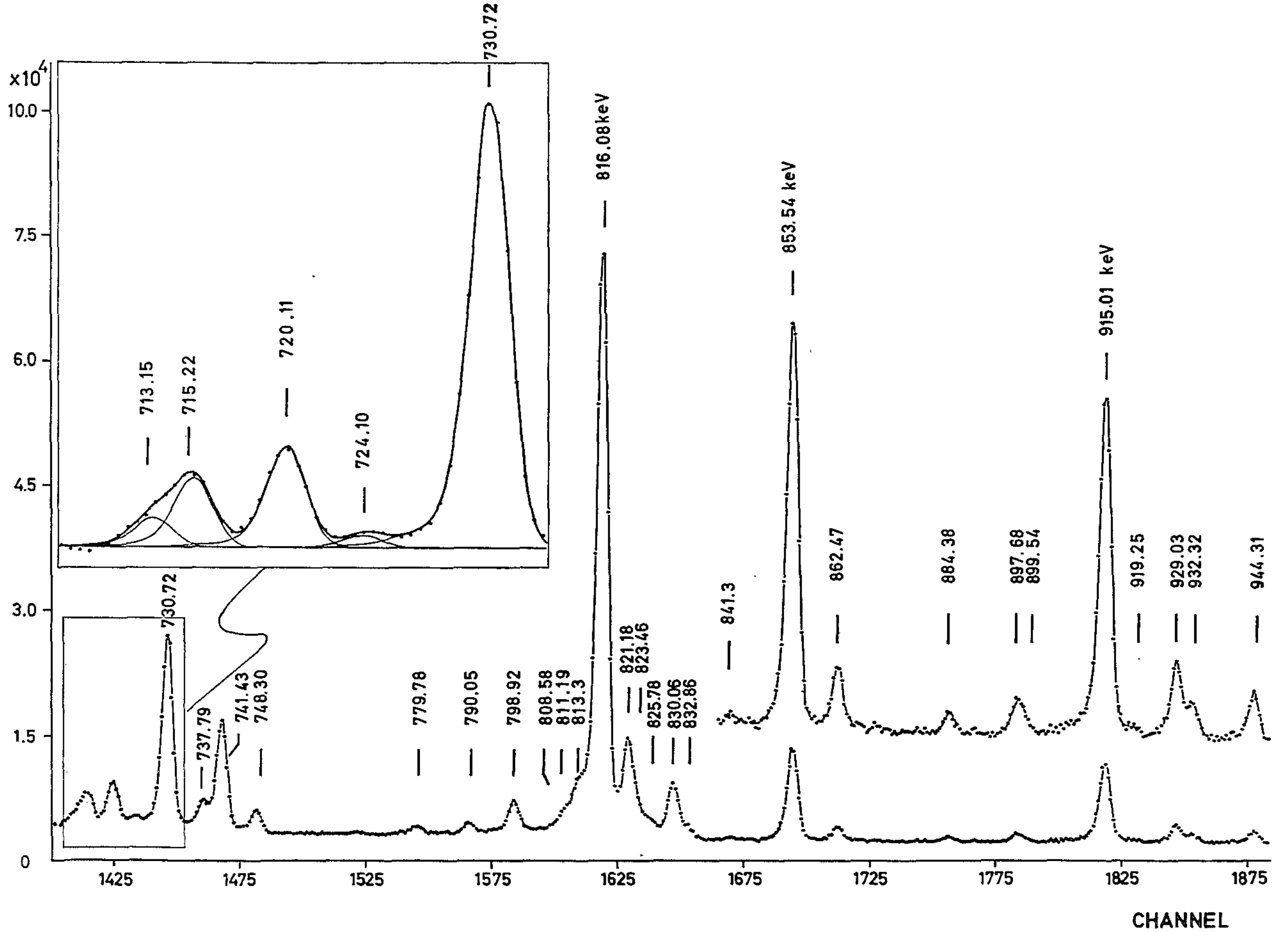


Fig. 1. Sectional display of the neutron capture γ-ray spectrum as observed with the anti-Compton spectrometer from a natural erbium sample. The inset illustrates the computer analysis for a group of γ-rays using modified Gaussian functions.

seven transitions the difference in the derived level energies is larger than ± 0.5 keV. Six of the intermediate states listed in table 3 have not been observed in the resonance capture study, namely the levels at 549, 1693, 1728, 1837, 1886 and 1902 keV. The absence of a transition feeding the first of these levels is evident in view of the low intensity which is expected for E2 transitions in average resonance-capture spectra. As to the other levels, one might speculate on the possibilities that either still unidentified impurities are present in the thermal-capture spectrum, that the corresponding primary γ-rays are obscured in the resonance spectra or that these transitions have E2 multipolarity. Additional levels have been observed in the resonance study at 1652, 1848 and 1867 keV. The failure to detect the associated transitions in thermal capture is easily understood on the basis of the well-known random fluctuations in radiation widths. Nevertheless, the present research demonstrates that in careful measurements with thermal neutrons only little information is lost by these fluctuations.

3.3. TRANSITION DIAGRAM OF ^{168}Er

Using the Ritz combination principle the data from subsect. 3.1 and 3.2 allow the construction of a considerably extended transition diagram as represented in fig. 2. The arrow widths give an approximate indication of the γ-ray intensities. In order to elucidate more clearly the intensity pattern of the primary γ-rays, the arrow widths for the primary and intermediate transitions have not been normalized to each other. Dashed arrows mean that the available data suggest the existence of these γ-rays and the position shown, but the assignment is considered to be somewhat tentative. If photons below 500 keV have been reported from crystal diffraction measurements with higher accuracy, the energy value was adopted from the previous data.

In order to arrive at some classification of the various rotational bands observed, K-values have been included in fig. 2, though it is realized that strong band mixing may cause the states to be no longer characterized by a unique K-quantum number.

From the energy of the most intense primary transitions and the precise level energies as obtained from the low-energy data, the neutron separation energy is calculated to 7771.24 ± 0.48 keV. In this result a proper recoil correction has been taken into account.

4. Discussion

The ground state rotational band, the $K^\pi = 2^+$ γ-vibrational band and the $K^\pi = 4^-$ band at 1094 keV are well known from previous investigations and the experimental data need not be discussed here in detail. Some additional weak transitions from table 2 have been fitted into the transition diagram. The properties of the ground state and γ-vibrational bands and their mixing have been studied intensively in ref. [27]).

The state at 1094 keV is interpreted to correspond to the two-quasiparticle neutron state $[633\uparrow - 521\downarrow]_{nn}$. Both the excitation energy which is predicted to be lower for the first 4^- neutron level than for the first 4^- proton level [3]) and the strong population in the (d, p) reaction [12]) are in favour of this assignment. Some authors [5,26,28]) have interpreted the 1094 keV state as the proton configuration $[523\uparrow + 411\downarrow]_{pp}$. Quite apart from the fact that the assumption of a proton level is in contradiction to the above arguments, the presence of a strong M1 transition between the first

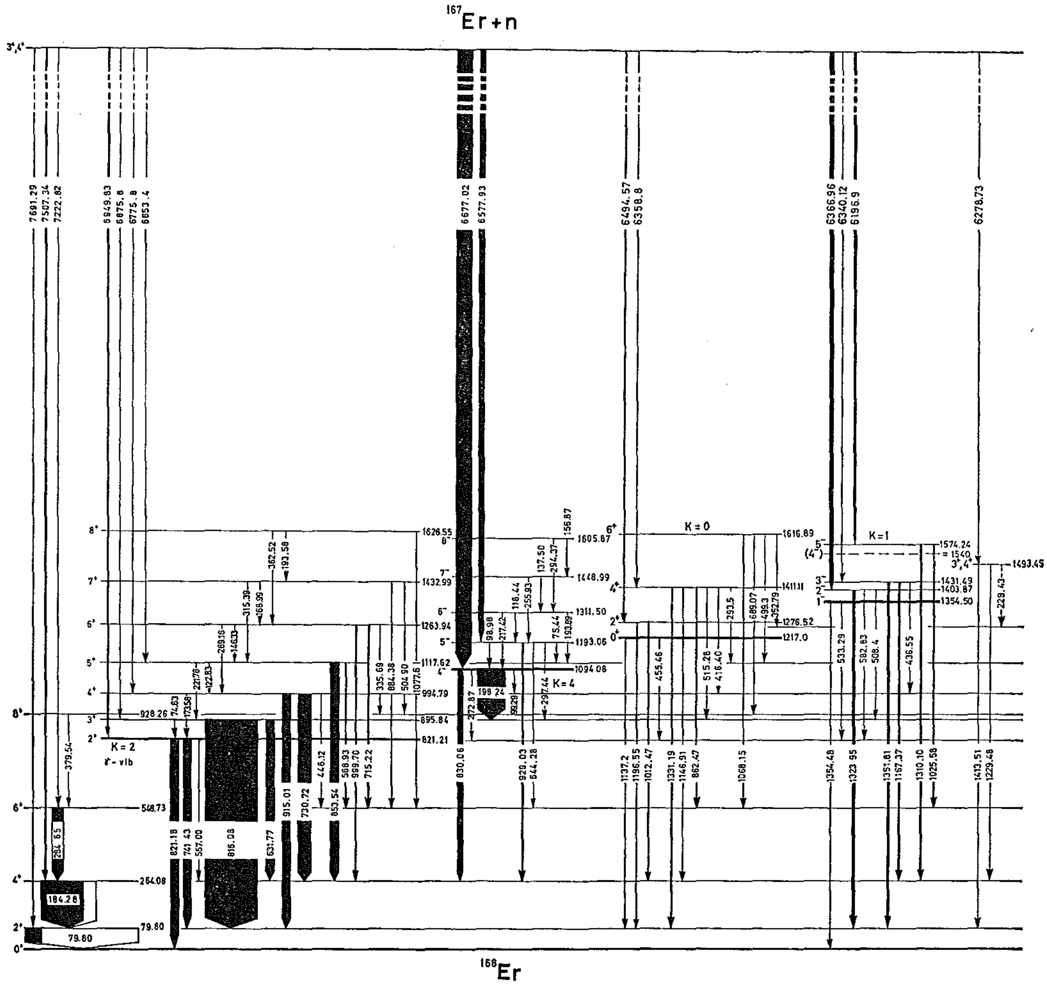
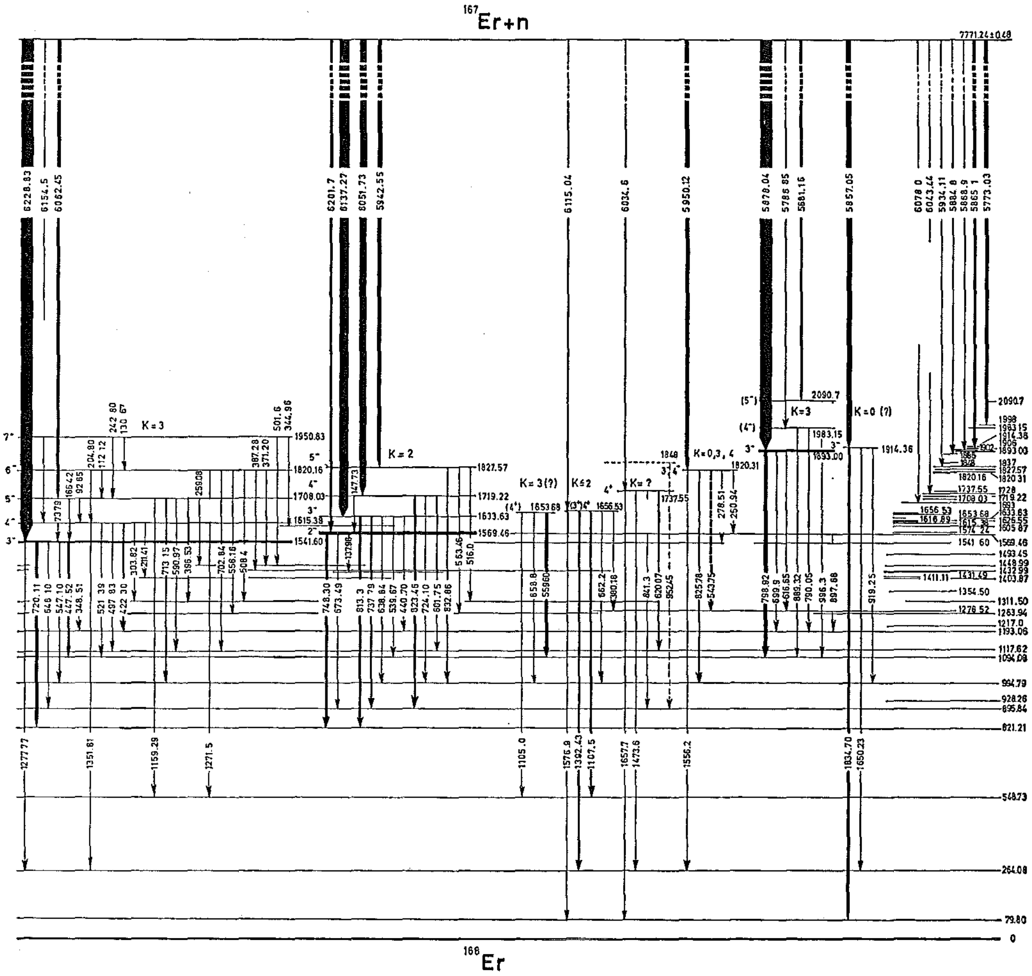


Fig. 2. Gamma-ray transition diagram of ^{168}Er based on the present research. Energies are quoted in keV. The arrow widths give an approximate indication of the γ-ray intensities, primary and secondary transitions being not normalized to each other (cf. text). The K-values only serve as a means for classifying the rotational bands. Levels corresponding to well established bandheads are indicated by heavy lines.

$K^{\pi} = 3^-$ state at 1542 keV and the 1094 keV level suggests that these levels can be regarded as the components of a doublet, i.e. the 1542 keV state would be the two-quasiparticle state $[523\uparrow - 411\downarrow]_{pp}$. This interpretation, however, is again inconsistent with both theoretical considerations and experimental data. Microscopic calculations on the structure of the first $K^{\pi} = 3^{-}$ octupole state in ^{168}Er have shown [4]) that the neutron configuration $[633\uparrow - 521\downarrow]_{nn}$ contributes to 99.8 % to this state and the differential cross sections observed in the (d, p) reactions were found to be large.



Thus the two-quasiparticle states $[633\uparrow + 521\downarrow]_{nn}$ and $[633\uparrow - 521\downarrow]_{nn}$ have to be ascribed to the 1094 and 1542 keV levels.

The ^{168}Tm ground state has spin and parity 3^{+}. Spin coupling rules predict the two-quasiparticle state $[411\downarrow - 633\downarrow]_{pn}$. It follows from the Clebsch-Gordan coefficient $C(j_i \lambda j_f | -\Omega_{2i} \nu \Omega_{2f})$ which appears in the transition matrix element for the decay $[411\downarrow - 633\uparrow]_{pn} \rightarrow [523\uparrow + 411\downarrow]_{pp}$ with $\Omega_{2i} = \Omega_{2f} = \frac{7}{2}$ that for this coefficient to be different from zero one must have $\lambda \geqq 7$. Since $\lambda \leqq 1$ for first forbidden transitions, the decay to the proton configuration $[523\uparrow+411\downarrow]_{pp}$ is at least 6 times Ω-forbidden [ref. [28])]. Thus the transition will be appreciably retarded. In order to explain the experimental $\log ft$ value 8.0 for the transition to the 1094 keV state, one has to postulate strong first order Coriolis coupling between the rotational bands associated with the 3^- and 4^- proton states, according to the fact that the decay to the $[523\uparrow-411\downarrow]_{pp}$ configuration is not Ω-forbidden. On the other hand, the $\log ft$ value is easily understood if the 1094 keV level is interpreted to correspond to the neutron state $[633\uparrow+521\downarrow]_{nn}$. The decay to this state is Ω-allowed. It is true that the $\log ft$ value 8.0 is considerably higher than the values which are observed for first-forbidden beta transitions in neighbouring odd-mass nuclei (e.g. $^{171}\mathrm{Tm}\ \frac{1}{2}^+[411] \rightarrow {}^{171}\mathrm{Yb}\ \frac{1}{2}^-[521]$, $\log ft = 6.2$). However, this retardation is obvious on the basis of the selection rules associated with the asymptotic quantum numbers. The transition operator has to transform $\Lambda_{1i} = 1$ into $-\Lambda_{1f} = -1$ and $\Sigma_{1i} = -\frac{1}{2}$ into $-\Sigma_{1f} = +\frac{1}{2}$. This transformation cannot be accomplished by the class of operators $(z, \sigma_z z, \sigma_z \nabla_z, \sigma_\pm(x \mp iy), \sigma_\pm \nabla_\mp$, etc), associated with first forbidden transitions. For transitions between two-quasiparticle states with different relative couplings the selection rules require [29]) $\Lambda_i = \Lambda_f = 0$ and $\Sigma_i = \Sigma_f = \frac{1}{2}$. Thus the decay has to be classified as hindered. Such transitions are systematically slower than corresponding transitions which are unhindered. The hindrance is found to be on the average of the order of a factor of 100.

The lifetimes of the 1542 keV level is less than [5]) 8×10^{-10} sec, so that with $g_R \approx Z/A$ a forbiddenness factor $F_N \leqq 10^4$ is obtained for the M1 transition to the 1094 keV state. For a pp $\rightarrow$ nn transition this factor is much too small, whereas the upper limit 10^4 would be somewhat high for an unhindered single-particle M1 transition. However, analysis of the transition matrix element for the neutron levels $[633\uparrow+521\downarrow]_{nn}$ and $[633\uparrow-521\downarrow]_{nn}$ shows that the transition between these states is Λ-forbidden and a considerable retardation is expected. Within the classification of collective vibrational states the 1542 keV state has to be regarded as the $K^\pi = 3^-$ octupole state.

As shown in fig. 2, the present research suggests a well developed $K^\pi = 0^+$ band at 1217 keV with rotational levels at 1277 keV (2^+), 1411 keV (4^+) and 1617 keV (6^+). This result is consistent with the spin assignment 2^+ or 5^+ for the 1277 keV state and positive parity of the 1411 keV state, as reported in the resonance-capture work [18]). Most probably, the 1217 keV level has to be identified with the level observed at 1215 keV in (d, d′) reactions [13]). The level is only weakly populated in inelastic scattering and no positive evidence has been found for the occurrence of a $K^\pi = 0^+$ band. The present data, however, seem to be quite convincing and they demonstrate that the neutron capture process provides a very powerful tool to extend the information on nuclear level schemes. The theoretical knowledge of the structure of $K^\pi = 0^+$ bands is still limited. The excitation energies of the first two 0^+ states have been calculated in ref. [30]) for several rare-earth nuclei using both long-range quadrupole and spin-quadrupole residual interactions. These calculations which have been performed with different interaction constants show that satisfactory agreement with the experimental energies of the states cannot be achieved with only one type of force. If we compare our result with the theoretical predictions, we obtain for the quadrupole and spin-quadrupole interaction constants κ_q and κ_t the values 5.3 and 8.8 (in units of $A^{-\frac{1}{3}}\hbar\omega_0$), respectively. Many two-quasiparticle states may contribute to the wave function of the 0^+ state. Possible candidates are in particular the neutron configurations $[633\uparrow - 633\uparrow]_{nn}$ and $[521\downarrow - 521\downarrow]_{nn}$ as well as, with probably smaller amplitudes, the proton levels $[523\uparrow - 523\uparrow]_{pp}$ and $[411\downarrow - 411\downarrow]_{pp}$. The spin-quadrupole force may also give rise to remarkable amplitudes for configurations of the type $[521\uparrow - 512\downarrow]_{nn}$ or $[523\downarrow - 512\uparrow]_{nn}$. From the experimental point of view it would be very interesting to detect the E0 ground state transition from the bandhead by internal conversion electron measurements. The energy pattern of the rotational levels observed in the present study suggests the rotational factors $A = 9.873$ keV and $B = -8.39$ eV.

TABLE 4

Relative intensities of γ-ray transitions leaving the 3^- level at 1542 keV

E_γ (keV)	J_f [a]	Intensity			
		^{168}Tm decay		(n, γ)	
		Ref. [14]	Ref. [26]	Ref. [11]	This work
1462	2^+	1.5	1.5		< 3
1278	4^+ ←	7.4	7.5	100	113; complex
720	2^+	50	52	96	94; pd [b]
646	3^+ ←	6.4	5.8	31	27
547	4^+ ←	11	11	38	34; pd
448	4^-	100	100	100	100
349	5^-	1.4	1.5	2	≈ 2

[a]) The arrows indicate possible transitions from a closely spaced 4^- level with $K = 1$.
[b]) The second component most probably corresponds to the transition 1615 → 896.

Another new rotational band has been introduced into the transition diagram at a bandhead energy of 1354 keV. Spin and parity of this state are most probably 1^- and rotational levels have been found at 1404 keV (2^-), 1431 keV (3^-) and 1574 keV (5^-). The first three levels are believed to correspond to the excited states observed at 1357 keV, 1393 keV and 1427 keV in (d, p) measurements [12]). The spin and parity assignments deduced from the present experimental data are supported both by the results of (d, d′) experiments [13]) and the resonance-neutron capture data [18]). In the first of these studies a 3^- level is reported to occur at 1428 keV. The average resonance-capture spectra suggest the spin assignments 2^- or 5^- for each of the levels at 1404 keV and 1574 keV as well as negative parity for the 1431 keV state. Since additional primary transitions of sufficient strength leading to states between 1200 and 1540 keV are observed neither in thermal nor in resonance-neutron capture, we are forced to conclude that the levels discussed here belong to the same rotational band. It is conspicuous that the 4^- level of this band does not come forward distinctly from our measurements. We believe that this state lies very close to the 1542 keV 3^- level and that, as a consequence, the corresponding primary transition is obscured by the strong 6229 keV γ-ray which feeds the 1542 keV state. Evidence for this assumption is obtained by looking at the intensities of the transitions leaving the well established 1542 keV level. In table 4 the γ-ray intensities as observed in the ^{168}Tm decay and in (n, γ) experiments are compared with each other. The intensities have arbitrarily been normalized to a value of 100 for the 448 keV transition which due to the K selection rules can certainly not contain interference from a closely spaced 4^- level with $K = 1$. Several conclusions may be drawn from table 4.

(i) As to the "pure" transitions at 349, 448 and 1462 keV the data obtained from both methods are in excellent agreement.

(ii) The 720 keV γ-ray has been found in the present study to be a possible doublet. This has already been suggested in the previous (n, γ) study [11]) on the basis of energy considerations. Indeed, a closely spaced transition is expected proceeding from the 1615 keV 4^- level to the 896 keV level with spin and parity 3^+. This doublet character is not observed in decay studies, since the 1615 keV state is populated in the EC decay only with very low intensity.

(iii) The 1278 keV line has a complex structure in neutron capture experiments. Most probably there are at least three components. Less than 10 % of the total intensity have to be attributed to the transition 1542 keV(3^-) $\rightarrow$ 264 keV (4^+). This low intensity of a E1 transition is consistent with the retardation due to the K selection rule and the intensities of γ-rays deexciting the other members of the $K = 3$ rotational band to the ground state rotational band. The second component probably corresponds to an allowed E1 transition from the postulated closely spaced 4^- level. A third component may arise from deexcitation of the 1277 keV 2^+ level by E2 radiation reaching the ground state.

(iv) The intensities of the 547 keV and 646 keV γ-rays are much higher in neutron capture than in the ^{168}Tm decay. This can be well understood by assuming that (allowed) E1 transitions proceed from a closely spaced 4^- level and, in fact, the 547 keV line has been found in the present study to be probably a doublet. The failure to prove the doublet character for the 646 keV γ-ray is ascribed to the more unfavourable intensity division between the two components in this case.

In summary, we may conclude from these considerations that there is ample evidence for the presence of a closely spaced level doublet at 1542 keV. Thus the missing 4^- level of the $K = 1$ rotational band should occur at approximately this excitation energy. It would be very interesting to investigate in detail the intensity of the 6229 keV peak in the average resonance-capture spectrum. The intensity should be consistent with a triplet structure at that energy †.

† One component arises from ^{167}Er isotopic impurity.

The energies of the states in the $K^\pi = 1^-$ band do not follow the simple rotational-energy systematics. This is not very surprising, since we have to identify this band with the first octupole-vibrational band. It is expected [9]) that the Coriolis coupling, in particular with the $K^\pi = 0^-$ octupole band, is strong and thus may distort considerably the energy systematics. This also shows that the assignment of a K-value can only serve as a means to arrive at some classification of the observed rotational bands. The properties of the $K^\pi = 1^-$ state are probably rather close to those of a two-quasiparticle state. The configuration $[512\uparrow - 633\uparrow]_{nn}$ is believed to contribute the dominant amplitude to the wave function. The EC decay to this state then has to be classified as 1* u. This explains the large experimental $\log ft$ value for the transition to the 1431 keV level ($\log ft = 10.0$). For 1* u transitions values > 8.5 are usually observed.

In agreement with the resonance-capture work a weak primary transition is observed at 6279 keV. This γ-ray indicates the existence of a level with 1493 keV excitation energy. The resonance-capture spectra suggest the spin and parity assignment 3^+ or 4^+. The branching of transitions obtained in the present study is consistent with this assignment, but does not allow any definite decision between these two possible spin values. A level at 1493 keV has been observed neither in the (d, d′) nor the (d, p) reaction. The information on this state is too limited to draw any conclusions on the nuclear structure involved.

Another new rotational band has been introduced at a bandhead energy of 1569 keV. The existence of this band is confirmed both by strong primary transitions from the capture state and a considerable number of secondary transitions to lower-lying excited states. These transitions proceed mainly to the γ-vibrational band. The data from tables 2 and 3 suggest the spin and parity assignments $2^-, 3^-, 4^-$ and 5^- to the levels at 1569, 1634, 1719 and 1828 keV, respectively. This is in good agreement with the resonance-capture results which comprise the following levels: 1570 keV ($3^+, 4^+$ or $2^-, 5^-$), 1633 keV (3^- or 4^-), 1719 keV (3^- or 4^-) and 1828 keV (negative parity). None of these states has been observed in the (d, p) reaction, while in inelastic deuteron scattering a strong group appeared corresponding to an excitation energy of 1630 keV. The spin 3^- has tentatively been assigned to this level in the (d, d′) study which is in excellent agreement with our result. All these experimental data point at a pronounced collective nature and one may conclude that the origin of the 1569 keV band is the $K^\pi = 2^-$ octupole vibration. Probably several two-quasiparticle states contribute with appreciable amplitude to the wave function. The lowest-lying candidates are the configurations $[642\uparrow - 521\downarrow]_{nn}$ and $[411\uparrow - 523\uparrow]_{pp}$. From the exact level energies one obtains the rotational factors $A = 10.55$ keV and $B = +5.7$ eV.

In the resonance capture investigation a level is reported at 1652 keV excitation energy with the possible spin and parity assignments 3^+ or 4^+. A corresponding primary transition has not been clearly identified in the present study with thermal neutrons. However, due to a possibly lower intensity this transition may be obscured by the neighbouring primary γ-ray which feeds the state at 1657 keV. From the data given in table 2 three transitions can be fitted to a level at 1653.7 keV, but the possibility that these energy coincidences are accidental cannot be excluded. In addition, the agreement with ref. [18]) in the excitation energy is poorer than it is observed for other levels. Therefore the assignment of the three γ-rays has to be considered as somewhat tentative. The E1 multipolarity of the 560 keV transition as measured in ref. [31]) would be consistent with the position shown in the transition diagram. Assuming that the assignments are correct one may conclude from the de-excitation that the spin 4^+ is more probable than the spin 3^+ and that the K quantum number is perhaps 3. The most likely candidate for a $K^\pi = 3^+$ band in this energy region would be the two-quasiparticle state $[521\downarrow + 512\uparrow]_{nn}$. Indeed, this configuration would ensure a K-allowed E1 transition to the 1094 keV level, but the retardation which is expected from the selection rules in the asymptotic quantum numbers throws some doubt on such an interpretation. Other 3^+ states, e.g. the configuration $[523\downarrow + 521\downarrow]_{nn}$, are predicted at much higher energies and give rise to similar difficulties in explaining the above assignment. Therefore further experimental data are required for clarifying the properties and the origin of the 1652 keV level. So far the level has been observed neither in (d, p) and (d, d′) reactions nor in decay studies.

A weak primary γ-ray with 6115 keV energy indicates the existence of a level at 1657 keV with probably even parity. The low-energy data from table 2 suggest the spin assignment 4^+. This is in agreement with the average resonance-capture spectra which predict a 3^+ or 4^+ state at 1656 keV. Provided that the position of the γ-rays which can be fitted to this level is correct, one may conclude that the de-excitation occurs preferably to the ground state rotational band, that these transitions may have E2 multipolarity and that the K-value is $\leqq 2$. Assuming $K = 0$, one might speculate on the possible occurrence of a second $K^\pi = 0^+$ band. If we take the quadrupole and spin-quadrupole interaction constants $\kappa_q = 5.3$ and $\kappa_t = 8.8$, which we have derived from the well established first $K^\pi = 0^+$ band, we obtain from the data given in ref. [30]) an excitation of about 1.57 MeV for the second band of this type. Thus there would be reasonable agreement with the above speculation, if the 1657 keV level is the 4^+ rotational member of this band. Unfortunately, no other excited states have been found that might be fitted with confidence into a rotational band involving the 1657 keV state. The assumption $K = 0$ considerably reduces the number of primary transitions which must have escaped detection both in thermal and resonance neutron capture. The level at 1657 keV has been observed neither in (d, p) and (d, d′) reactions nor in EC decay. Thus the situation is similar to that found for the first $K^\pi = 0^+$ band. All these considerations require further experimental support.

In the most recent study of the ^{168}Tm EC decay [14]) an excited state with spin 4^+ or 5^+ has been reported at 1716 keV. From the data obtained in the present research it was not possible to find any combinations around this energy. In addition, this level should be directly fed from the capture state, but both in thermal and resonance-neutron capture such a transition has not been observed. The neutron capture measurements therefore call in question the existence of this level.

At 1738 keV we have introduced a level with spin and parity 4^+. It is de-excited to the ground state rotational band and, with somewhat higher intensity, to the γ-vibrational band. The spin assignment is in agreement with the resonance-capture investigation which revealed a 3^+ or 4^+ state at this energy, and with (d, d′) measurements which indicated a level at 1733 keV with the tentative spin assignments 3^- or 4^+. Provided that the proposed spin 4^+ is correct, the branching to the ground state rotational band seems to suggest the occurrence of collective E2 transitions. This would be consistent with the relatively strong population in the (d, d′) reaction. When looking for the origin of even-parity collective states at approximately twice the γ-vibrational energy, it is useful to recall the predictions of some nuclear models for this energy region. The rotation-vibration theory [32]) permits ordering the unperturbed bandheads by means of the formula

$$E_{n_2, n_0} = (n_0+\tfrac{1}{2})E_\beta+(2n_2+\tfrac{1}{2}K+1)E_\gamma,$$

where E_β and E_γ are the β- and γ-vibrational energies and n_0, n_2 characterize the vibrational quantum numbers. At about $2E_\gamma$ above the ground state we thus expect the states $n_2 = 1$, $K = 0$ and $n_2 = 0$, $K = 4$. The microscopic theory with inclusion of both quadrupole and spin-quadrupole [33]) forces predicts a second 2^+ state at 1.76 MeV, if we derive the interaction constants $\kappa_q = 4.6$ and $\kappa_t = 5.4$ from the first 2^+ state at 821 keV. Possibly the 1738 keV level represents a member of one of these rotational bands, the state with $K = 4$ being less probable because of the K selection rule. In this connection it is of interest that at 1848 keV there is another level with even parity [18]) which due to (d, d′) experiments [13]) also shows some collective behaviour. Unfortunately, possible transitions to several members of the γ-vibrational band are obscured by intense γ-ray lines in the low-energy spectrum.

A strong γ-ray at 5950 keV in the primary spectrum reveals the existence of an excited state with odd parity at 1820 keV which is obviously not identical with the 6^- 1820 keV member of the rotational band based on the 3^- state at 1542 keV. The low-energy data from table 2 seem to suggest that the spin of the second 1820 keV level is 3^-. This result would be consistent with the average resonance-capture spectra which indicate a level with spin 3^- or 4^- at this energy. Nevertheless, the level properties remain unsettled in several respects. The spin assignment 3^- is essentially dependent on the question whether the position of the 544 keV γ-ray is correct. This transition presumably has E1 multipolarity [31]) in agreement with spin 3^- and the position shown in the transition diagram. If, however, the energy coincidence is accidental, the spin may also be 4^-. As regards the K quantum number, the values 1 and 2 can be excluded with high probability, since the level spin is certainly not lower than 3 and, on the other hand, no E1 transition from the capture state to a possible 2^- level has been detected. If the level spin is 4^-, then K must be 4. In this case the 544 keV transition has to be discarded. For $K = 3$ a dipole transition to the 1277 keV level would be highly K-forbidden. Conclusions from higher-lying states are difficult, because the level structure becomes more and more complex. Information from other experimental methods is not available, since the 1820 keV state has been observed neither in (d, p) and (d, d′) reactions nor in decay studies. Thus considerations on a possible origin remain more or less speculative. If $K = 0$, one might regard the level as the 3^- rotational member of the $K^\pi = 0^-$ octupole vibrational state. However, the fact that the level is not populated in inelastic deuteron scattering throws some doubt on such an interpretation (cf. also discussion of the 1914 keV level), though, in particular cases, the theoretical cross section may be small [9]). For $K = 3$ or 4 one might speculate on the proton configurations $[523\uparrow - 411\downarrow]_{pp}$ and $[523\uparrow + 411\downarrow]_{pp}$, respectively. It is worth mentioning that the coupling rules predict the 4^- components of this doublet to occur below the 3^- state. On the basis of the present results the existence of a 4^- proton level below 1820 keV can be ruled out with high probability.

A new rotational band has tentatively been introduced at a bandhead energy of 1893 keV. The strong primary feeding from the capture state ensures odd parity and the de-excitation together with the systematics of two-quasiparticle excitations suggest the spin assignment 3^-. Two other levels with reasonable energy spacings and de-excitation characteristics can be fitted into a rotational band based on this state. Further experimental data would be useful. In particular, the tentative assignment of spin 4^- to the 1893 keV level has to be confirmed by other methods, since the corresponding primary γ-ray – possibly due to fluctuations in the radiation width – is rather weak for an E1 transition. On obvious explanation for a 3^- state with strong de-excitation to the neutron level $[521\downarrow + 633\uparrow]_{nn}$ is provided by the neutron configuration $[521\downarrow + 642\uparrow]_{nn}$. This interpretation would be consistent with the observed population of the 1893 keV level in the (d, p) reaction.

Another 3^- state is strongly excited at 1914 keV. Spin and parity assignment are confirmed by the (d, d′) measurements which suggest a level with 3^- or 4^+ at this energy. De-excitation occurs preferably to the ground state rotational band. Since no 2^- level is fed from the capture state within a reasonable energy interval below 1914 keV, one may thus conclude that the K quantum number is 0. If this assumption is correct, a possible interpretation for the origin is to regard the 1914 keV level as the 3^- rotational member of the $K^\pi = 0^-$ octupole vibrational band. The bandhead then should occur approximately at 1.7 to 1.8 MeV excitation energy (cf. also discussion of the 1820 keV level).

In table 5 we compare the experimental results with the predictions of various calculations. It should be pointed out that the blocking effect may reduce somewhat the calculated excitation energies for octupole states, when the structure is close to that of a two-quasiparticle state. The most striking result which can be obtained from table 5 is that the simple model of pairing plus state-independent octupole force provides a surprisingly good microscopic description of octupole vibrations.

Some final remarks seem to be useful. The present investigation has brought about a considerable extension of our knowledge of the even nucleus ^{168}Er and it is demonstrated that the radiative neutron-capture process can serve as a very powerful tool in nuclear structure studies. It should be realized, however, that the γ-ray spectra from this reaction are extremely complex and that the results described here are ex-

TABLE 5

Comparison of experimental results with the predictions of various theoretical models

Experiment		Theory [a]) Energy (MeV)						
state	Energy (MeV)	Ref. [3]) BCS	SIF	Ref. [7]) SDI	POF	Ref. [4]) POF	Ref. [8]) POF	Refs. [30, 33]) PQS
collective	0.82							0.83 { $\kappa_q = 4.6$, $\kappa_t = 5.4$
$[633\uparrow + 521\downarrow]_{nn}$	1.09	1.1						
collective	1.22	(1.2)						1.23 { $\kappa_q = 5.3$, $\kappa_t = 8.8$
{ collective: $[512\uparrow - 633\uparrow]_{nn} + \ldots$	1.35	1.5	1.52	1.64	1.62	1.75	1.82	
$[633\uparrow - 521\downarrow]_{nn}$	1.54	1.1	1.50	1.60	1.60	1.60		
collective	1.57		1.95	2.00	2.03	1.95	1.87	
collective	1.7-1.8		1.79	1.65	2.22	1.8	1.78	
$[521\downarrow + 642\uparrow]_{nn}$	1.89	2.2						

SIF = pairing plus state-independent octupole force.
SDI = surface delta interaction.
POF = pairing plus octupole force.
PQS = pairing plus quadrupole and spin-quadrupole force.

clusively based on precise energy determinations and the application of the Ritz combination principle. Thus the possibility cannot be ruled out that some few transitions have been placed into the transition diagram in a wrong position. Therefore, further improvement in the energy accuracy, coincidence measurements or experimental data from other techniques would be very helpful. No use has been made of the Alaga rule in the present research, since in the energy region studied strong configuration mixing as well as the complex structure of the γ-ray spectrum (cf. table 4) may considerably affect the results.

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