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Study of ^{166}Er by means of the (^{3}He, d) and (α, t) reactions*

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Two-proton quasiparticle states in ^{166}Er have been studied with (^{3}He,d) and (α,t) reactions on ^{165}Ho. Rotational bands built upon quasiparticle states formed by the [523↑] proton state coupled with the [411↓], [404↓], and [541↓] proton states were identified. For each rotational band, the cross sections have a characteristic pattern which has been used to identify the band. Assignments were checked by comparing the ratios of (^{3}He,d) and (α,t) cross sections for each level.

[NUCLEAR REACTIONS ^{165}Ho(^{3}He,d)^{166}Er, E = 35.6 MeV, ^{165}Ho(α,t)^{166}Er, E = 46 MeV; measured $\sigma(E_d, \theta)$ and $\sigma(E_t, \theta)$; ^{166}Er deduced levels, J, π.]

I. INTRODUCTION

Several recent experiments[1-4] have used pickup and stripping reactions to study intrinsic states in rare earth nuclei. The cross sections for levels in rotational bands were found to have characteristic patterns and the nature of the intrinsic states on which the bands are built could be determined. Two-neutron configurations were recently observed[2] in ^{166}Er by means of the (d, t) reaction. Two-proton states in ^{166}Er should be reached with proton-stripping reactions. In the present experiment, ^{166}Er has been studied with (^{3}He, d) and (α, t) reactions. These stripping reactions selectively populate proton states consisting of the odd-mass target proton coupled with the un-

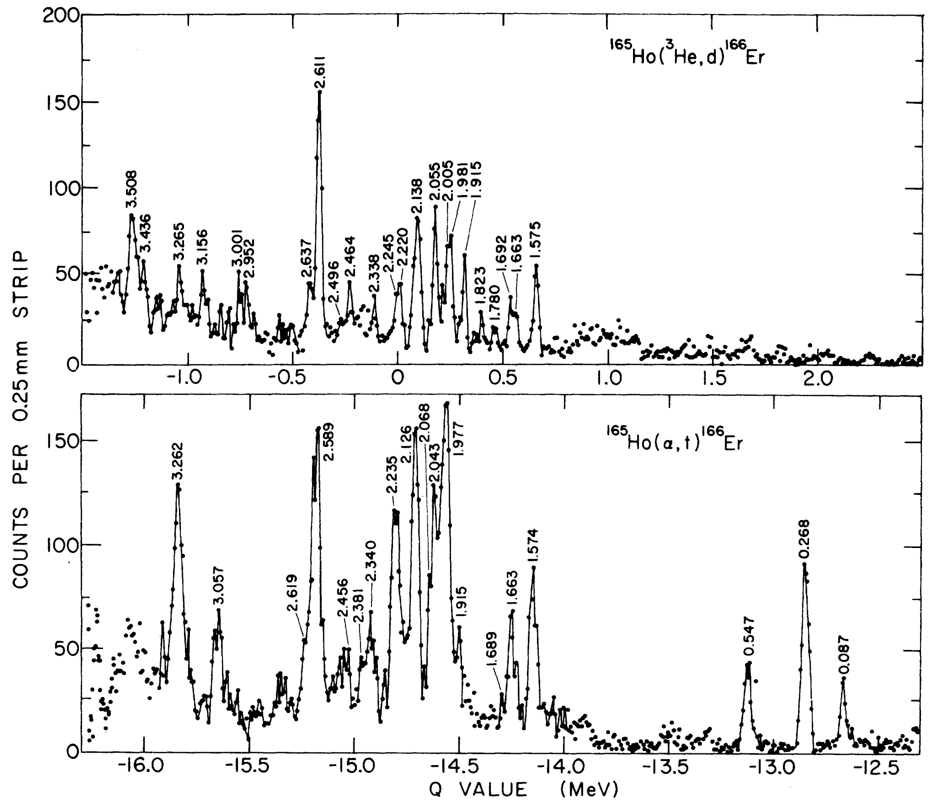

FIG. 1. Experimental spectra obtained for the ^{165}Ho(^{3}He,d)^{166}Er and ^{165}Ho(α,t)^{166}Er reactions at 25 and 30°, respectively.

paired transferred proton. The nucleons couple their spin projections Ω_1 and Ω_2 either parallel or antiparallel to form states with $K \gtrless = |\Omega_1 \pm \Omega_2|$. The energy splittings and the excitation energies of the $K^>$ and $K^<$ states are useful for comparison with calculations which yield information about the proton-proton residual interaction. Energy shifts can be extracted from unperturbed two-quasiparticle level energies estimated from the energies of one-particle states in neighboring odd-A nuclei. The present results contribute to the data which may determine (1) the need for finite-range forces, and (2) the consistency between force and range parameters in the residual interaction in deformed nuclei and the corresponding parameters in spherical nuclei.

II. EXPERIMENTAL PROCEDURE

The experiments were performed using 35.6-MeV ^{3}He particles and 46-MeV α particles from the Argonne cyclotron. The target was ^{165}Ho, which has a natural abundance of 100%, and the target thickness was about 100 μg/cm^2. Deuterons and tritons were momentum-analyzed with a split-pole magnetic spectrograph and recorded on NTA nuclear emulsion plates. Data were obtained at

TABLE I. Energy levels in ^{166}Er observed with the (^{3}He,d) and (α,t) reactions. The brackets indicate intensities for unresolved levels.

^{165}Ho(^{3}He,d)^{166}Er					^{165}Ho(α,t)^{166}Er				
E(level)	$\frac{d\sigma}{d\Omega}$(μb/sr)				E(level)	$\frac{d\sigma}{d\Omega}$(μb/sr)			
(±0.02 MeV)	15°	20°	25°	30°	(±0.02 MeV)	15°	20°	25°	30°
ground state									
					0.087	68.5		90.3	17.3
					0.268	201.2	133.4	324.6	83.0
0.540	12.9				0.547	114.8	67.8	132.7	35.4
1.575	57.6	52.3	59.4	60.0	1.574	176.2	112.9	283.9	99.0
1.663	} 24.4	} 23.8	} 39.7	36.9	1.663	} 195.3	65.0	188.7	63.2
1.692				21.9	1.689		56.9	~45	37.3
1.724				8.5					
1.780			12.1	11.6	1.774	12.8		24.1	
1.823	10.4		17.2	12.8	1.825	30.6			7.8
1.866	8.3			15.7	1.885			59.0	
1.915	42.9		46.7	46.1	1.915	113.6	99.7	148.3	45.3
1.981	} 147.1	} 66.2	} 104.1	53.4	1.977	495.3	216.1	393.9	157.0
2.005				50.9	2.013	183.4	230.0	340.2	145.1
2.055	148.0	63.5	100.1	90.2	2.043	314.3	266.2	335.5	168.9
					2.068			151.0	
2.138	153.1	66.1	121.6	78.5	2.126	439.4	284.0	456.9	214.3
2.196	15.2				2.162	75.8	108.2	189.8	
2.220	} 82.9	} 31.4	} 57.7	30.4	2.201	166.5	~108	162.8	58.8
2.245				20.4	2.235	185.6	156.4	340.9	120.8
					2.297	25.8		~60	
2.338	27.1		31.5	20.6	2.340	100.2	53.0	173.3	
2.404	33.1		28.9	26.0	2.381	60.7	51.8	102.7	
					2.411	81.8			
2.464			39.0	37.5	2.456	94.5	63.6	129.6	
2.496		18.5	19.2	31.3	2.495	87.5	56.6	~130	
					2.553	72.6		101.2	
2.611	192.6	128.3	192.7	130.2	2.589	296.1	222.0	457.2	231.9
2.637	42.2		46.4	52.3	2.619	207.7	147.9	172.8	63.7
2.747	27.6			16.5	2.729	21.0			
2.779				20.9	2.767	42.5			
2.952	20.0		29.3						
3.001	17.8		30.2						
					3.057	151.0		121.8	35.8
3.156	35.4		37.0	24.6	3.148	40.7			
					3.234	118.5			
3.265	37.4		36.6		3.262	155.7		399.5	117.2
3.376	30.1		18.8						
3.436	20.3		47.2						
3.480	55.5		~50						
3.508	78.4	54.1	99.6	43.7					

TABLE II. Optical-model parameters used in DWBA calculations of ^{165}Ho(^{3}He,d)^{166}Er and ^{165}Ho(α,t)^{166}Er.

	V_0 (MeV)	r_0 (fm)	a (fm)	W_0 (MeV)	W_D (MeV)	r' (fm)	a' (fm)	r_{0_c} (fm)	a_c (fm)
^{3}He	−175	1.14	0.723	−17.5		1.6	0.81	1.4	0.723
d	−111	1.05	0.859		70.8	1.24	0.794	1.25	0.859
bound p	adjusted	1.25	0.65					1.25	0.65
α	−200	1.4	0.6	−20		1.4	0.6	1.3	
t	−200	1.4	0.6	−20		1.4	0.6	1.3	
bound p	adjusted	1.25	0.65					1.3	0.65

15, 20, 25, and 30°. The plates were scanned by an automatic plate scanner.[5] Figure 1 shows typical (^{3}He, d) and (α, t) spectra at 25 and 30°, respectively. The experimental resolution was ≈50 keV full width at half maximum (FWHM). The data were analyzed with the program AUTOFIT[6] in order to obtain excitation energies and relative cross sections (Table I). The estimated uncertainties are about 20 keV for the excitation energies and 10% for the cross sections.

Distorted-wave Born-approximation (DWBA) calculations were made using the program DWUCK[7] and the optical-model parameters[1] used in this calculation are shown in Table II. Calculated angular distributions were obtained for l values from 0 to 5. At each angle for which data were obtained, the appropriate l values were used to calculate the cross section for exciting a state of spin I in a band given by $[Nn_z\Lambda]K$ by means of[8]

$$\frac{d\sigma}{d\omega}(I,K)=2U_K{}^2C_{lj}{}^2(K,I)\sigma_{lj}(\theta).$$

$U_K{}^2$ is the emptiness probability of the state, σ_{jl} the intrinsic cross section for proton stripping, and $C_{lj}{}^2$ the spherical expansion coefficients. These calculations were made with the program BANDMIX.[9] By comparing the calculated patterns with the cross sections observed experimentally, rotational bands were identified. Further evidence for the classification of observed bands was found in the experimental ratios of the (^{3}He, d) and (α, t) cross sections. As pointed out earlier,[3] these ratios are good indicators of the l values of the members of a given rotational band.

III. RESULTS AND DISCUSSION

The reactions studied in the present experiments involve the stripping of a proton. One could expect therefore to observe in this experiment states arising from the coupling of the [523↑] proton configuration, which describes the ^{165}Ho ground state, with the proton states which have been found as excited states in neighboring odd-proton nuclei. The possible two-proton configurations expected at relatively low excitation energy are shown in Table III. In Table I the energies of levels observed presently and the cross sections at each angle are given for the (^{3}He, d) and (α, t) reactions. Table IV contains the experimental and calculated ratios, R, of the cross sections for (^{3}He, d) and (α, t) where data is available. These results are grouped by members of proposed bands. The calculated values of R for a given angle decrease with increasing spin of the rotational states. Due to inadequate statistics in some cases, and due to the nature of the intensity patterns, the experimental values of R are not available at every angle. However, in most cases the present results support the proposed level schemes for the rotational bands. The ratio of the experimental to calculated values of R, normalized at each level to 1.0 for the lowest angle, are in most cases ~1.0.

A two-proton state at 1.574 MeV excitation has been suggested[10] as a possible 4^- coupling of the [523↑] and [411↓] states. In the present experiment, strongly populated states at 1.574 and 1.663 MeV have the proper energy relationsip and intensity pattern to be members of the 4^- band. The state at 1.981 is a good candidate for the state made by the 3^- coupling. Because the cross sections fall off rapidly, the observation of only 3 or 4 states might be expected. Figure 2 shows the agreement with the calculated patterns of strength. Further evidence for the assignments of $K^\pi=4^-$ and 3^- for bands at 1.574 and 1.981 MeV, respectively, is the values of the ratios R of (^{3}He, d) and (α, t) cross sections. Earlier, a 1.572-

TABLE III. Two-proton configurations in ^{166}Er expected on the basis of proton states in Tm isotopes.

		$K^\pi{}_<$	$K^\pi{}_>$
$[523\uparrow]^{7/2-}$	$[411\downarrow]^{1/2+}$	4^-	3^-
	$[404\downarrow]^{7/2+}$	7^-	0^-
	$[541\downarrow]^{1/2-}$	4^+	3^+
	$[514\uparrow]^{9/2-}$	8^+	1^+

MeV state, weakly populated in the (d, t) reaction,[2] was tentatively assigned to the 4^- band considered here. This state may possibly be identified with the 1.574-MeV state; the energy resolutions in these two experiments, however, are not sufficient for definitive conclusions on this point. As noted,[2] a positive identification could possibly be explained by the existence of an admixture in the two-proton state of a two-neutron state formed by the coupling of the [633↑] and [521↓] orbitals.

TABLE IV. Summary of experimental and calculated values of the ratio R of the cross sections for (^{3}He,d) and (α,t) reactions on ^{165}Ho. For each level, the calculated value of R is normalized to the experimental value at 15°. The excitation energies E_x are the best values from the (^{3}He,d) and (α,t) data.

K^π	J^π	E_x	θ_{lab} (deg)	R Exp	R Calc	R_{exp}/R_{calc}
4^-	4^-	1.574	15	0.330	0.330	1.00
			20	0.467	0.443	1.05
			25	0.208	0.633	0.33
			30	0.607	0.723	0.84
	5^-	1.663	30	0.587		
3^-	3^-	1.981	15	0.298	0.298	1.00
			30	0.341	0.647	0.53
	4^-	2.07				
	5^-	2.17	15	0.202		
0^-	0^-	2.005				
	1^-	2.055	15	0.469	0.469	1.00
			20	0.238	0.361	0.67
			25	0.299	0.960	0.31
			30	0.534	0.800	0.67
	2^-	2.138	15	0.349	0.349	1.00
			20	0.233	0.269	0.87
			25	0.265	0.712	0.37
			30	0.366	0.597	0.61
	3^-	2.235	30	0.017		
	4^-	2.338	15	0.271	0.271	1.00
			25	0.182	0.555	0.33
	5^-	2.464	25	0.305		
7^-	7^-	2.611	15	0.651	0.651	1.00
			20	0.578	0.505	1.15
			25	0.422	1.340	0.32
			30	0.562	1.110	0.51
	8^-	2.779				
4^+	4^+	2.637	15	0.203	0.203	1.00
			25	0.268	0.427	0.63
	5^+	2.747	15	1.310		
1^+	1^+	(2.958) [a]				
	2^+	(3.000) [a]				
	3^+	(3.057) [a]				
	4^+	3.156	15	0.258	0.258	1.00
			25	0.304	0.155	1.96
			30	0.689	0.152	4.53
	5^+	3.265	15	0.241	0.241	1.00
			25	0.918	0.143	6.42

[a] Energy estimated on the basis of the energies of other members of the band.

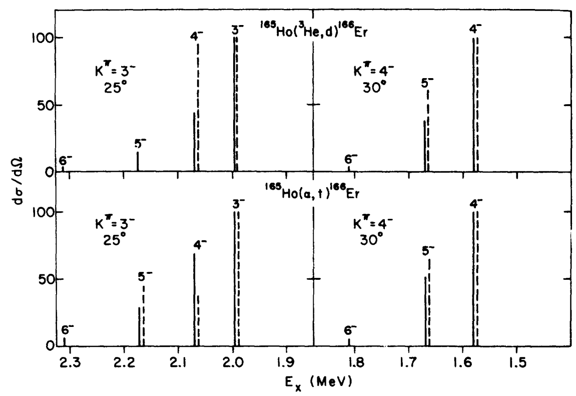

FIG. 2. Comparison of experimental cross section with BANDMIX calculations (solid lines) for bands built on the state formed by the coupling of the [523↑] and [411↓] proton configurations.

The cross sections for exciting the states assigned to the 0^- rotational band at 2.005 MeV (Fig. 4) follow the pattern predicted for the band based upon the state formed by the coupling of the [523↑] and [404↓] proton configurations. The comparison with calculated values is shown in Fig. 3. The present assignment is also supported by the values of R for the band members. The moment of inertia parameter for this band is $\hbar^2/2\mathscr{G} \approx 13$. Members of the band based on the $K^\pi = 7^-$ coupling of the [523↑] and [404↓] Nilsson states

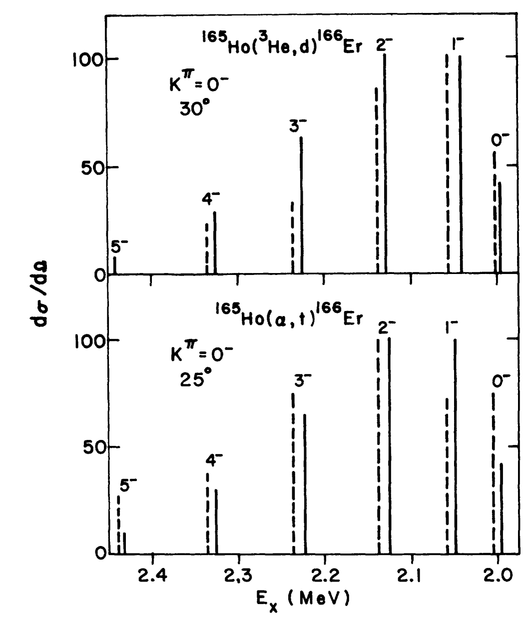

FIG. 3. Comparison of experimental cross section with BANDMIX calculations (solid lines) for bands built on the state formed by the coupling of the [523↑] and [404↓] proton configurations.

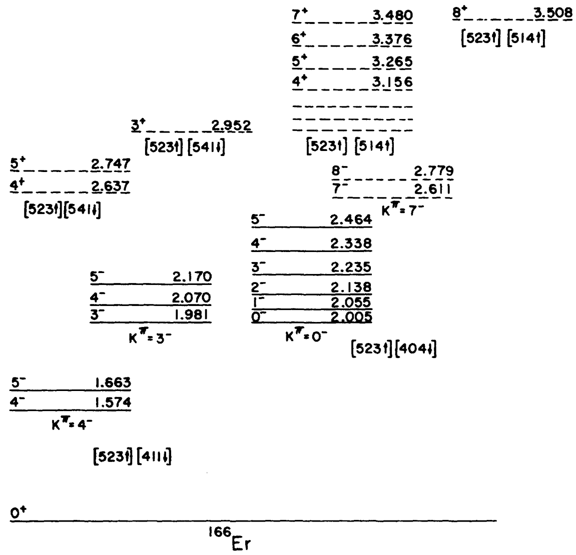

FIG. 4. Two-proton states in ^{166}Er determined from the (^{3}He, d) and (α, t) reactions on ^{165}Ho. Dashed lines represent observed states whose assignment to the indicated rotational band is tentative.

are not expected to be strongly populated in the present experiment because of the large l transfers required. A state of 2.611 MeV has a large cross section but does not fit into the patterns for any other bands and therefore has been assigned as the $K^\pi = 7^-$ band head.

The remaining bands shown in Fig. 4 are only tentatively proposed. The levels were seen in the (^{3}He, d) reaction; however, the corresponding levels were not seen in (α, t) with sufficient intensity or resolution for the calculation of the ratios of cross sections. The assignment of $K^\pi = 4^+$ and 3^+ bands at 2.637 and 2.952 MeV and the 1^+ and 8^+ bands are based on the intensity patterns and energy relationships of the levels observed with the (^{3}He, d) reaction. Only the band head at 3.508 was observed for the 8^+ band. The first three members of the 1^+ band are expected to be only weakly populated. Using the values of the energies of the 4^+ and 5^+ states the energy of the 1^+ band head has been estimated to be 2.958 MeV.

A summary of the present results is shown in Table V in which the rotational parameters and band-head energy splittings are given. The values of $\hbar^2/2\mathscr{I}$ are ≈11 keV for all the bands identified in the present study. These are comparable to

TABLE V. Summary of moment-of-inertia parameters and band-head splitting energies for 2-proton states in ^{166}Er.

K^π	E_K	$\frac{\hbar^2}{2\mathscr{I}}$	ΔE_K (keV)
4^-	1.574	8.9	407
3^-	1.981	11.0	
0^-	2.005	≈13	606
7^-	2.611	≈11	
4^+	2.637	≈11	315
3^+	2.952		
1^+	(2.958) [a]	10.9	(550) [b]
8^+	3.508		

[a] Not observed. Energy estimated on the basis of the energies of other members of the band.
[b] Approximate value using the estimated energy of the 1^+ band head.

the values (~13 keV) for known bands built on neutron configurations in ^{166}Er.

The definite determination of the bands proposed in the present study requires further experimental evidence. No other charged-particle transfer data are available for comparison with the present results. The 4^- band at 1.572 was suggested[2] from the (d, t) reaction and levels at 1.572 and 1.666 MeV, assigned[11,12] 4^- and 5^- in the decay of ^{166}Ho and ^{166}Tm, may possibly be identified with the members of the 4^- band proposed in the present study. Little correlation is apparent for states above 2-MeV excitation energy.

The present results could be the basis of a detailed analysis of two-proton quasiparticle states in ^{166}Er. The comparison of this data with calculations of the energy splittings for bands based on the $K_<$ and $K_>$ couplings of individual proton angular momenta could give more information about the proton-proton effective residual interaction. Such calculations are beyond the intentions of the present paper; the hope, however, is that this data will stimulate further theoretical investigations.

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