Search for the $K^{\pi}=1^{+}$ two-proton band in ^{166}Er

H. Li, P. V. Magnus,* M. S. Smith,† and P. D. Parker
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511

J. A. Cizewski, C. S. Lee,‡ and D. Barker§
Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903

C. Wesselborg
Institut für Kernphysik, Justus-Liebig-Universität, Giessen, Germany

A. E. Champagne**
Department of Physics, Princeton University, Princeton, New Jersey 08544
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The ^{165}Ho (α,t) and $(^{3}\text{He},d)$ reactions have been measured at beam energies of 40 and 25 MeV to look for the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ two-proton band structure in ^{166}Er. Reaction products were analyzed using a quadrupole-three-dipole spectrometer. Distorted-wave Born approximation predictions were used to extract candidate states with angular momentum transfer $l=5$. The measured strengths of all the candidates for $l=5$ transitions were compared with the Nilsson fingerprint pattern of the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ band to identify the structure. No strong population of this configuration was found. At best two tentative candidates for the $I^{\pi}=3^{+}$ and 4^{+} members of this band could be identified, which would represent at most 38% of the expected strength for this configuration. The bandhead for this tentative $K^{\pi}=1^{+}$ excitation does not correspond to any $I^{\pi}=1^{+}$ state observed in the ^{166}Er(γ,γ') reaction.

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I. INTRODUCTION

The existence of an $I^{\pi}=1^{+}$ state with enhanced $M1$ strength in rare-earth nuclei was proposed in 1978 by Lo Iudice and Palumbo [1] using a two-rotor model (TRM) which allows the proton and neutron ellipsoids with the same moment of inertia to rotate freely against each other in a "scissors" movement. This $I^{\pi}=1^{+}$ state is excited by the isovector component of the $M1$ transition operator. For $A=180$ nuclei with deformation $\delta=0.25$, using a rigid two-rotor approximation, the excitation energy was estimated to be about 10 MeV, with a $B(M1)$ strength of about $17\mu_N^2$. Iachello also predicted [2] the existence of low-lying $I^{\pi}=1^{+}$ states in the SU(3) and O(6) limits of the interacting boson model IBM-2 as the result of the not fully symmetric interaction between valence proton and neutron bosons.

The first experimental evidence for low-lying $I^{\pi}=1^{+}$ excitations with enhanced $M1$ strengths was found in 1984, when Bohle *et al.* [3] studied ^{156}Gd(e,e') scattering at backward angles. A sharp peak at 3.075 MeV in excitation energy was found and assigned to $I^{\pi}=1^{+}$. The form factor and the excitation energy, as well as the transition probability of this state, agree with those calculated by the IBM-2 for the $I^{\pi}=1^{+}$ $M1$ states. The $B(M1)$ strength of this state was measured as $(1.3\pm0.2)\mu_N^2$. Subsequent experiments on ^{168}Er, ^{164}Dy, ^{174}Yb, and other well-deformed nuclei [4], showed similar low-lying excitations with enhanced $M1$ strength (typically $1\mu_N^2$). The measured form factor of the $M1$ transitions showed good agreement with the IBM-2 and the TRM. When (e,e') measurements were made on a nucleus which was not a good rotor, such as ^{146}Nd, no $I^{\pi}=1^{+}$ states with enhanced $M1$ strength were observed at the expected [4] excitation energy of $66\delta A^{-1/3}$. Therefore, the $I^{\pi}=1^{+}$ states in deformed nuclei were interpreted as collective isovector excitations.

Shortly after the above experiments and interpretations were published, Hamamoto and Åberg [5] presented a noncollective explanation for these states. With two protons circulating in high angular momentum orbitals, in particular, $l=5$, they could reproduce the experimental $M1$ strengths of these states. Although the form factors are not well reproduced, they concluded that a low-lying

*Present address: Nuclear Laboratory GL-10, University of Washington, Seattle, WA 98195.

†Present address: Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831.

‡Present address: Department of Physics, Chung-Ang University, Seoul 156-756, Korea.

§Present address: LOGICA, Cobham, Surrey KT11 3LX, U.K.

**Present address: Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599.

$I^{\pi}=1^{+}$ excitation with enhanced $M1$ strength could be formed by two $h_{11/2}$ photons, and, hence, these states could be of a two-particle nature.

The present measurement was designed to test this noncollective interpretation of the low-lying $M1$ excitations by single-proton transfer experiments. In doing this, ^{165}Ho, the only stable isotope with an $h_{11/2}$ proton as its ground state, was chosen as the target. The ground state of ^{165}Ho has $I^{\pi}=\frac{7}{2}^{-}$ and is of the $\frac{7}{2}^{-}[523]$ Nilsson configuration. Since the $\frac{9}{2}^{-}[514]$ orbital is close to the ground state (about 3 MeV above the Fermi surface), it is possible that in a stripping reaction an $h_{11/2}$ proton is transferred to populate the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ band. The identification of this band could provide a test of the microscopic structure of the low-lying $M1$ excitations in ^{166}Er and in other rare-earth nuclei.

II. EXPERIMENTAL PROCEDURE

The experiment was performed using the Princeton University AVF cyclotron facility with beams of 40 MeV ^{4}He^{++} and 25 MeV ^{3}He^{++} particles. The target was metallic holmium evaporated onto a 30 μg/cm^{2} carbon foil. The reaction products were momentum analyzed by the quadrupole-three-dipole (Q3D) spectrometer and detected by a position-sensitive detector [6] located at the focal plane. This detector was 60 cm in length and consisted of a position-sensitive resistive-wire gas proportional counter and a scintillator detector. The reaction products were identified by plotting ΔE vs E_{residual}. The measurements were calibrated internally using known [7,8] excitation energies in ^{166}Er and with proton-transfer reactions on ^{118,120}Sn targets, where the reaction products were measured at identical spectrometer settings and the known [9] energies of states in ^{119,121}Sb were used.

In this experiment we measured the low-energy structure of ^{166}Er up to 4.4 MeV. The previously identified [7] two-proton band $K^{\pi}=8^{+}\{\frac{9}{2}^{-}[514]+\frac{7}{2}^{-}[523]\}$ has its bandhead $I^{\pi}=8^{+}$ state at 3076 keV, and the Gallagher rule [10] predicts the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ band should be lower in energy, because like nucleons tend to couple to spin-zero pairs. The energy separation of the two bands is determined by the energy it takes to flip one proton spin, which has been empirically determined [7] to be 400 keV for this nucleus. Thus, the two-quasiparticle band of interest was expected to be in the excitation energy range of 2.6 MeV. Taking into account the observed fragmentation of the $M1$ excitations in other rare-earth nuclei [4], the energy range of our measurements was expanded to two times that of the pairing gap to include all possible two-proton excitations with bandhead energies up to 3.4 MeV in excitation.

To identify the $h_{11/2}$ two-proton band required candidates for $l=5$ angular momentum transfer. Usually this assignment is done by angular distribution measurements. However, distorted-wave Born approximation (DWBA) calculations [11] of the angular distributions of $l=4$ and 5 transitions are essentially identical in shape for the (α,t) reaction, and show little difference for the $(^{3}\mathrm{He},d)$ reactions. This means it was not possible to distinguish $l=5$ from $l=4$ transfers in the $(^{3}\mathrm{He},d)$ or (α,t) reactions by comparing the measured angular distributions to the DWBA predictions. An alternative method to assign the angular momentum transfer is to compare the cross sections to the same state in ^{166}Er in the (α,t) and $(^{3}\mathrm{He},d)$ reactions. The (α,t) reaction, with a large Q-value mismatch, favors high angular momentum transfer; small angular momentum transfer is favored by the $(^{3}\mathrm{He},d)$ reaction, since there is no Q-value mismatch. Thus, ratios of the cross sections measured in these two reactions will have a strong dependence on the transferred angular momentum, separating the states with high l values from those with low l values. This was the method used to extract l-transfer values in the present work: we chose the cross section ratio

$$R=[\sigma(^{3}\mathrm{He},d)\text{ at }65^{\circ}]/[\sigma(\alpha,t)\text{ at }20^{\circ}]$$

for comparisons. As an example, our DWBA calculations with the code [12] DWUCK4 and the optical-model parameters in Table I predict the cross-section ratios of states populated with $l=4$ transfer to be larger by a factor of 3 than those populated with $l=5$ transfer.

The angles for these measurements were chosen to avoid the contaminant states which emerge from the proton transfer reactions on ^{13}C (in the target backing) and ^{18}O (in the target). The (α,t) reaction was measured at 20° and 30° and the $(^{3}\mathrm{He},d)$ reaction was measured at 40° and 65°.

Figure 1 shows the experimental spectra obtained at 20° for the (α,t) reaction and at 40° for the $(^{3}\mathrm{He},d)$ reaction. Energy levels up to 4.4 MeV in ^{166}Er were identified. Since the spectra are not linear at the low momentum end, the overlap portions of the spectra were

TABLE I. The optical-model parameters used in the DWBA calculation. r and a are the radius and the diffuseness of the corresponding potential, respectively. r_{0c} is the Coulomb charge radius, $R_c=r_{0c}A^{1/3}$. Taken from Ref. [7].

Reaction		V (MeV)	r_V (fm)	a_V (fm)	W (MeV)	r_W (fm)	a_W (fm)	r_{0c} (fm)	W_D (MeV)	r_D (fm)	a_D (fm)
(α,t)	α	-200	1.4	0.6	-20	1.4	0.6	1.25			
	t	-200	1.4	0.6	-50	1.4	0.6	1.25			
	p							1.25			
$(^{3}\mathrm{He},d)$	^{3}He	-175	1.14	0.723	-17.5	1.6	0.81	1.4			
	d	-111	1.05	0.859				1.25	70.8	1.24	0.794
	p							1.25			

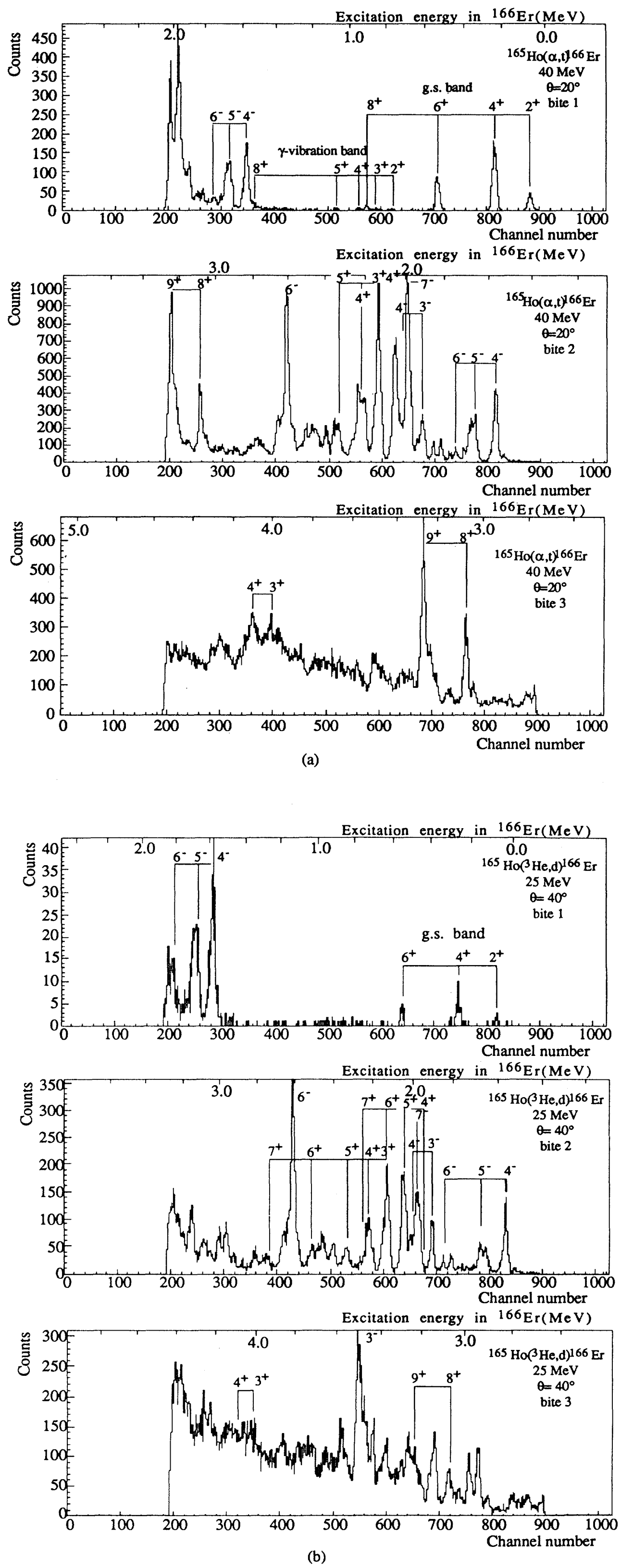

FIG. 1. (a) Energy spectra from the ^{165}Ho$(\alpha,t)^{166}$Er reaction at $\theta=20°$. (b) Energy spectra from the ^{165}Ho$(^{3}$He$,d)^{166}$Er reaction at $\theta=40°$.

analyzed using the higher momentum bites. The spectra show no signs of states from the contaminants. The spectra were analyzed with the peak-fitting program SAM [13]. The overall energy resolution was about 20 keV full width at half maximum (FWHM).

III. RESULTS AND ANALYSIS

Table II summarizes the states in ^{166}Er we identified in this experiment and shows the comparison to the previous measurements. The extracted excitation energies of states in ^{166}Er are in overall good agreement with the previous work [7,8] with differences in excitation energies typically no larger than 2 keV for the most strongly populated states; for the weakly populated peaks there can be deviations up to 7 keV.

The comparison between the DWBA predicted ratios and our experimental data is plotted in Fig. 2. The DWBA ratio predictions were normalized to the experimental values using two previously determined [7] pure l-transfer peaks, $l=4$ at 1998 keV and $l=5$ at 3273 keV.

^{166}Er is a well-deformed nucleus [7] with $\epsilon_2 \approx 0.29$ and $\epsilon_4 \approx 0.0125$. This indicates large Coriolis mixing, but small $\Delta N=2$ mixing in the Nilsson wave functions. The proton Fermi surface of this nucleus lies above the $\frac{7}{2}^{-}[523]$ orbital. For a proton stripping reaction the proton orbitals above the Fermi surface have the largest probability of transfer. These orbitals include $\frac{1}{2}^{+}[411]$, $\frac{7}{2}^{+}[404]$, $\frac{1}{2}^{-}[541]$, $\frac{5}{2}^{+}[402]$, and $\frac{9}{2}^{-}[514]$; the $\frac{3}{2}^{+}[411]$ orbital also should be taken into account due to partial occupancy near the proton Fermi surface produced by the pairing interaction. These result in a total of thirteen two-proton bands in the low-lying energy spectrum of ^{166}Er. They are

$$\tfrac{7}{2}^{-}[523]-\tfrac{7}{2}^{-}[523], \quad K^{\pi}=0^{+} \text{ ground-state band },$$

$$\tfrac{7}{2}^{-}[523]\pm\tfrac{1}{2}^{+}[411], \quad K^{\pi}=4^{-},3^{-} ,$$

$$\tfrac{7}{2}^{-}[523]\pm\tfrac{7}{2}^{+}[404], \quad K^{\pi}=7^{-},0^{-} ,$$

$$\tfrac{7}{2}^{-}[523]\pm\tfrac{1}{2}^{-}[541], \quad K^{\pi}=4^{+},3^{+} ,$$

$$\tfrac{7}{2}^{-}[523]\pm\tfrac{5}{2}^{+}[402], \quad K^{\pi}=6^{-},1^{-} ,$$

$$\tfrac{7}{2}^{-}[523]\pm\tfrac{9}{2}^{-}[514], \quad K^{\pi}=8^{+},1^{+} ,$$

$$\tfrac{7}{2}^{-}[523]\pm\tfrac{3}{2}^{+}[411], \quad K^{\pi}=5^{-},2^{-} .$$

All of these bands, except for the $K^{\pi}=1^{+}$, 0^{-}, and 5^{-} bands were identified previously [7] and are indicated in Table II. The ground-state band, including the 81, 258, 545, and 912 keV states, was clearly seen in our data, with the exception of the ground state, which was outside of the range of the first momentum bite. The γ-vibrational band, starting from 781 keV, though weakly excited, was seen up to $I^{\pi}=8^{+}$. This band includes the 781, 863, 958, 1075, and 1557 keV states. The $I^{\pi}=6^{+}$ and 7^{+} members of this band, at 1216 and 1376 keV, were not seen in the spectra of bite 1. This band is only weakly excited because its wave function does not contain any large amplitudes of configurations accessible to the proton stripping reaction.

TABLE II. States in ^{166}Er.

Energy (NDS)	$I^{\pi a}$ (NDS)	Energy this work	K^{π}	I	Interpretation
0	0^+				$\frac{7}{2}^-[523]-\frac{7}{2}^-[523]$
80.574	2^+	81	0^+	2	$\frac{7}{2}^-[523]-\frac{7}{2}^-[523]$
264.986	4^+	258	0^+	4	$\frac{7}{2}^-[523]-\frac{7}{2}^-[523]$
545.44	6^+	545	0^+	6	$\frac{7}{2}^-[523]-\frac{7}{2}^-[523]$
785.89	2^+	781	2^+	2	γ-vibrational band
859.38	3^+	863	2^+	3	γ-vibrational band
911.18	8^+	912	0^+	8	$\frac{7}{2}^-[523]-\frac{7}{2}^-[523]$
956.20	4^+	958	2^+	4	γ-vibrational band
1075.26	5^+	1075	2^+	5	γ-vibrational band
1215.94	6^+				γ-vibrational band
1349.6	10^+				
1376.00	7^+				γ-vibrational band
1458.0	$(2)^-$				
1528.2	(2^+)	1529			
1555.67	8^+	1557	2^+	8	γ-vibrational band[b]
1572.1	$(4)^-$	1572	4^-	4	$\frac{7}{2}^-[523]+\frac{1}{2}^+[411]$
1596.2	(4^-)	1594	4^-	4	$\frac{7}{2}^-[523]+\frac{1}{2}^+[411]$
		1651			
1665.76	$5^{(-)}$	1667	4^-	5	$\frac{7}{2}^-[523]+\frac{1}{2}^+[411]$
1692.28	$5^{(-)}$	1689	4^-	5	$\frac{7}{2}^-[523]+\frac{1}{2}^+[411]$
1721.7	(3^-)	1718			
1760.9		1755			
1786.93	6^-	1785	4^-	6	$\frac{7}{2}^-[523]+\frac{1}{2}^+[411]$
1812.5	$1^{(+)}$				
1827.52	6^-	1826	4^-	6	$\frac{7}{2}^-[523]+\frac{1}{2}^+[411]$
1865		1863			
1917.7	3^-	1914	3^-	3	$\frac{7}{2}^-[523]-\frac{1}{2}^+[411]$
1938.2	$(3)^+$	1939			
1978.4	$(3,4)^+$	1972	$(4^+$	4	$\frac{7}{2}^-[523]+\frac{1}{2}^-[541]$
1992.4	$(7)^-$	1988	7^-	7	$\frac{7}{2}^-[523]+\frac{7}{2}^+[404]$
2001.8	$(3)^-$	2000	3^-	4	$\frac{7}{2}^-[523]-\frac{1}{2}^+[411]$
2021	$(2,3)^-$	2022			
2047.0	(3^+)	2047	$(4^+$	5	$\frac{7}{2}^-[523]+\frac{1}{2}^-[541])$
2056		2059	{$(1^-$	1	$\frac{7}{2}^-[523]-\frac{5}{2}^+[402])$
			$(2^-$	2	$\frac{7}{2}^-[523]-\frac{3}{2}^+[411])$
2073	(2^-)	2076			
2115	(6^+)	2119			
2132.9	3^+	2134	{$(4^+$	6	$\frac{7}{2}^-[523]+\frac{1}{2}^-[541])$
			$(3^+$	3	$\frac{7}{2}^-[523]-\frac{1}{2}^-[541])$
			$(2^-$	3	$\frac{7}{2}^-[523]-\frac{3}{2}^+[411])$
2152	(2^-)	2154	$(1^-$	2	$\frac{7}{2}^-[523]-\frac{5}{2}^+[402])$
2166	(2^-)				
2204		2204			
2215.8	$(2,3)^-$				
2223		2220	{$(1^-$	3	$\frac{7}{2}^-[523]-\frac{5}{2}^+[402])$
			$(2^-$	4	$\frac{7}{2}^-[523]-\frac{3}{2}^+[411])$
2243.1	(4^+)	2239	$(3^+$	4	$\frac{7}{2}^-[523]-\frac{1}{2}^-[541])$
2265.1	(2^-)				
		2264	$(4^+$	7	$\frac{7}{2}^-[523]+\frac{1}{2}^-[541])$[b]
2283	(3)	2283			
2290.6	3^+	2288			
2315	$(3,4)^+$	2315			
2333		2337			
2347.7	(1)				
2358.7	(1^-)				
		2361	$(3^+$	5	$\frac{7}{2}^-[523]-\frac{1}{2}^-[541])$[b]

Energy (NDS)	$I^{\pi a}$ (NDS)	Energy this work	K^{π}	I	Interpretation
2367	(6^-)				
2384.1	$(3,4)^+$				
2402	(2^-)	2402			
2413.6	(3)	2430			
2441.2	$(3,4)^+$				
2459	(2)	2454			
2478		2478			
2505.7	$(3,4)^+$	2509			
2534		2536			
2563		2568	$(3^+$	6	$\frac{7}{2}^-[523]-\frac{1}{2}^-[541])$[b]
2586	$(3,4)^+$	2586			
2608	(6^-)	2608	6^-	6	$\frac{7}{2}^-[523]+\frac{5}{2}^+[402]$
2633.1	$(3,4)^+$	2632			
2655		2658			
2670					
		2684			
2728	$(3,4)^+$	2713	$(3^+$	7	$\frac{7}{2}^-[523]-\frac{1}{2}^-[541])$[b]
		2742			
2768	(1)	2766			
2782.7	(2^+)	2786			
2808.7	(2^+)	2808			
2880	(14^+)	2880	c		
2912		2920			
2953		2959			
2993					
3001		3000			
3057		3043			
3076	(8^+)	3075	8^+	8	$\frac{7}{2}^-[523]+\frac{9}{2}^-[514]$
3087		3096			
3147		3148			
3161		3168			
		3211			
3234		3235			
3240		3253			
3273	(9^+)	3273	8^+	9	$\frac{7}{2}^-[523]+\frac{9}{2}^-[514]$
		3296			
		3322			
		3345			
		3371			
		3394			
		3429			
		3459			
3476		3482			
3501		3503			
		3554			
		3579			
		3600			
		3627			
		3663			
		3721			
		3751			
		3783			
		3808			
		3838			
		3856			
		3881			
		3907			
		3932			
		3978			

TABLE II. (*Continued*).

Energy (NDS)	$I^{\pi a}$ (NDS)	Energy this work	K^{π}	I	Interpretation	Energy (NDS)	$I^{\pi a}$ (NDS)	Energy this work	K^{π}	I	Interpretation
		4002	$(1^{+}$	3	$\frac{7}{2}^{-}[523]-\frac{9}{2}^{-}[514])^{b}$			4256			
		4026						4274			
		4045						4297			
		4064						4329			
		4087	$(1^{+}$	4	$\frac{7}{2}^{-}[523]-\frac{9}{2}^{-}[514])^{b}$			4359			
		4106						4381			
		4126						4407			
		4149						4418			
		4174						4442			
		4227									

[a]Adopted by Nucl. Data Sheets, Ref. [8]. Only adopted levels which could be identified with those seen in the present or earlier (Ref. [7]) proton transfer reactions are listed.
[b]Assignments made in the present work.
[c]It is unlikely that the (14^{+}) 1880 keV level adopted in Ref. [8] corresponds to the state populated in the present proton transfer measurement.

Except for a few cases (such as $\frac{7}{2}^{+}[404]$, $\frac{9}{2}^{-}[514]$), the Nilsson orbits in this mass region are usually populated in proton transfer by a mixture of l transfers. In general, for the bands that consist of a proton in the ground state and a proton in another Nilsson orbital, Fig. 2 provides only a qualitative guide for the assignment of l transfers. Therefore, there will be no discussion of the l transfers to those states which lie in the middle of Fig. 2. However, the states with small cross-section ratios are candidates for $l=5$ transfer. Although Fig. 2 only displays the ratios for the (^{3}He,d) data at 65° with respect to the (α,t) data at 20°, four such plots are available from our measurements, and all were used to determine candidates for $l=5$ transfer.

We have identified additional members of the $K^{\pi}=3^{+}$ and 4^{+} bands which are populated by the transfer of an $h_{9/2}$ proton in the $\frac{1}{2}^{-}[541]$ configuration. The comparisons between the fingerprint pattern expected with Coriolis mixing and our results are given in Fig. 3.

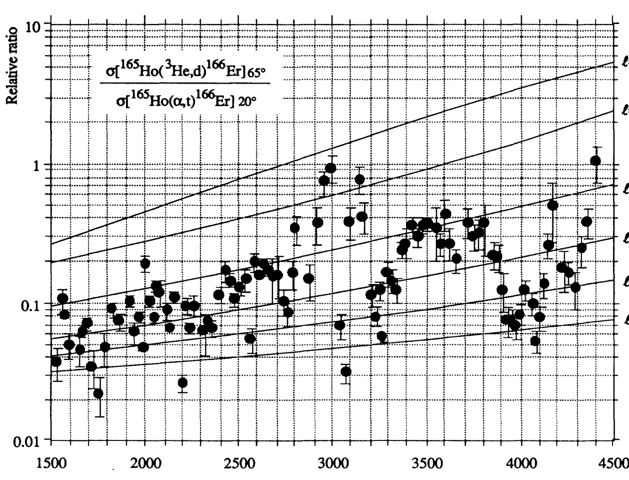

FIG. 2. Ratio of cross sections to states in ^{166}Er: $R=[\sigma(^{3}\mathrm{He},d)$ at $65°]/[\sigma(\alpha,t)$ at $20°]$.

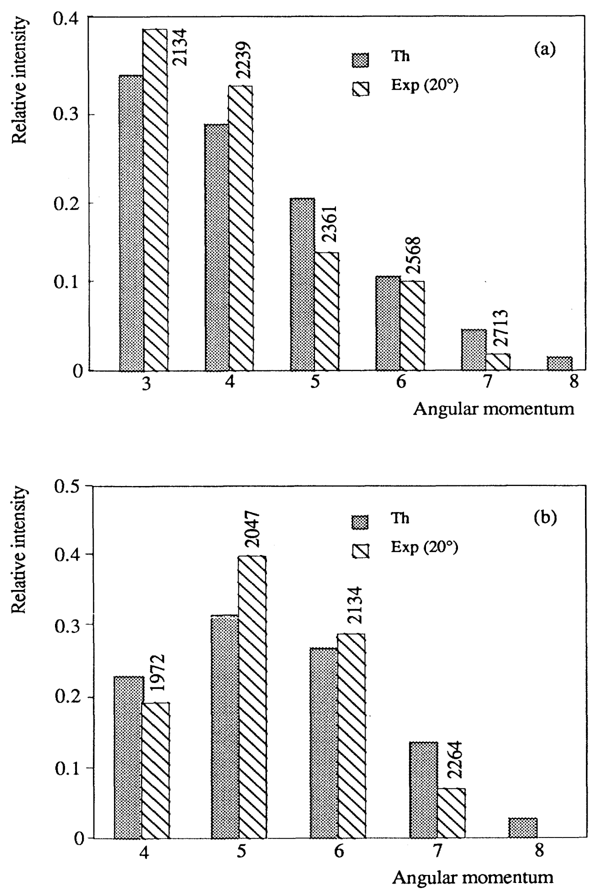

FIG. 3. Comparison between measured and calculated $l=5$ transitions to the $K^{\pi}=3^{+},4^{+}$ two-proton bands in ^{166}Er. The fingerprint patterns were calculated using the Nilsson model with Coriolis coupling code EVE [14]. (a) Relative intensities of $l=5$ transitions to the $K^{\pi}=3^{+}\{\frac{7}{2}^{-}[523]-\frac{1}{2}^{-}[541]\}$ band members measured in the (α,t) reaction at 20°. (b) Relative intensities of $l=5$ transitions to the $K^{\pi}=4^{+}\{\frac{7}{2}^{-}[523]+\frac{1}{2}^{-}[541]\}$ band members measured in the (α,t) reaction at 20°.

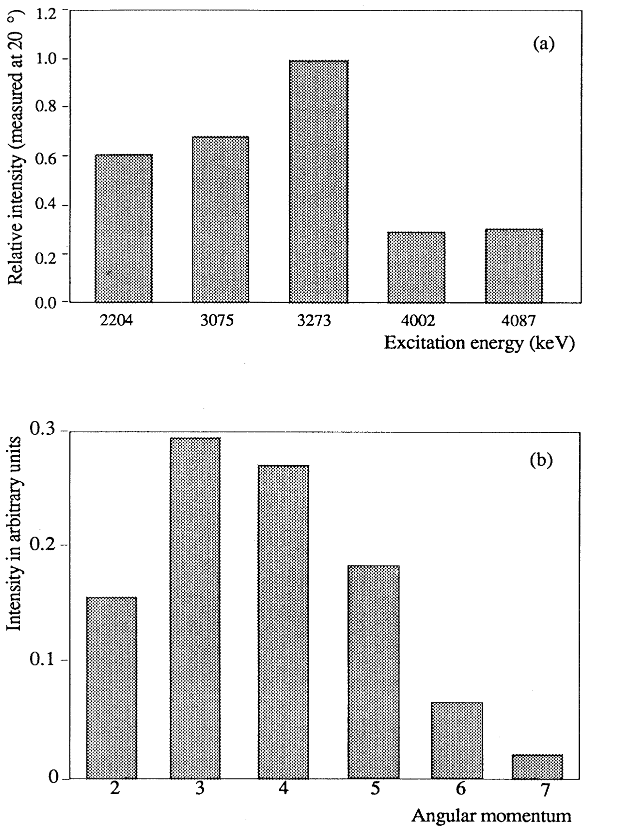

FIG. 4. Comparison between measured and calculated $l=5$ transitions in ^{166}Er. (a) Relative intensities of $l=5$ transitions measured in the (α,t) reaction at 20°. (b) Fingerprint pattern for the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ two-proton band in ^{166}Er, calculated with the Nilsson plus Coriolis coupling code EVE [14].

The intensities of other candidates for $l=5$ transitions (normalized to that of the 3273 keV state) measured at 20° in the (α,t) reaction are shown in Fig. 4(a). The motivation for the present work was to search for the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ band. The Nilsson fingerprint pattern for this band is displayed in Fig. 4(b), and shows that the 3^{+} and 4^{+} band members should be the most strongly populated. As is evident in Figs. 1 and 4(a), there are no strong candidates for $l=5$ transitions to configurations which had not been previously identified. However, it is clear in the bite 3 spectra at $E_x\approx 4.0$ and 4.1 MeV that there are two structures in the (α,t) data that are moderately strongly excited and for which no structures of comparable strength are observed in the $(^{3}\mathrm{He},d)$ data. A detailed analysis of the data with the peak-fitting code SAM indicates that two candidates for $l=5$ transitions can be identified. In this analysis monotonically increasing linear backgrounds were assumed and the broader structure at $E_x\approx 4.1$ MeV was analyzed as a multiplet. The comparison of the two parts of Fig. 4 shows that the 4002 and 4087 keV states exhibit the relative intensity pattern of the $I=3$ and 4 members of the $K^{\pi}=1^{+}$ band of interest, which are expected to be the strongest transitions. The excitation energies can be fitted by

$$E_I=3874.5+10.6I(I+1)\ \text{keV}$$

yielding $\hbar^2/2\mathcal{J}\approx 10.6$ keV for this candidate band, where $\mathcal{J}$ is the moment of inertia. When compared with other two-proton bands, such as $\hbar^2/2\mathcal{J}\approx 13$ keV for the $K^{\pi}=0^{+}$ ground-state band and $\hbar^2/2\mathcal{J}\approx 11$ keV for the $K^{\pi}=8^{+}$ band, $\hbar^2/2\mathcal{J}\approx 10.6$ keV for this $K^{\pi}=1^{+}$ candidate band is quite reasonable. It would be better if we could see more than two band members in order to confirm this assignment. Unfortunately, the level density rises sharply above 3.5 MeV of excitation energy, and it is not possible for us to identify the weaker members of this band. In the following discussion we shall assume that these two states are candidates for the $K^{\pi}=1^{+}$ two $h_{11/2}$ proton band. However, we recognize that these candidates are far from unambiguous and that any conclusions we shall draw only represent upper limits.

To evaluate the fragmentation of the $\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]$ configuration, we have assumed that this tentative $K^{\pi}=1^{+}$ band should hold the same intensity as that observed for the $K^{\pi}=8^{+}$ band with parallel coupling of these orbitals, and that the $K^{\pi}=8^{+}$ band is not significantly fragmented. With these assumptions, the tentative candidates for the $K^{\pi}=1^{+}$ two-proton band contain at most 38% of the total intensity of the $\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]$ configuration.

IV. DISCUSSION

This experiment was designed to search for a $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ two-proton band in ^{166}Er, in order to investigate the nature of low-lying $I^{\pi}=1^{+}$ states in rare-earth nuclei. The identification of this band could provide information on the microscopic nature of these $I^{\pi}=1^{+}$ states, which have been observed with enhanced $M1$ strengths. This band was not previously identified, which alone suggests that the two-proton strength in $K^{\pi}=1^{+}$ bands might be fragmented: the nonfragmented band should have its bandhead energy around 2600 keV, according to the Gallagher rule and the empirical spin-flip splitting of $\approx$400 keV for proton configurations. We have tentatively assigned two states as candidates for the $I^{\pi}=3^{+}$ and 4^{+} members of the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ band. The excitation energies of these two states indicate a bandhead energy of $E_x\approx 3.90$ MeV. At best, this candidate band has only 38% of the $l=5$ strength which can be expected for this configuration. The $l=5$ strength associated with this configuration in ^{166}Er is clearly fragmented. Therefore, the two-proton component of the $M1$ strength associated with this configuration in ^{166}Er would also be fragmented.

That we see only a fragment of the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ two-proton excitation is not unexpected. Above two times the pairing gap energy ($2\Delta\approx 1.7$ MeV for ^{166}Er), another proton pair can be broken, and more degrees of freedom, such as four-quasiparticle states, can be excited. Therefore, the number of ways to construct $K^{\pi}=1^{+}$ bands rapidly increases beyond 3 MeV in excitation energy, which could be the reason for the observed fragmentation of the

TABLE III. Summary of the results of the ^{166}Er(γ,γ') reactions [15,16]. Only candidates for $K=1$ states are included and the transition probabilities (in units of μ_N^2) are calculated on the assumption that all transitions are $M1$.

Energy (MeV)	Wesselborg (μ_N^2)		Metzger (μ_N^2)
1.812	0.67[a]	13	0.35 4
2.201[b]	0.48	13	0.36 7
2.464			0.10 3
2.524			0.19 5
2.599	0.52	10	0.37 7
2.678			0.22 7
2.766	0.21	8	0.16 5
2.992			0.06
3.123			0.07
3.143	0.46	9	0.41 6
3.174	0.18	4	0.14
3.186	0.19	4	0.16
3.195	0.34	5	0.26 4
3.240			
3.287[c]	0.15	7	<0.3
3.328			
3.358			
3.386	0.17	5	
3.429			
3.551			
3.567			
3.709			
3.752			
3.786			
3.808			

[a]Branching ratio taken from Ref. [15].
[b]Positive parity taken from the linear polarization results of Ref. [15], although the branching ratio suggests $K=0$.
[c]While the results of Ref. [15] are consistent with $K=1$, the results of Ref. [16] indicate $K=0$, and hence a 1^- state. The quoted transition probability assumes $K^{\pi}=1^{+}$.

$K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ $l=5$ strength.

To probe the $M1$ excitation in ^{166}Er, (γ,γ') measurements have been made [15–17]. Table III shows the published results, which lists about fifteen $I=1$ states in the excitation energy range from 1.8 to 3.8 MeV. The linear polarization measurements made by Metzger [15] were only conclusive for the 1812 and, possibly, 2201 keV states. For the other states listed in Table III, there is no way to tell accurately how many of these are $M1$ transitions. The strengths of these states are typically $\approx(0.2-0.6)\mu_N^2$ if they are $M1$ transitions. Even if only one-half of them are $M1$ transitions, it still means considerable fragmentation of the $M1$ strength. Figure 5 shows the comparison [16] by Wesselborg of the $M1$ strength in a number of rare-earth nuclei. The Er isotopes have been investigated recently in the (γ,γ') work [17] by Lindenstruth *et al.* While the newer data are higher, they still indicate that the total $M1$ strength in ^{166}Er is less than observed in its isotone ^{164}Dy.

Although the (γ,γ') measurements indicate considerable fragmentation of $M1$ strength in ^{166}Er, we see no clear correspondence between our tentative

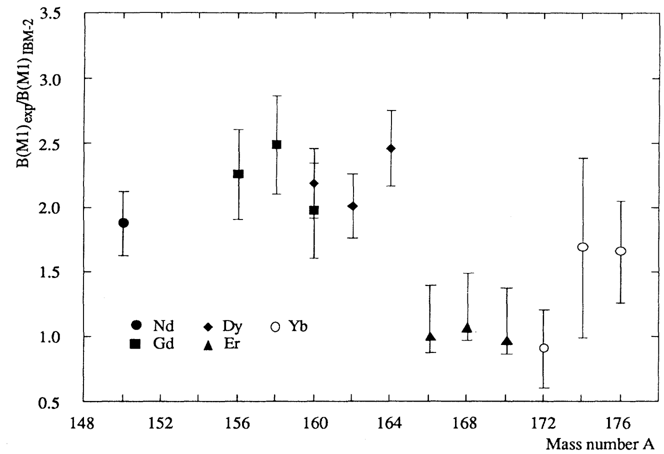

FIG. 5. The relative $M1$ strength in ^{166}Er and adjacent nuclei, normalized to the IBM-2 predictions, where $B(M1)\uparrow=(3/4\pi)(g_\pi-g_\nu)^2\{8N_\pi N_\nu/[2(N_\pi+N_\nu)-1]\}$. This figure was adopted from Ref. [16] which used the $g_\pi=0.65$ and $g_\nu=0.08$ values from Ref. [18].

$K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ two-proton component and a dipole transition measured in the (γ,γ') work. Wesselborg *et al.* [16] did observe a weak dipole excitation at 3926 keV, which is somewhat too high compared to the expected head of our candidate band. More importantly, this state has the decay branching characteristics of a $K=0$ state, so is most likely a 1^-, not 1^+, state. Our results do show that the strongest transitions in the (γ,γ') measurements do not have major $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ components.

Our proton stripping results are in contrast with the proton pickup (t,α) measurements [19] on a ^{165}Ho target. This work did identify the two $h_{11/2}$ proton $K^{\pi}=1^{+}\{\frac{7}{2}^{-}[523]-\frac{5}{2}^{-}[532]\}$ band in ^{164}Dy and found that it did correspond to a 1^+ excitation in this nucleus populated [16] with $\approx0.30\mu_N$ in (γ,γ'). However, this proton pickup measurement did not observe the $K^{\pi}=6^{+}$ band (below 4 MeV in excitation) which arises from the parallel coupling of the same proton orbitals. For this configuration the fingerprint pattern concentrates the $l=5$ strength in fewer states, and less mixing with other degrees of freedom should be present for the $K^{\pi}=6^{+}$ band.

In ^{164}Dy the $M1$ strength is also highly fragmented, and only one transition had a sizeable component of this two-proton $h_{11/2}$ configuration. Also, no additional $l=5$ strength up to 4 MeV in excitation was observed, which means that the strongest $M1$ transitions to states at ≈3 MeV excitation do not have sizeable components of this configuration.

V. CONCLUSION

The present work indicates that the $K^{\pi}=1^{+}\{\frac{9}{2}^{-}[514]-\frac{7}{2}^{-}[523]\}$ component does not contribute significantly to the $M1$ strength in ^{166}Er, while earlier work [19] showed that the $K^{\pi}=1^{+}\{\frac{7}{2}^{-}[523]-\frac{5}{2}^{-}[532]\}$ does contribute to one of the 1^+ states strongly populated in ^{164}Dy. For the other $I^\pi = 1^+$ states seen in the (γ, γ') reactions on ^{166}Er and ^{164}Dy, configurations inaccessible to proton transfer reactions may contribute strongly to their wave functions. Proton $h_{11/2}$ components were expected [5] to play a major role in $M1$ excitations, but are present in only a small fraction of the accessible $K^\pi = 1^+$ excitations. This observation supports a collective isovector interpretation for much of the $M1$ enhancements.

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