Levels in Er^{168}†

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(Received 19 September 1966; revised manuscript received 26 April 1967)

12.0-MeV deuterons were used to study the levels in Er^{168} using the reaction $Er^{167}(d,p)Er^{168}$. The ground-state Q value for the reaction has been determined as 5541 ± 6 keV. The ground-state rotational band has been observed up to the 8+ state. Members of the γ vibrational band have been observed from the 2+ state at 823 keV to the 6+ state. In addition, ten states of the $K\pi=4-$ and 3− bands of the two-neutron configuration [633↑±521↓] have been observed. Absolute differential cross sections for the population of these states by the (d,p) reaction are in agreement with theoretical predictions.

I. INTRODUCTION

THE levels in even-even deformed nuclei, of which Er^{168} should be a typical example, are expected[1] to involve a ground-state rotational band with spins and parities, $I\pi=0+$, 2+, 4+, 6+, ⋯, and a γ vibrational band with $K=2$, which typically lies near 1 MeV of excitation with spins and parities 2+, 3+, 4+, ⋯. Additionally, a β vibrational band and a pairing-vibrational band[2] with $K\pi=0+$ and spins the same as the ground-state band are expected. Indeed, previous decay-scheme[3–5] and neutron-capture[6] studies have indicated the existence of well-developed ground state and γ vibrational rotational bands. Finally, one expects to observe two-quasiparticle states[7] beginning at an energy approximately 1.2 MeV above the ground state. Isoya[8] has studied Er^{168} levels via low-resolution (d,p) experiments on natural Er targets. He observed some members of the ground-state band, the γ vibrational band, and identified some of the two-quasiparticle states. However, his experimental conditions did not allow a very thorough analysis of the higher excitations in Er^{168}. In the (d,p) experiment undertaken in this research, it is difficult to populate two-quasiparticle proton states or any four-quasiparticle states. Excitation of two-quasiproton states would involve excitation of protons in the (d,p) reaction, which is basically a neutron-capturing process. An upper limit of one part in 10^3 has been set for this type of proton excitation in the $Y^{89}(d,p)Y^{90}$ reaction.[9] With these exceptions, it should be possible to observe most of the low-lying states in the nucleus Er^{168} utilizing the reaction $Er^{167}(d,p)Er^{168}$. After this experiment was completed, research on the levels in Er^{168} using the reaction $Er^{167}(n,\gamma)Er^{168}$ was communicated to us by Koch.[10] The interpretation of the high-resolution, bent-crystal spectra of Koch[10] has been a great aid to our analysis.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Three targets were prepared by evaporating approximately 700 $\mu g/cm^2$ of Er_2O_3 enriched to 58.8% in Er^{167} onto approximately 30 $\mu g/cm^2$ self-supporting carbon backings. Energy spectra of Er^{168} were obtained from the reaction $Er^{167}(d,p)Er^{168}$ using the Florida State University tandem Van de Graaff accelerator at laboratory angles of 45° and 60° (first target) and of 65° (second target) with respect to the incident 12.0-MeV deuteron beam. In addition, 12.0-MeV runs at 25° and 65° and a 12.5-MeV run at 45° (all on the third target) were used to determine the ground-state Q value, but were not used to determine the energy-level spectrum. The 60-cm, Browne-Buechner-type[11] spectrograph entrance slits were set to subtend a solid angle of 1.75×10^{-4} sr for all exposures. Lengths of exposures were 7500 μC at 45°, 6350 μC at 60°, and 10 000 μC at 65° for the runs used in determining energy levels. The beam energy was defined by a 90° magnet and slit system. The fields of the 90° magnet and of the spectrograph were set and monitored with nuclear-magnetic-resonance probes. The basic calibration of plate-distance versus particle-trajectory radius for the spectrograph was performed with Po^{210} α particles. For each run, the spectrograph field measured with an NMR probe and the $O^{16}(d,p)O^{17}$

† Taken in part from the thesis submitted to The Florida State University by R. A. Harlan in April 1963, in partial fulfillment of the requirements for the Ph.D. Degree. Supported at The Florida State University under contract No. AT-(40-1)-2434 with the U. S. Atomic Energy Commission. The Florida State University Tandem Van de Graaff research program was supported by the U. S. Air Force Office of Scientific Research under contract No. AFOSR-62-423, and by the Nuclear Program of the State of Florida.
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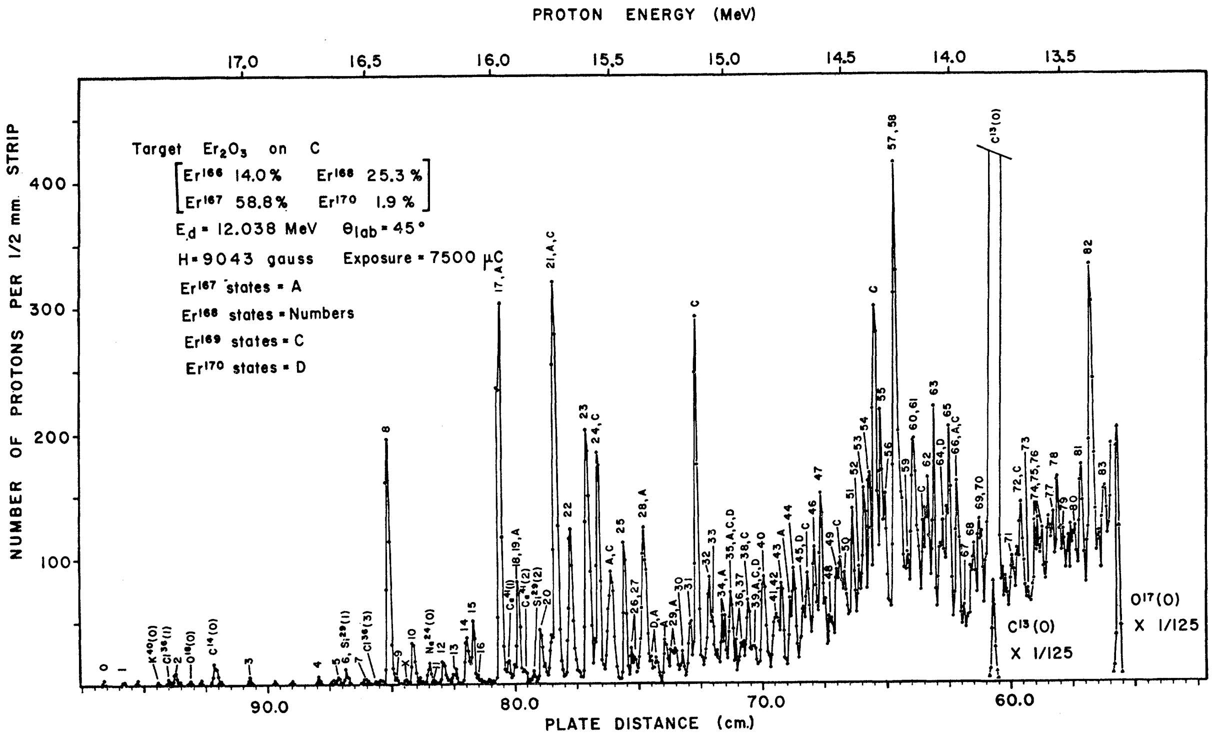

FIG. 1. Protons observed from the reaction $Er^{167}(d,p)Er^{168}$. Energy levels in Er^{168} are labeled consecutively, with the ground state labeled 0. Proton groups due to isotopic Er impurities are labeled A (Er^{167} states), C (Er^{169} states), and D (Er^{171} states). Extremely weak and uncertain proton groups are not numbered. (See text.)

ground-state proton group were used to calculate Q values for the Er groups. In these experiments the $C^{13}(d,p)C^{14}$ ground-state proton group, being well removed from the $O^{16}(d,p)O^{17}$ ground-state group, furnished a convenient second reference point to check the consistency of energy determinations. The Q values for these two reference groups were obtained from the mass compilation by König *et al.*[12]

The proton-energy spectrum observed at 45° is shown in Fig. 1. The energy levels deduced from all the runs are listed in Table I.

It should be noted that the relatively large amount of other Er isotopic impurities created a severe problem in analyzing the proton spectra in the region of higher excited states. This was reflected in the fact that energy reproducibility for the higher excited states between different runs was less than that for the 1094-keV state (group 8), and for other groups on the plates above the beginning of intense odd-mass Er groups. The first strong $Er^{166}(d,p)Er^{167}$ group[13] occurs on the plates at a position corresponding to a Q value of 4001 keV, unresolved from Er^{168} group number 17. On the basis of the consistency observed in these experiments and general knowledge of the effect of impurities in determining level energies, we believe that our excitation energies are usually accurate to ± 3 keV.

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The $Er^{167}(d,p)Er^{168}$ ground-state Q value was determined to be 5541 ± 6 keV using the Q value (4447 ± 6 keV) of the strong proton group numbered "8" in Fig. 1 and the known excitation energy (1094.05 ± 0.03 keV)[10] of the corresponding Er^{168} state. The $C^{13}(d,p)C^{14}$ ground-state group lies within 1.5 cm of group 8 at 60° and 65°. Because of this proximity, the error in determining the group-8 Q value is small, consisting of approximately ± 2 keV in the position determined for group 8 and of ± 4 keV in the position determined for the smaller C^{14} ground-state proton group. The value 5541 ± 6 keV seems preferable to the ground-state Q value of 5538 ± 12 keV directly determined from data for the group labeled "0" in Fig. 1. The few counts contained in group 0 prevent as accurate a determination of its position as is possible with the many counts in group 8.

It is valuable for interpretation of the levels to determine absolute differential cross sections for populating the lower excited states in Er^{168} via the (d,p) reaction. For this purpose, it is also necessary to know the contributions of isotopic Er-impurity groups, whenever they are unresolved from $Er^{167}(d,p)Er^{168}$ groups. To accomplish these objectives, runs at 45° leading to levels in Er^{168}, Er^{169}, and Er^{171} were normalized to an $Er^{166}(d,p)Er^{167}$ run at 45° made on a thin, very uniform target of enriched Er^{166}. The amount of erbium in this target was estimated by scattering 4-MeV deuterons from it, and assuming that the intensity of the elastically

TABLE I. Energy levels in Er^{168} This table presents the mean Q value determined from the reaction $Er^{167}(d,p)Er^{168}$ at 45°, 60°, and 65°. It is estimated (see text) that the energy levels in Er^{158} which are deduced are generally accurate to ±3 keV.

Level No.	Q value (keV)	Energy level (keV)	Comments, other isotopes contributing
0	5538	3±3	Ground state of Er^{168}; because of weak population, the ground-state Q value was determined using group No. 8 as 5541±6 keV (see text).
1	5462	79	
2	5277	264	
3	4991	550	
4	4718	823	
5	4642	899	
6	4608	933	Si impurity affects energy determination
7	4543	998	
8	4447	1094	First strong proton group
9	4431	≈1110	Weak state, unresolved, energy uncertain
10	4348	1193	
11	4276	≈1265	Very weak, energy uncertain
12	4229	1312	
13	4184	1357	
14	4148	1393	
15	4114	1427	
16	4089	1452	Very weak; energy uncertain
17	3999	1542	Second strong proton group
18	3936	1605	See high-energy side of level 19
19	3926	1615	
20	3832	1709	
21	(3773)	(1768)	Probably entirely Er^{167} and Er^{169} isotopic impurity
22	3715	1826	
23	3644	1897	
24	3597	1944	93% Er^{169} impurity
25	3489	2052	
26	3452	2089	Light impurities possible; therefore level not certain
27	3439	2102	Light impurities possible; therefore level not certain
28	3405	2136	
29	3286	2255	
30	3242	2299	
31	3206	2335	
32	3111	2430	
33	3095	2446	
34	3063	2478	$Er^{167,169}$ levels contribute ~80%
35	3035	2506	Observed similar Q all Er but 168 present
36	3004	2537	
37	2988	2553	Small Er^{167}
38	2957	2584	Er^{167}
39	2927	2614	Observed similar Q all Er; therefore doubtful
40	2890	2651	
41	2843	2698	
42	2825	2716	Er^{167}
43	2806	2735	
44	2755	2786	
45	2715	2826	Er^{171}
46	2662	2879	Er^{167}
47	2632	2909	Er^{169}
48	2592	2949	
49	2565	2976	
50	2525	3016	Er^{167}
51	2491	3050	Er^{167}
52	2461	3080	Er^{167}
53	2439	3102	
54	2414	3127	
55	2363	3178	Er^{169}
56	2345	3196	
57	2299	3242	Large Er^{169}
58	2265	3276	
59	2246	3295	
60	2221	3320	
61	2207	3334	
62	2156	3385	
63	2124	3417	Er^{169}
64	2084	3457	Large Er^{169} and Er^{171}
65	2052	3489	Large Er^{171}
66	2025	3516	*Note:* No particular effort made after this point to separate the 168 intensity from other Er isotopes because of high level density
67	1988	3553	
68	1956	3585	
69	1926	3615	
70	1911	3630	
71	1770	3771	
72	1728	3813	
73	1702	3839	
74	1668	3873	
75	1649	3892	
76	1602	3939	
77	1577	3964	
78	1551	3990	
79	1507	4034	
80	1477	4064	
81	1449	4092	
82	1405	4136	
83	1343	4198	

scattered deuterons could be calculated from the Rutherford scattering law. The isotopic analyses furnished by the Stable Isotopes Division of Oak Ridge National Laboratory were assumed to be correct, and the internal standard used for normalization was proton group 8 in Fig. 1, which also appeared on the plates of runs to odd-mass Er levels. Absolute cross sections were calculated for all Er isotopes investigated using the normalization and target thickness data. Although *relative* errors in cross sections obtained by the normalization were determined mainly by statistical considerations and may be as large as ±15% in unfavorable cases, the absolute cross sections determined are assigned an error of ±60%, because an unfortunate 40% discrepancy was discovered in the beam-integrating circuit between the time the runs were made and the time target thicknesses were measured. Odd-mass Er levels will be the subject of a subsequent publication.[13] The cross sections determined for $Er^{167}(d,p)Er^{168}$ at 45° are given in Table II.

III. DISCUSSION

The analysis of the proton spectrum from the reaction $Er^{167}(d,p)Er^{168}$ clearly indicates the existence of the ground-state, γ vibrational, $K\pi=4-$ and $K\pi=3-$ rotational bands, which are presented together with their assignments and energies in Fig. 2. We will discuss first

TABLE II. Differential cross sections for the reaction $Er^{167}(d,p)Er^{168}$ populating the lower-lying states in Er^{168}. States are classified in rotational bands.

Rotational band	Level No.	Spin parity	Energy (keV)	Experimental differential cross section in μb/sr at 45°	Calculated differential cross section using theoretical values for $d\sigma_J/d\Omega$[a]
Ground-state rotational band ($K=0$)	0	0+	3±3	1.5	0.01
	1	2+	79	1.2	1.3
	2	4+	264	~2.5[b]	2.1
	3	6+	550	2.1	1.4
	6	8+	933	~1.0[b]	0.3
	14	10+	(1393)	31[c]	0.008
γ vibrational band ($K=2$)	4	2+	823	2.1	≈0.7[e]
	5	3+	899	2.8	≈0.9[e]
	7	4+	998	1.6	≈0.8[e]
	9	5+	~1110	1.1	≈0.5[e]
	11	6+	1265	~0.7[c]	≈0.02[e]
$K=4-$ band [633↑+521↓]	8	4−	1094	140	144
	10	5−	1193	23	28
	12	6−	1312	13.9	15.4
	16	7−	1452	~3.0	4.0
	18	8−	(1605)	~1.1	0.4
$K=3-$ band [633↑−521↓]	17	3−	1542	157	123
	19	4−	1615	53	40
	20	5−	1709	28	19
	22	6−	1826	62[d]	8.2
	24	7−	~1944	(*d*)	1.8
$K=1-$? [633↑−512↑]	13	1−	1357	7.3	9.5
	14	2−	1393	31[c]	27
	15	3−	1427	27.3	35

[a] U^2 values are assumed to be 0.4 for the [633↑] orbital and to be 0.7 for the [521↓] and [512↑] orbitals, in obtaining the theoretical cross sections.
[b] Possible light impurity interferes in the differential cross section at 45°. The cross section is estimated from data at 60° or 65°, assuming little or no angular dependence. These are to be regarded as "order-of-magnitude" estimates.
[c] The same proton group has been used elsewhere in the interpretation.
[d] Large impurity masks cross section.
[e] Approximate calculation. See the text.

the energy systematics of these bands and second the cross sections for their population.

A. Energy Systematics in Er^{168}

The ground-state rotational band in Er^{168} has been previously observed.[3–6,8,10] The energies of the levels below 1312 keV excited in this experiment agree within our experimental error with those previously reported, with two exceptions. One case, group 6 reported herein at 933 keV, is within 5 keV of the 8+ rotational state reported by Koch[10] at 928 keV. The other exception is group 9, whose excitation energy determined here is 7 keV lower than that of Koch.[10] Both of these proton groups are weak. The first is influenced at 45° by a Si^{28} impurity and the second is located in the tail of the strong group 8. Agreement with previously determined levels, up to an excitation energy of 1709 keV, is within our reported errors of ±3 keV, whenever a group observed in this work can be identified as a previously determined level.[10]

Thus, states at 79, 264, 550, and 933 keV are interpreted as the 2+, 4+, 6+, and 8+ members of the ground-state rotational band, respectively.

The γ vibrational band has also been previously observed.[3–6,8,10] The energy differences of the proton groups numbered 4, 5, and 7 (see Table I) agree well with what is expected for a $K=2$ band. The excitation energies determined for the extremely weak states at ≈1110 and 1265 keV are, of course, less precise than those for more intense groups. Therefore, these data corroborate previous experimental results and suggest that the states at 823, 899, 998, ≈1110, and ≈1265 keV are the 2+, 3+, 4+, 5+, and 6+ members, respectively, of the γ vibrational band.

No clear evidence is found for any $K=0$ states other than the ground state. Several very weak and uncertain proton groups have not been labeled in Fig. 1, but have been observed in several runs. In some cases they are not observed at all angles, in others they lie under or near known impurities. Somewhat uncertain excitation energies which can be derived from the energies of these proton groups, if it is assumed that they are Er^{168} states, are ≈1124, 1163, 1218, 1291, 1385, 1508, and 1694 keV. Because of the uncertainty in experimental assignment, some of these states are almost certainly nonexistent. They are mentioned because they lie very close to the region in which Soloviev[14] has predicted a $K=0+$ band. A preliminary attempt at band assignment leads to at least two different possible interpretations. Therefore, both because of the ambiguity in band assignment and the uncertainty about their existence, we leave their evaluation to future experiments.

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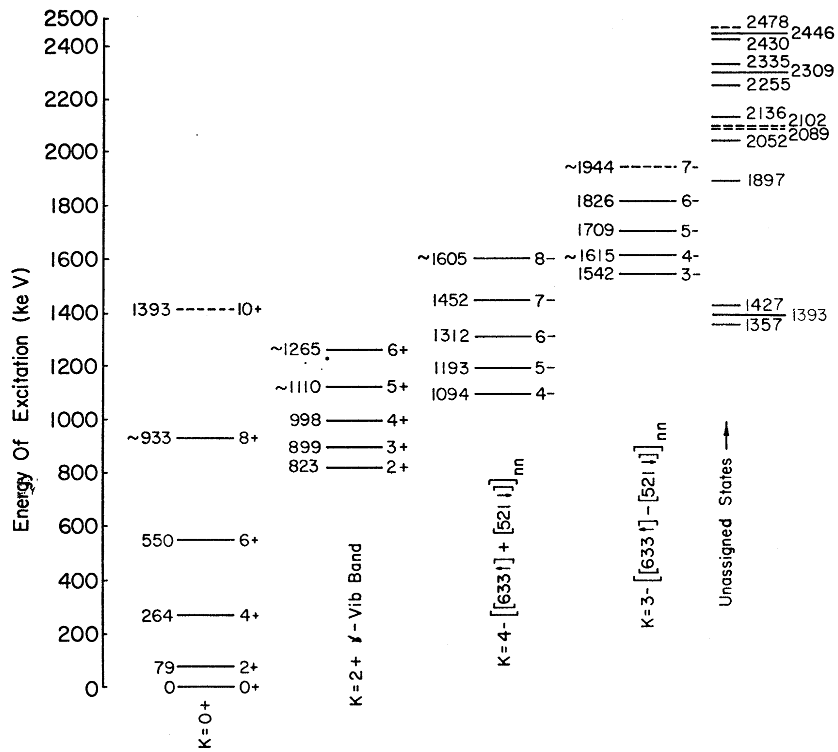

FIG. 2. Energy levels in Er^{168} as deduced from the energies and cross sections of the reaction $Er^{167}(d,p)Er^{168}$. Those states which are unassigned are indicated at the right of Fig. 1. It should be noted that the states at 1357, 1393, and 1427 may constitute a $K=1-$ band (see text). The 1393-keV 10+ state and the 1605-keV 8− state are shown dashed because the identity (in the former case) and the existence (in the latter case) of the proton groups must be questioned.

The lowest-lying, two-quasiparticle neutron states are expected to have the configuration $[633\uparrow\pm521\downarrow]$ with $K\pi=4-$ and $3-$, because the ground state of all known 99-neutron nuclides is found to be $\frac{7}{2}+[633\uparrow]$ and the lowest-lying excited state is the particle excitation $\frac{1}{2}-[521\downarrow]$. In Er^{167}, for example, the $\frac{1}{2}-[521\downarrow]$ state lies 207.8 keV above the ground state, whereas in Dy^{165} it lies 108 keV above the ground state.[15] According to the Gallagher-Soloviev rules,[7] one expects that, of these two, the $K=4-$ band will be the lowest lying. Indeed, as suggested by Koch,[10] we believe the strong proton group at 1094 keV represents the $I=4$ band head of the $K\pi=4-$ band. We find states at 1193, 1312, 1452, and ≈1605 keV with spin and parities 5−, 6−, 7−, and 8−, respectively, (in excellent agreement with the more precise energies of Koch[10]). The intense proton group at 1542 keV is believed to be the band head of the $K\pi=3-$ band. Additional states at ≈1615, 1709, 1826, and ≈1944 keV are interpreted as the 4−, 5−, 6−, and 7− members of this band.

This interpretation accounts for all the states below 1894 keV observed in the $Er^{167}(d,p)$ reaction, with the exception of the states at 1357, 1393, and 1427 keV. The predicted position for the 10+ member of the ground-state band is ≈1399 keV, using the rotational-energy parameters determined by Koch.[10] However, the observed intensity of the 1393-keV peak is ≈4000 times greater than that expected for this 10+ rotational state. Perhaps even more significant is the fact that this intensity is much greater than that expected theoretically for the sum of the cross sections for excitation of all members of the ground-state rotational band (see Table II). Consequently, we believe the largest contribution to the intensity of this peak must arise from a different configuration, and the contribution to this peak from the 10+ state can be a few percent at most. For this reason the 10+ state is indicated in Fig. 2 as a dashed line.

The cross section for the ground-state proton group is also much larger than expected theoretically. Although we have no easy explanation for this fact, the ground-state group does have a cross section comparable to other members of the ground-state band.

On a very tentative basis, we suggest that the states at 1357, 1393, and 1427 keV might be interpreted in terms of a band from the configuration $[633\uparrow-512\uparrow]_{K\pi=1-}$. The sequence of levels in this interpretation would be the 1− state at 1357 keV, a 2− state at 1393 keV, and a 3− state at 1427 keV. It is obvious that the energies of the states in this tentative 1− band do not follow the simple rotational-energy systematics. On the other hand, a similar situation has been found[16] in Gd^{158}. In both of these instances, it appears that the mixing of a $K\pi=0-$ collective octupole band into the intrinsic state may distort the energy systematics. In any case,

[15] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.).

[16] W. N. Shelton and R. K. Sheline (to be published).

however, this interpretation must be considered to be highly tentative.

B. Differential Cross Sections for the Reaction $Er^{167}(d,p)Er^{168}$

Systematic analysis of the differential cross section of the (d,p) reaction leading to even-even deformed nuclei is underway in this laboratory.[17] We have used the results from the analysis[17] in interpreting some cross sections in this paper. The differential cross section for populating the ground and the two-quasiparticle states in an even-even nucleus is given[18,19] by the following equation:

$$\frac{d\sigma}{d\Omega}(a, I_i, K_i=\Omega_a \to ab, I_f, K_f=|\Omega_a\pm\Omega_b|) = \tfrac{1}{2}g \sum_j \frac{d\sigma_j}{d\Omega}(0\to b, j, K=\Omega_b) \times \langle j, \pm\Omega_b, I_i, \Omega_a | I_f, \Omega_a\pm\Omega_b\rangle^2, \quad (1)$$

with

$$g = 2V^2{}_b/U^2{}_b \text{ for the ground state } (a=b),$$
$$=1 \text{ for the two-quasiparticle state } (a\neq b),$$

where a and ab denote the quasiparticle configuration in the initial and final states, while U^2 and V^2 are usual occupation probabilities.[1]

The quantity $d\sigma_j/d\Omega$ in Eq. (1) is given in terms of the distorted-wave Born approximation (DWBA) cross section ϕ_l and the Nilsson amplitude C_{jl}, as

$$\frac{d\sigma_j}{d\Omega}(0\to b, j, K=\Omega_b) = 2U^2{}_b C^2{}_{jl}\phi_l, \quad (2)$$

which is the (d,p) cross section from even to odd nuclei. It can be obtained either theoretically or from experimental measurement on the appropriate odd-A nucleus. Values of $d\sigma_j/d\Omega$ given in the last column of Table II are theoretical values, as opposed to empirically determined values. The experimentally measured cross sections for the excitation of members of the ground-state rotational band are so small that it may be difficult to draw significant conclusions. There does seem to be some tendency both experimentally and theoretically that the 4+ and 6+ members of this band are more strongly populated than the remaining levels of this band.

The tentative assignment of proton groups 13, 14, and 15 as the 1−, 2−, and 3− members of the configuration, $[633\uparrow - 512\uparrow]_{K=1}$, can also be checked by comparing the theoretical and experimental cross sections. This is done in Table II. However, since only three proposed members of the band are observed and mixing with the octupole band has been postulated, the satisfactory agreement between experiment and theory cannot be taken as strong evidence for this tentative assignment.

In populating the γ vibrational band, the reaction should proceed mainly through those admixtures of two-quasiparticle states which have the $[633\uparrow]$ orbital as one of the two orbitals. Based on relative values of the $U^2{}_bC^2{}_{jl}$ and the calculated amplitudes[17] of the various two-quasiparticle configurations, this band should be populated primarily through the $[633\uparrow - 631\uparrow]_{K=2}$ configuration. We have made a simplified estimate of the differential cross section for exciting the various members of the γ vibrational band by multiplying the square of the forward amplitude[17] of the $[633\uparrow - 631\uparrow]$ configuration times the cross sections estimated for exciting the pure $[633\uparrow - 631\uparrow]$ band. The results of this calculation, given in Table II, show excellent agreement with experiment in relative intensities, but absolute values predicted are considerably smaller than experimental values. More detailed calculations[17] of (d,p) cross sections for populating γ vibrational bands in Er^{168} and several other even-even deformed nuclei have been carried out by Kern *et al.*[17]

The agreement between both the $K=4-$ and $K=3-$ experimental and calculated differential cross sections is very gratifying. This seems to indicate that the "fingerprint" method, which has worked so successfully in the interpretation of quasiparticle states in odd-A and odd-odd nuclei, will also be useful in interpreting two-quasiparticle states in even-even nuclei.

ACKNOWLEDGMENTS

The authors wish to thank Dr. H. R. Koch and the Risø Laboratory for communicating their data to us prior to publication. We wish especially to thank Dr. Takeshi Udagawa for his aid in preparing this manuscript and Dr. C. W. Reich for critically reading and commenting on it. We are also grateful to Dr. R. A. Kenefick, Dr. W. N. Shelton, Dr. C. W. Watson, Dr. C. L. Nealy, R. T. Jernigan, the plate scanners and the supporting personnel of the FSU tandem Van de Graaff for helpful discussions and/or material aid in operating the accelerator and reducing the data.

One of us, (R.H.) wishes to acknowledge the Tennessee-Eastman Company for a fellowship during the experimental part of this work and some support given the reanalysis of a part of these data under U. S. Atomic Energy Commission Contract No. AT-(40-1)-3235 at the University of Arkansas.

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