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Levels in ^{168}Er above 2 MeV and the onset of chaos

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Extremely high statistics γ-γ coincidence data for ^{168}Er have been recorded following thermal neutron capture on ^{167}Er. The results alter considerably recent experimental and theoretical work on ^{168}Er and affect conclusions concerning the quality of the K quantum number in the neutron resonance region: earlier claims that K remains good and that this energy region is nonchaotic are shown to be based in part on band assignments that need to be seriously reexamined.

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I. INTRODUCTION

In 1981, a detailed level scheme for ^{168}Er, based on (n,γ) data was published [1]. The "completeness " features of this reaction led to a level scheme that was complete for negative-parity states up to about 2200 keV and for positive-parity states to about 2000 keV. It was thought prudent to halt the development of the ^{168}Er level scheme at about these energies due to the difficulties inherent in extending it into the next energy region and to the desire to preserve the completeness property. These results formed the basis for a number of successful tests [2–4] of the IBA model and the completeness of the scheme has made this nucleus a touchstone testing ground for subsequent experimental [5–8] and theoretical [9–13] work. Recently, Davidson and Dixon [14] have further analyzed the original 1981 data and added new data in order to propose a considerable extension of the level scheme along with rotational band assignments up to energies (well above the pairing gap) as high as nearly 2800 keV.

In principle, such a level scheme can be used to test concepts of chaos and the order-to-chaos transition with increasing nuclear temperature. Such a test was recently published [15] in which an analysis was made of the neutron capture data for primary transitions in ^{168}Er (and ^{178}Hf, see Ref. [16]). These data, including those transitions populating band members assigned in Ref. [14], were used to argue that there is a distinction in intensity for final states of low and higher K ($K = 0,1$ vs $K = 2-5$) and therefore to conclude that K remains a good quantum number in the neutron resonance energy region ($E_x \sim$ 7–8 MeV). This conclusion, which is contrary to the usual perception that this energy regime is chaotic at low spin and that the neutron capture levels are complex compound nuclear states, has aroused considerable interest.

For example, Ref. [17] contains a critique of the theoretical implications and the experimental analysis of the first article in Ref. [15]. The last two papers in Ref. [15] provide new details of the analysis, including the fact that the original analysis included not only the levels and band assignments of Ref. [1] but those of Ref. [14] as well. Since these additional band assignments add considerably to the statistical ensemble of states used to test the goodness of the K quantum number, it is critical to assess the reliability of these new assignments.

The assignment of levels by Ritz combinations in the region above the pairing gap is of course notoriously difficult. The number of accidental (and incorrect) energy combinations increases nearly an order of magnitude for every few hundred keV or less of added excitation energy. Partly this is due to the greatly increased number of levels; partly it is due to poorer energy resolution of deexciting transitions that are both rather high in energy (1–2 MeV, typically) and rather weak in intensity; partly it is due to lack of transition multipolarities (since internal conversion is so weak at higher energies) which can often be used at lower energies to spot incorrect Ritz combinations. In addition, the analysis and use of ARC data in this region of high excitation energy and high level density are risky since the ARC intensities are small (they decrease roughly as E_γ^5) and there will be many unresolved multiplets. Therefore, if one were to attempt to assign levels in this energy region, much stricter standards and criteria need to be imposed. Unfortunately, the lack of extensive data instead led the authors of Ref. [14] to actually relax the criteria for new levels.

Ultimately, though, the question of the validity of the band (and hence K) assignments of Ref. [14] should not be addressed in this indirect way but by direct experimental tests. Given the interest attached to these new assignments because of their implications for the chaos question, we have therefore carried out a new (n,γ) experiment at the BNL HFBR with the aim of achieving maximum statistics for γ-γ coincidences among higher-energy transitions.

More than 1.6×10^9 coincidence events were recorded. Our aim is *not at all* to achieve a complete level scheme at these higher energies. Indeed, our criteria for assigning new levels are so strict that it is virtually certain that additional levels exist in the same energy range. Rather, our purpose was to use the coincidence data to test some of the γ-ray placements of Ref. [14] and to see if the set of levels assigned there was in any way complete. This latter issue is important since patterns of rotational spacings were used in Ref. [14] to assign levels to rotational bands. If new levels, with similar spins, were now to be disclosed in the same energy range, the band assignments of Ref. [14] would need to be reexamined. In fact, this is exactly the result of our study: With the present data it was possible to discover 19 new levels between 2100 and 3000 keV and to assess a number of level and spin assignments proposed in Ref. [14]. The results, to be described below, cast doubt on, and reduce overall confidence in, the rotational band assignments in that work, and therefore in any analysis [15] of order and/or chaos based upon the assigned K values.

II. EXPERIMENTS AND DATA ANALYSIS

The experiments were carried out at the H1-B beamline of the High Flux Beam Reactor (HFBR), Brookhaven National Laboratory. A target of 559 mg Er_2O_3 powder, enriched to 91.54% in ^{167}Er, was exposed to a thermal neutron beam. The neutron capture γ radiation in the energy range from 100 keV to 2 MeV was detected with three Ge detectors which were placed about 9 cm from the sample at $\sim 55°$, 125°, and $-90°$, respectively, with respect to the neutron beam. The crystals were covered with lithium shields to prevent damage by neutrons and a bismuth shield was placed between the neighboring counters at 55° and 125° in order to reduce the number of random coincidences caused by scattered radiation. A graded absorber consisting of $\sim$ 5 mm lead and $\sim$ 3 mm copper was placed between target and detectors in order to considerably decrease the counting rate of low-energy γ rays and therefore, given a certain maximal counting rate, to increase the detection efficiency for higher energies. Altogether, as noted, $\sim 1.6 \times 10^9$ γ-γ coincidences were recorded, event by event, on magnetic tape.

To allow for energy and efficiency calibration via the reaction ^{35}Cl$(n,\gamma)^{36}$Cl, the Er_2O_3 target was replaced by 1 g of NaCl at the end of the coincidence experiment and, without further changes in the setup, ^{36}Cl singles spectra were recorded.

In the pair spectrometer measurement of the primary γ-ray spectrum in Ref. [1] the intensities were determined only in relative units. Since the knowledge of the absolute intensities of the primary transitions allows a check of the population-depopulation balance of proposed states, it can be of help in unmasking incorrect assignments. Therefore, we changed the amplification of the detector signals to cover the full energy range up to the neutron binding energy of ^{168}Er and recorded additional singles spectra using the same geometry as described above to determine the scaling factor between the relative units of

TABLE I. Comparison between the transitions observed in the coincidence spectra belonging to the *821 keV* state and the γ rays assigned in Ref. [14] to populate this state. Only transitions with an intensity $I > 3$ per 10 000 neutron captures are listed. The γ-ray energies and intensities are taken from Table 1 of the second entry of Ref. [14].

Energy (keV)	Intensity	Coincidences[a] (present work)	Ref. [14][b]
173.577	7.8		X
272.876	3.8		X
429.779	20.5	R	
455.096	5.2	C	X
457.664	58.9	R	
582.567	37	C	X
589.913	3.0		X
720.392	110	C	X
748.281	86	C	X
812.287	69	C	X
832.362	16	C	X
1006.912	11.7	C	X
1027.112	4.1		X
1094.43	12		X
1109.36	3.9		X
1151.192	6.6		X
1234.760	30	C	X
1259.270	12	C	X
1372.051	20	C	X
1409.148	13	C	X
1433.74	15	C	X
1441.41	19		M
1452.50	7	D#	
1481.71	10	C	X
1501.92	(18)[c]	C	X
1515.98	51	R, D	M
1524.18	14	C#	
1552.55	6	C#	
1572.41	4	C	X
1580.72	38	R#	
1604.09	5		X
1656.84	8	O	M
1658.76	7	O	
1663.21	5		X
1672.84	19	D#	
1696.30	9	C#	
1750.21	29	R, D	
1965.19	7	C#	

[a]The symbols used in this column have the following meaning: R, transition is observed with a somewhat reduced intensity in the coincidence gates; C, transition is observed in coincidence with the γ rays which depopulate the 821 keV state in the present work; D, transition is observed in more than one coincidence gate; #, the coincidences are used in the construction of the newly proposed states (see Table V); ( ), composite γ-ray intensity of unresolved doublet; O, it is not clear which γ ray of this multiplet is observed in the gate.

[b]The symbols used in this column have the following meaning: X, transition is assigned to populate the gated level (here the 821 keV state) in Ref. [14]; M, the γ ray has been assigned a double placement in the level scheme of Ref. [14].

[c]Composite γ-ray intensity of unresolved doublet.

Ref. [1] and an absolute scale. Since the neutron binding energy of ^{36}Cl (8.58 MeV) is higher than that of ^{168}Er (7.77 MeV), a calibration run using a NaCl target determined the detector efficiency over the entire energy range. The resulting absolute efficiency scale for ^{168}Er primary transitions is such that a relative intensity of 50(3) units (see Table 3 of Ref. [1]) corresponds to 1 primary transition per 10^4 neutron captures. This value is in excellent

TABLE II. Comparison between the transitions observed in the coincidence spectra belonging to the *896 keV* state and the γ rays assigned in Ref. [14] to populate this state, the 1094 keV 4^- and the 1193 keV 5^- levels. Note that γ rays feeding the 1094 and 1193 keV states should be found with reduced intensities in the 896 keV gate (see text). Only transitions with an intensity $I > 3$ per 10 000 neutron captures are listed. The γ-ray energies and intensities are taken from Table 1 of the second entry of Ref. [14]. The same notation as in Table I is used.

Energy (keV)	Intensity	Coincidences (present work)	Ref. [14] 896 keV	Ref. [14] 1094 keV	Ref. [14] 1193 keV
198.241	2240	*C*	*X*		
221.775	21.3		*X*		
422.318	116	*R*			*X*
447.515	223	*R*		*X*	
457.664	58.9	*R*			
474.04	20.1	*R*			
507.936	3.7		*X*		
527.884	64.4	*R*			
543.667	135	*R*			*X*
559.510	158	*R*		*X*	
645.775	35	*C*	*X*		
645.939	24	*C*	*X*		
673.666	38	*C*	*X*		
679.180	30	*R*		*X*	
719.550	78	*C*	*X*		
737.686	82	*C*	*X*		
790.001	53	*R*			*X*
798.89	160	*R*		*X*	
811.043	115	*R*		*X*	
823.386	85	*C*	*X*		
840.890	28	*R*	*X*		
932.269	51	*C*	*X*		
952.611	7.8		*X*		
965.937	65	*R*		*X*	
997.245	4.2		*X*		
1019.568	5.3		*X*		
1034.488	4.6		*X*		
1076.524	19	*C*	*X*		
1106.650	7		*X*		
1144.112	59	*R*		*X*	
1160.077	14	*C*	*X*		
1173.557	47	*R*		*X*	
1201.757	26	*C*	*X*		
1273.738	15	*C*	*X*		
1292.657	10.6	*C*	*X*		
1297.320	7.7	*C*	*X*		
1358.904	29	$C^{\#}$			
1366.914	23	*C*	*X*		
1383.36	5.0	*C*		*X*	
1406.93	7.0		*X*		
1427.40	4		*X*		
1440.41	10	*C*	*X*		
1441.41	19	*C*	*M*		
1449.26	7	$C^{\#}$			
1452.50	7	D	*X*		
1477.38	8	*C*			
1486.78	15	$C^{\#}$			
1496.76	5.0	*C*	*X*		
1497.94	5		*X*		
1501.92	(18)	*C*			
1502.73	(18)	$C^{\#}$			
1506.49	22	*C*	*X*		
1515.98	51	*R*, *D*	*M*		
1529.67	3		*X*		
1560.16	22	$C^{\#}$			
1582.95	9		*X*		
1588.75	4		*X*		
1617.75	11	*C*			
1651.49	7		*M*		
1656.84	8	*C*			
1665.74	8		*X*		
1672.84	19	*R*, *D*			
1675.49	20.0	*R*		*X*	
1750.21	29	*R*, *D*			
1762.19	13	O			
1763.41	(10)	O			
1765.02	(10)	*C*			
1890.93	4	$C^{\#}$			

agreement with 44(11) estimated under the simple assumption that the intensity sum of all known primary γ rays [1] is the same as the intensity sum of all known ground-state transitions. This latter value is somewhat smaller because only those primary transitions above a certain detection threshold were taken into account.

In an off-line analysis the event-mode data were first corrected for gain shifts and then sorted into three coincidence matrices, one for each detector pair. Only prompt events within a certain time window were used and events within a delayed time window of the same width were subtracted in order to correct for time-uncorrelated random coincidences. Because the three detectors had slightly different energy resolutions the different matrices were not summed up but treated separately. Coincidence spectra were generated from these matrices by setting gates on peaks and neighboring background regions and subtracting the latter spectrum from the former. After proper normalization to the same energy calibration the three spectra deduced from the three detector pairs were summed. Due to the use of absorbers (see above) it was not possible to create coincidence spectra for the low-energy transitions within the ground-state band (79.8, 184.3, and 284.7 keV). All further discussions in this paper are therefore based on the information obtained from the coincidence gates on strong transitions from the decay of the gamma band. For the 821.2 keV 2^+_γ state coincidence spectra for the two strongest decay branches (821.2 and 741.4 keV) were added and this summed spectrum will be referred to in the remainder of the paper as

TABLE III. Comparison between the transitions observed in the coincidence spectra belonging to the *995 keV* state and the γ rays assigned in Ref. [14] to populate this state. Only transitions with an intensity $I > 3$ per 10 000 neutron captures are listed. The γ-ray energies and intensities are taken from Table 1 of the second entry of Ref. [14]. The same notation as in Table I is used.

Energy (keV)	Intensity	Coincidences (present work)	Ref. [14]
99.289	155		*X*
269.161	23.9		*X*
416.352	13.1	*C*	*X*
546.802	22.7	*C*	*X*
546.96	39.8	*C*	*X*
620.590	3.9		*X*
622.059	3.1		*X*
638.710	55	*C*	*X*
713.257	43.6	*C*	*X*
724.432	32.8	*C*	*X*
825.729	60	*C*	*X*
833.294	32	*C*	*X*
844.614	6.6	*C*	*X*
920.783	14.5	*C*	*X*
1007.571	7.5		*X*
1036.38	3.4		*X*
1061.128	6.9	*C*	*X*
1102.805	6.1		*X*
1174.557	7.6	*C*	*X*
1194.08	4.6	$C^\#$	
1260.09	25	*R*	*X*
1267.83	10	*C*	*X*
1328.57	3.7	*C*	*X*
1341.58	11	*C*	*X*
1353.784	43	*R*	
1398.046	12	*C*	*X*
1407.67	7	*C*	*X*
1417.053	15	*C*	
1445.26	4	$C^\#$	
1456.15	7	*C*	*X*
1461.13	8	$C^\#$	
1484.46	17	$C^\#$	
1491.17	6	*C*	
1518.95	9		*X*
1532.18	3		*X*
1534.05	21	$C^\#$	
1552.55	6		*X*
1556.84	27	$R^\#$	
1563.85	15	$C^\#$	
1665.74	8	$C^\#$	
1745.58	7	*C*	
1975.08	9	$C^\#$	

TABLE IV. Comparison between the transitions observed in the coincidence spectra belonging to the *1118 keV* state and the γ rays assigned in Ref. [14] to populate this state. Only transitions with an intensity $I > 3$ per 10 000 neutron captures are listed. The γ-ray energies and intensities are taken from Table 1 of the second entry of Ref. [14]. The same notation as in Table I is used.

Energy (keV)	Intensity	Coincidences (present work)	Ref. [14]
193.888	3.3		*X*
284.655	1010	*C*	
315.383	11.8		*X*
497.768	19.1	*C*	*X*
499.233	6.7		*X*
601.603	57	*C*	*X*
643.181	11.4	*C*	*X*
702.576	8.6	*C*	*X*
702.914	12.8	*C*	*X*
832.049	20	*C*	*X*
973.695	3.8		*X*
979.996	30	*C*	*X*
991.388	8.8		*X*
1051.860	4.1		*X*
1180.868	13	*C*	
1185.480	16.4		*X*
1218.677	7.0		*M*
1231.042	4.0	*C*	*X*
1275.316	18.0	*C*	*X*
1281.034	10	$C^\#$	
1294.05	21.0	*R*, *D*	*X*
1333.44	9.8		*M*
1396.125	11.0	*C*	*X*
1422.582	4	*C*	
1440.41	10	*O*	
1441.41	19	*O*	
1444.06	4.0		*X*
1542.94	6	$C^\#$	
1575.11	5	*C*	
1787.60	8	*C*	

the "821 keV gate." In the same way, gates on the 816.0 and 631.7 keV lines were summed up for the "896 keV gate" (3^+_γ state), gates on the 914.9 and 730.7 keV transitions for the "995 keV gate" (4^+_γ state), and the sum of the 853.5 and 568.8 keV gates form the "1118 keV gate" (5^+_γ state). All transitions observed in these four coincidence spectra are summarized in the first columns of Tables I–IV, respectively. Figures 1 and 2 present two different energy regions of these coincidence spectra. Whereas the γ rays belonging to the lines below 1 MeV visible in Fig. 1 depopulate well-established states below 2.1 MeV excitation energy, the γ rays corresponding to the peaks in Fig. 2 connect higher-lying states which will be discussed in detail below with the γ band.

A special situation occurs for the lowest-lying negative-parity state, i.e., the 4^- bandhead at 1094.0 keV. This isomeric state has a half-life of $T_{1/2} = 112$ ns and decays predominantly via a 198.2 keV γ ray to the 895.8 keV 3^+_γ state. Whereas this γ ray is again too low in energy to be detected with sufficient statistics, the strongest transitions populating the 1094.0 keV level are observed with a somewhat reduced intensity in the 896 keV gate. Taking into account the width of the time window used in the sort of the raw data and the branching of the decay of the 1094 keV state, the reduction factor in the coincidence intensities can be estimated from the half-life to be roughly five, in agreement with the experimental data (compare Fig. 1). In the same way the strongest transitions populating the 1193.0 keV 5^- state are seen in the 896 keV gate since the 5^- level decays to the 1094.0 keV state mentioned above. In this case the observed intensity is further reduced because the branching ratio for the decay of the 1193 keV level to the 1094 keV state is only 60%.

Before presenting our results we will briefly comment on the assumption that the high-energy γ rays observed in the four coincidence gates (see Tables I–IV) populate *directly* the 821, 896, 995, and 1118 keV states, respectively. *A priori*, they could as well feed the γ band via one or more intermediate states. However, in that case only a part of their intensity, determined by the branching of the intermediate state, would be observed. This would lead to an intensity reduction by typically a factor of at least 3 or 4. Since the intensities of the observed high-energy transitions (known from Ref. [14]) are small,

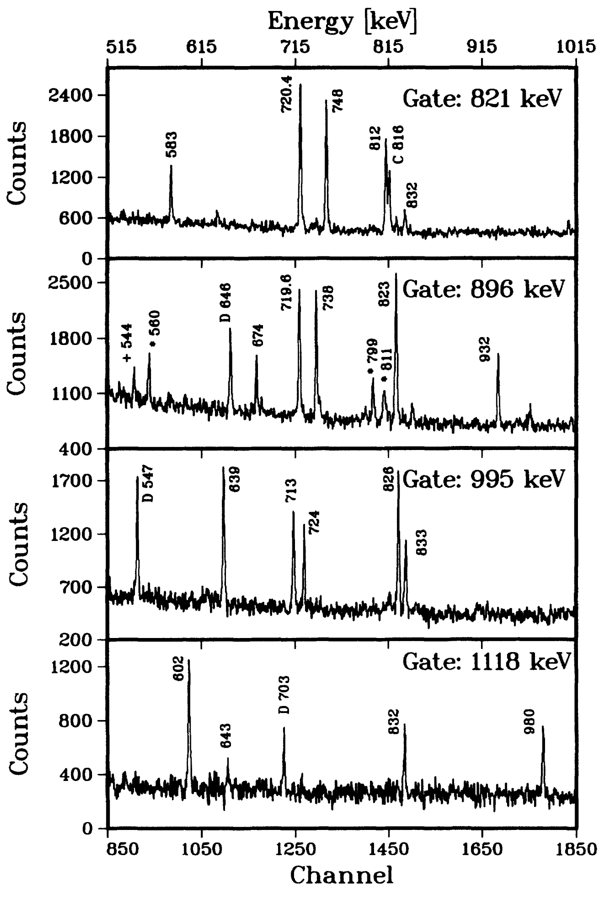

FIG. 1. Low-energy portion of the 821, 896, 995, and 1118 keV coincidence gates. The labeled transitions connect the γ band to well-established states in ^{168}Er below 2.1 MeV. Lines known to be doublets from the crystal spectrometer measurements [14] are marked by a "*D*." In the 896 keV gate the transitions feeding the 896 keV state via the 1094 keV 4^- bandhead are marked by an asterisk and the one populating the 1193 keV 5^- state by a "plus" (see text for further explanation).

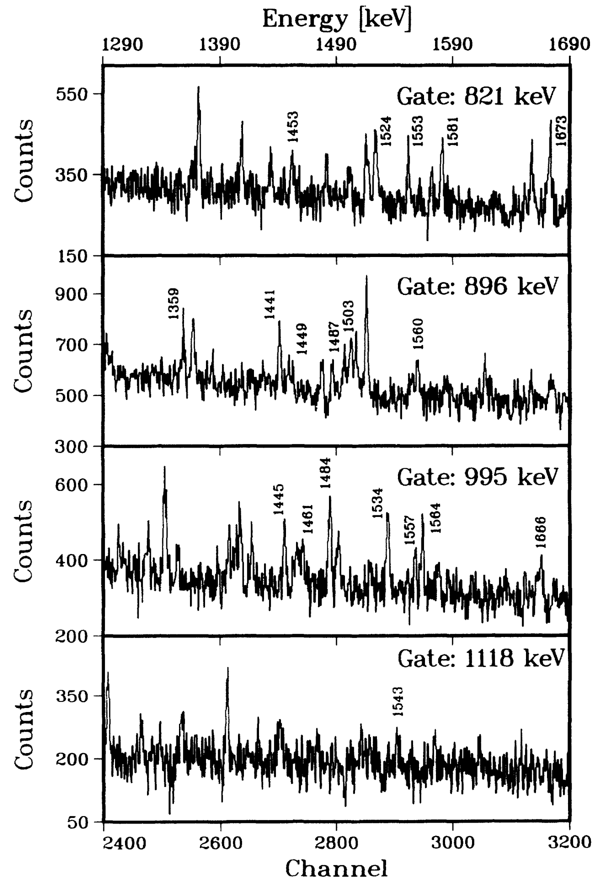

FIG. 2. High-energy portion of the 821, 896, 995, and 1118 keV coincidence gates. The labeled transitions are used in the construction of the newly proposed states above 2.1 MeV excitation energy (compare Table V).

a reduction by such a factor would barely allow these lines to be observed in our spectra. Due to the high level density and therefore strong fragmentation of the γ flux at higher excitation energies, it is generally more reasonable to place a transition as low in the excitation scheme as possible. Moreover, most of the new levels to be discussed below are supported by known primary feeding in addition to the coincidences. Of course, in a few exceptional cases with favorable branching, this argument is no longer valid. Therefore, we *cannot* exclude that one or two of the placements based on the coincidence data are incorrect. However, for the purpose of this paper, this is not important. The reason is that we are neither aiming for completeness (indeed, one of our main claims is that this is impossible with current techniques in this excitation energy region) nor attempting to assign new rotational bands. We are only aiming to test whether the earlier extension of the band assignments in Ref. [14] is reliable. One test of this is if new levels are found in the same excitation energy range as in Ref. [14] since this would impact the assignment of *any* levels in this region to rotational bands. Whether we find 17 or 19 new states therefore has no significance to the basic argument.

III. RESULTS

Of course, these new coincidence data are only useful *in combination with* and *as a complement to* the existing crystal and pair spectrometer data from previous neutron capture work. Whereas the high-energy resolution and the extremely large dynamical intensity range (5 orders of magnitude) of the crystal spectrometer data are indispensable for the successful application of the energy combination method, only the observation of coincident transitions allows a *definite* level assignment, especially at high excitation energy (high level density) where the probability of incorrect energy combinations increases rapidly. On the basis of the γ-ray energies and intensities summarized in Table 1 of the second entry of Ref. [14], energies and intensities for the primary transitions from Table 3 of Ref. [1], multipolarities and conversion coefficients from Table 2 of the second entry of Ref. [14], and the transitions observed in the coincidence spectra and summarized in Tables I–IV, we will discuss below the possible existence of states not previously proposed as well as comment on some others already suggested in Ref. [14].

A. Discussion of proposed new states

In the following section evidence for the existence of new states at excitation energies above 2 MeV will be presented. It is important to stress the strict criteria used: only states whose decay involves at least one of the observed coincidence cascades are considered as possible candidates. New levels are *not* proposed solely from Ritz combinations. However, further support for these new levels is given by Ritz combinations of additional populating or depopulating secondary γ rays and in many cases by known primary feeding (pair spectrometer data from Ref. [1]). The feeding and decay properties of these states are summarized in Table V. A "*C*" in the last column indicates that the placement of the transition is confirmed by the coincidence data. In assembling the evidence for new states we do *not* use any transitions which can be placed more than once in the deexcitation scheme of ^{168}Er as evidence for the new states, so that the discussion is restricted to unequivocal arguments. Note that, in some cases, the coincidence data show a different placement for a previously placed transition. We therefore use such new placements although it is not ruled out that the singles line could be a doublet and the earlier placement may also be correct. Examples of such doublets occur for the states at 2254.7 and 2273.6 keV (see below). It should also be mentioned that most of the γ rays populating or depopulating the newly proposed states were *not* placed by Davidson and Dixon in their extended decay scheme [14]. Exceptional cases where they place a transition elsewhere in the level scheme, marked by an asterisk in column (a) of Table V, will be discussed individually. The new levels will be discussed in order of increasing excitation energy. Note that in the following new states are denoted by italics.

2188.6 keV: A 1194.1 keV γ ray is observed in coincidence with the transitions depopulating the 995 keV 4^+ member of the γ band defining a state at *2188.6 keV*. A second transition from this level to the first 2^+ state restricts the possible spin values to 2^+, 3^+, 4^+, and 3^-. The placement of the $M1$ 349.2 keV γ ray feeding a 5^+ state would finally lead to a unique spin assignment of $I^\pi=4^+$. However, since this transition had been placed in [14] depopulating the single $K=7_1^-$ bandhead at 2122.4 keV (which is, however, only defined by two very weak decay branches) we do not use it to deduce a unique spin assignment for the new 2188.6 keV level. A 471.9 keV transition connects the 2188.6 keV state to another new level at 2660.4 keV which will be discussed below. Note that this 2188.6 keV state is not identical with the 2188.4 keV 5^+ ($K=2_3^+$) level proposed in [14].

2254.7 keV: A state at *2254.7 keV* decays via a 1358.9 keV transition to the 896 keV 3^+ member of the γ band and this γ ray is observed with a somewhat reduced intensity in the 896 keV gate. Therefore the 1358.9 keV line seems to be a doublet, the stronger part of which is the ground-state transition from the 1358.9 keV 1^- state and the weaker part depopulates the newly proposed 2254.7 keV level. Two additional decay branches to 0^+ and 3^- states, respectively, define the spin of the 2254.7 keV level to be $I^\pi=2^+$. This state is only a few hundred eV below the 2254.9 keV 3^+ level proposed in [14] and the primary transition of 5516.4(3) keV therefore cannot be unambiguously assigned to one or both states.

2273.6 keV: The observation of the 1452.5 keV γ ray in the 821 keV gate together with a primary transition suggests a state at *2273.6 keV*. The 1452.5 keV transition is however also observed in the 896 keV gate and hence this line in the singles spectrum must be a doublet. The additional placement of a 2009.6 keV γ ray decaying to the 4_g^+ level limits the possible spin values to $I^\pi=2^+,3^+,4^+,3^-$.

TABLE V. Population and depopulation pattern of the newly proposed states. Transitions in parentheses can also be placed elsewhere and were therefore *not* used in the determination of the energies and spins of the new states. The population by primary feeding is included in this table although the headings E_x^{initial} and E_x^{final} have to be exchanged for these entries.

E_x^{initial} (keV)	I_i^π	E_γ (keV)	Intensity ($\gamma/10\,000n$)	Multip.	[a]	E_x^{final} (keV)	I_f,K^π	[b]
2188.573(4)	$2^+,3^+,4^+$	2108.85(15)	11	-		79	$2,0_1^+$	
	3^-	1194.08(16)	4.6	-		995	$4,2_1^+$	C
		349.229(3)	1	$M1$	*	1839	$5,3_1^+$	
		471.874(6)	1	-		2660	new	
2254.708(20)	2^+	1358.904(27)	29	-	*	896	$3,2_1^+$	C
		1037.877(182)	2.4	-		1217	$0,0_2^+$	
		426.659(30)	1.22	-		1828	$3,3_2^-$	
		[5516.36(27)	1.8	-		7771	$3^+,4^+$]	
2273.579(21)	$2^+,3^+,4^+$	2009.56(16)	10	-		264	$4,0_1^+$	
	3^-	1452.50(11)	7	-	*	821	$2,2_1^+$	C
		1009.675(21)	21.2	$E2$	*	1264	$6,2_1^+$	
		5498.44(70)	0.9	-		7771	$3^+,4^+$	
2345.295(24)	3^-	2081.15(35)	3	-		264	$4,0_1^+$	
		1524.18(13)	14	$E1$		821	$2,2_1^+$	C
		1449.26(12)	7	-		896	$3,2_1^+$	C
		322.910(6)	0.18	-		2022	$3,1_2^-$	
2373.654(13)	$2^+,3^+$	1552.55(25)	6	-	*	821	$2,2_1^+$	C
	$2^-,3^-$	[480.619(5)	3.5	-	*	1893	$2,0_4^+$]	
		401.343(11)	0.25	-		1972	$2,1_2^-$	
		5398.07(24)	2.8	-		7771	$3^+,4^+$	
2382.582(9)	2^+	2382.22(24)	6	-		0	$0,0_1^+$	
		2303.22(20)	12	-		80	$2,0_1^+$	
		1486.78(8)	15	$E1,E2$		896	$3,2_1^+$	C
		383.366(3)	6.6	$E1$		1999	$3,3_3^-$	
		351.422(14)	0.27	-		2031	$4,0_4^+$	
		5388.15(30)	1.7	-		7771	$3^+,4^+$	
2398.553(65)	$4^+,5^+$	1502.73(9)	18	-		896	$3,2_1^+$	C
		1281.034(68)	10	$M1$	*	1118	$5,2_1^+$	C
		5373.21(22)	12.7	-		7771	$3^+,4^+$	
2401.880(24)	$1^+,2^+$	2401.92(24)	8	-		0	0_1^+	
	1^-	2322.51(30)	10	-		80	$2,0_1^+$	
		1580.72(8)	38	-	*	821	$2,2_1^+$	C
		384.510(9)	0.51	-		2786	new	
		[5369.17(18)	20	-		7771	$3^+,4^+$]	
2440.069(9)	2^+	1445.26(8)	4	-		995	$4,2_1^+$	C
		1223.00(7)	5	-		1217	$0,0_2^+$	
		526.079(7)	1.2	-		1914	$3,0_1^-$	
		445.234(20)	0.92	-		1995	$3,4,2_3^+$	
		5331.68(52)	1.2	-		7771	$3^+,4^+$	
2455.721(14)	$3^+,4^+,5^+$	2191.48(20)	11	-		264	$4,0_1^+$	
	4^-	1560.16(8)	22	-	*	896	$3,2_1^+$	C
		1461.13(8)	8	-		995	$4,2_1^+$	C
		267.359(8)	0.22	-		2188	$5,2_3^+$	
		5316.28(70)	1.2	-		7771	$3^+,4^+$	
2479.144(122)	$3^-,4^-,5^-$	[1582.95(20)	9	-	*	896	$3,2_1^+$]	
		1484.46(8)	17	$E1$		995	$4,2_1^+$	C
		[5292.56(18)	41.9	-		7771	$3^+,4^+$]	

TABLE V. *(Continued).*

$E_x^{\rm initial}$ (keV)	I_i^π	E_γ (keV)	Intensity (γ/10 000n)	Multip.	a	$E_x^{\rm final}$ (keV)	I_f,K^π	b
2494.021(75)	$2^-,3^-$	2414.33(19)	8	-		80	$2,0_1^+$	
		[2229.27(20)	5	-		264	$4,0_1^+$]	
		1672.84(9)	19	$E1$		821	$2,2_1^+$	C
		5277.43(19)	11.6	-		7771	$3^+,4^+$	
2517.434(11)	$3^+,4^+$	1696.3(2)	9	-		821	$2,2_1^+$	C
		408.457(8)	0.78	-		2109	$5,2_2^+$	
		5254.40(26)	4.9	-		7771	$3^+,4^+$	
2528.686(47)	$3^-,4^-,5^-$	1534.05(10)	21	$E1$		995	$4,2_1^+$	C
		986.938(50)	4.4	-	*	1541	$4,1_1^-$	
		5242.53(18)	13.2	-		7771	$3^+,4^+$	
2551.583(13)	$3^+,4^+,5^+,6^+$	1556.84(15)	27	-		995	$4,2_1^+$	C
	$4^-,5^-$	814.768(70)	1.6	-		1737	$4,3_1^+$	
		442.593(20)	0.6	-		2109	$5,2_2^+$	
		313.420(14)	0.21	-		2238	$4,4_2^+$	
2558.637(47)	4^+	1563.85(9)	15	-		995	$4,2_1^+$	C
	$3^-,4^-,5^-$	[1199.610(37)	7.8	$E2$	*	1359	$1,1_1^-$]	
		984.419(77)	2	-		1574	$5,1_1^-$	
		235.652(18)	0.2	-		2323	3^-	
		5212.50(19)	19.3	-		7771	$3^+,4^+$	
2660.447(7)	$4^+,5^+$	1665.74(8)	8	$M1$	*	995	$4,2_1^+$	C
		1542.94(25)	6	-		1118	$5,2_1^+$	C
		512.133(24)	2.2	-		2148	$5,4_3^-$	
		471.874(6)	1	-		2189	new	
		5111.52(33)	19.1	-		7771	$3^+,4^+$	
2786.390(29)	$2^+,3^+,4^+$	1965.19(15)	7	-		821	$2,2_1^+$	C
	$2^-,3^-$	1890.93(35)	4	-		896	$3,2_1^+$	C
		384.510(9)	0.51	-		2402	new	
		308.309(5)	0.6	-		2478	$3,1_2^+$	
		4984.49(21)	14.6	-		7771	$3^+,4^+$	
2969.694(93)	$4^+,5^+$	2420.71(24)	16	-		549	$6,0_1^+$	
		1975.08(30)	9	-		995	$4,2_1^+$	C
		1875.69(12)	9	$E1$		1094	$4,4_1^-$	
		4801.68(24)	20.4	-		7771	$3^+,4^+$	

[a]The asterisk in this column marks transitions which were previously placed by Davidson [14] elsewhere in the level scheme.
[b]A C in this columns indicates that the transition is observed in the corresponding coincidence spectrum in the present work.

From energy considerations the 1009.7 keV transition, which is assigned to depopulate the 2663.2 keV state in Ref. [14], could equally well depopulate the new 2273.6 keV level to the 6^+ member of the γ band.

2345.3 keV: Four γ rays, two of them observed in coincidence, define a new state at *2345.3 keV*. The $E1$ multipolarity of the 1524.2 keV transition feeding the γ bandhead together with the deexcitation to a 4^+ level leads to an $I^\pi=3^-$ spin assignment for this new state.

2373.7 keV: The observation of a 1552.6 keV transition in the 821 keV gate suggests a level at *2373.7 keV*. This transition is placed in [14] to populate the 995 keV 4_γ^+ state from the 2547.2 keV level but since it is *not* observed in the 995 keV gate that placement cannot be correct. A second depopulating γ ray feeding a 2^- level and primary feeding from the $3^+,4^+$ capture state limits the spin range for this new state to $I^\pi=2^\pm,3^\pm$. A 480.6 keV γ ray is another possible decay branch but can also be placed elsewhere.

2382.6 keV: A new level at *2382.6 keV* is defined by a Ritz combination of five depopulating transitions, none of them placed previously. The 1486.8 keV γ ray populates the 3_γ^+ state and is observed in the 896 keV coincidence gate. The $E1$ character of the 383.4 keV transition to a 3^- state together with the observation of a ground-state transition leads to a unique $I^\pi=2^+$ spin assignment. A primary γ ray into this new state is observed in the pair spectrum.

2398.6 keV: The 1281.0 keV $M1$ γ ray which depopulates the 2474.2 keV 6^- state in [14] is observed in coincidence with the 853 keV transition from the decay of the 1117.6 keV 5^+_γ level. Since the line has the full intensity in the gate, the placement in [14] has to be incorrect. Together with a 1502.7 keV transition observed in the 896 keV gate and a primary transition this information leads to a new state at *2398.6 keV* with possible spins $I^\pi=4^+,5^+$.

2401.9 keV: At an excitation energy of 2402 keV there is again evidence for the existence of a closely spaced doublet of states. The 2402.4 keV 4^- level proposed in [14] on the basis of two depopulating γ rays is confirmed by our coincidence data. We observe a 1580.7 keV transition with a reduced intensity in the 821 keV gate. In [14], this transition is assigned to depopulate the 2129 keV 5^- level, but the energy fits there only within 2.3 σ. These facts suggest that the 1580.7 keV transition could be an unresolved doublet. This γ ray is unlikely to come from the known 2402.4 keV level since the energy disagrees by 3 σ. However, this γ ray and two others, a ground-state transition and a feeding γ ray, do define a new level at 2401.9 keV. Note that the 2401.9 keV γ ray cannot decay to the ground state from the 2402.4 keV state because the latter is a 4^- state. The observation of a ground-state transition limits the possible spin range for the new level at *2401.9 keV* to $I^\pi=1^+$, 2^+, and 1^-. As in the case of the 2254 keV level doublet, the observed primary transition cannot be uniquely assigned to one of the two states due to its large energy uncertainty compared to the level spacing.

2440.1 keV: A state at *2440.1 keV* is defined by four depopulating transitions and none of them has previously been placed in the level scheme of [14]. The 1445.3 keV γ ray feeding the 995 keV 4^+ member of the γ band is observed in the corresponding coincidence gate. A second decay branch to a 0^+ level immediately determines the spin of the new 2440.1 keV state to be $I^\pi=2^+$. A primary γ ray feeding this new level is observed in the pair spectrum.

2455.7 keV: The 1560.2 keV transition previously assigned [14] to depopulate the 2108 keV 5^+ state is, however, seen in coincidence with the 816 keV transition depopulating the 896 keV 3^+_γ state. In the same way the not previously placed 1461.1 keV γ ray is seen in the 995 keV gate and thus populates the 4^+_γ level. Both these γ rays define a state at *2455.7 keV* which is also depopulated by 2191.5 keV and 267.4 keV transitions to 4^+ and 5^+ levels, respectively. Since no multipolarities are known the spins $I^\pi=3^+,4^+,5^+,4^-$ are possible for the new 2455.7 keV state. A primary transition further supports this new state.

2479.1 keV: Two states at 2477.2 keV and 2478.2 keV were suggested in [14] as a $K=5^-_2$ bandhead and, tentatively, as a 3^+ level, respectively. The observation of the 1484.5 keV transition in the 995 keV gate indicates the existence of a third level at 2479 keV since the sum of 994.746(2) keV level energy and 1484.46(8) keV transition energy of about 2479.21 keV is much too far away from the other states considering the energy uncertainty of less than 100 eV. The 1583.0 keV transition is placed in [14] to depopulate the 2478.2 keV level but the energy discrepancy is somewhat larger than if it is placed out of the present 2479.1 keV level. Further indication for the existence of a third level is given by the absolute intensity of the 5292.6 keV primary transition which exceeds the depopulating intensity of each of these levels. Therefore, the 5292.6 keV line in the pair spectrum is a multiplet and its intensity is distributed over more than one final state.

2494.0 keV: The $E1$ 1672.8 keV γ ray is observed in the 821 keV gate, suggesting a new level at 2494 keV. This is supported by an energy sum with the 2414.3 keV transition decaying to the first 2^+ state, and a direct feeding transition from the capture state. These placements establish a new level at *2494.0 keV* with possible spin $I^\pi=2^-,3^-$. In addition the placement of a 2229.3 keV transition to the first 4^+ state is possible within 2.7 σ but was not used to eliminate a 2^- assignment because of the larger energy disagreement.

2517.4 keV: A new state at *2517.4 keV* is defined by its decay to the γ bandhead via a 1696.3 keV transition observed in the 821 keV gate and a second depopulating γ ray to a 5^+ level. That leads to the possible spins $I^\pi=3^+,4^+$ for this state, which is also directly populated via a 5254.4 keV primary transition.

2528.7 keV: A peak at 1534.1 keV in the 995 keV gate suggests a state at *2528.7 keV*. The $E1$ character of this γ ray limits the spin window for this state to $I^\pi=3^-,4^-,5^-$. A 986.9 keV γ ray fits easily in energy to depopulate this level to the 1541.7 keV 4^- state. The 986.9 keV γ ray was placed in [14] to depopulate the 2298.3 keV level but we note that the energy discrepancy was 2.7 σ.

2551.6 keV: The 1556.8 keV γ ray is observed with a somewhat reduced intensity in the 995 keV gate, suggesting a new level at *2551.6 keV*. Three more not previously placed transitions confirm this state and allow the values $I^\pi=3^+,4^+,5^+,6^+,4^-,5^-$ for its spin.

2558.6 keV: A state at *2558.6 keV* is proposed on the basis of a coincidence between the 1563.9 keV γ ray and the transitions depopulating the 995 keV 4^+_γ level, two more previously unplaced deexciting γ rays, and a strong primary. These placements lead to the spin window $I^\pi=4^+,3^-,4^-,5^-$ for the 2558.6 keV level. Furthermore the 1199.6 keV $E2$ transition might depopulate the state to the first 1^- level, but it has been placed to deexcite the 2392 keV 4^- state in [14].

2660.4 keV: The $M1$ 1665.7 keV γ ray assigned as feeding the 896 keV state in [14] is *not* observed in the 896 keV gate. Instead it is in coincidence with transitions from the decay of the 995 keV 4^+_γ level and therefore defines a new state at *2660.4 keV*. Further evidence for the 2660.4 keV level is given by the 1542.9 keV γ ray in the 1118 keV gate, two additional depopulating transitions and a strong primary transition into this level known from the pair spectrometer measurement. The decay to a 5^- level and the primary feeding limit the possible spin values for the new 2660.4 keV state to $I^\pi=4^+,5^+$.

2786.4 keV: The two γ rays with 1965.2 and 1890.9 keV observed in the 821 and 896 keV gates, respectively, suggest a new level at *2786.4 keV* excitation energy. A 384.5 keV transition connects this state to the newly proposed 2401.9 keV level assigned as 1^+, 2^+, or 1^- (see above) and a 308.3 keV γ ray populates the 2478.1 keV 3^+ state. The additional observation of a primary transition to this state limits the possible spin assignments for the new state to $I^\pi = 2^+, 3^+, 4^+, 2^-, 3^-$.

2969.7 keV: Finally, a state at *2969.7 keV*, very strongly populated by a primary transition, could be established through the observation of the 1975.1 keV γ ray in the 995 keV gate and two more previously unplaced highly energetic transitions populating states with spin 6^+ and 4^- , respectively. The $E1$ character of the 1875.7 keV γ ray feeding the 4^- level restricts the spin window for the new 2969.8 keV state to $I^\pi = 4^+, 5^+$.

B. Discussion of I^π assignments for selected states

In addition to the suggestion of new levels above 2 MeV the coincidence information can also be used, of

TABLE VI. Population and depopulation patterns suggested in Ref. [14] for some states, which are discussed in the text. The placements of the underlined transitions have been shown to be incorrect on the basis of the present coincidence data (see text).

E_x^{initial} (keV) Ref. [14]	E_γ (keV)	Intensity (γ/10 000n)	Multip.	E_x^{final} (keV)	I_f, K^π Ref. [14]	[a]	I_i^π Ref. [14]	I_i^π Present revision
2262.689(6)	1441.41(7)[b]	19	$E1$	821	$2,2_1^+$	896	3^-	$3^-,4^-$
	1366.914(20)	23	-	896	$3,2_1^+$	C		
	1267.83(10)	10	-	995	$4,2_1^+$	C		
	647.344(15)	3.4	$E2$	1615	$4,3_1^-$			
	629.184(20)	4.0	-	1633	$3,2_1^-$			
	609.164(9)	2.2	-	1654	$3,3_1^+$			
	263.421(18)	0.3	-	1999	$3,3_3^-$			
2298.255(3)	1105.260(16)	30.5	$E1$	1193	$5,4_1^-$		5^+	$4^+,5^+$
	986.938(50)	4.4	-	1311	$6,4_1^-$			
	458.910(3)	1.7	$M1$	1839	$5,3_1^+$			
	296.309(6)	0.39	-	2001	$5,4_2^-$			
	208.944(30)	0.08	-	2089	$4,3_3^-$			
2303.062(15)	1185.480(18)	16.4	$E1$	1118	$5,2_1^+$	no C	6^-	$5^+,6^+$
	1038.734(161)	3.4	-	1264	$6,2_1^+$			$5^-,6^-,7^-$
	729.001(50)	1.7	-	1574	$5,1_1^-$			
	542.352(35)	0.6	-	1761	$6,1_1^-$			
2393.694(83)	2393.47(18)	8	-	0	$0,0_1^+$		2^+	$1^+,2^+$
	2314.49(20)	14	-	80	$2,0_1^+$			
	2129.46(20)	6	-	264	$4,0_1^+$			
	1572.41(15)	4	-	821	$2,2_1^+$	C		
	1497.94(22)	5	-	896	$3,2_1^+$			
2402.368(72)	1506.49(12)	22	$E1$	896	$3,2_1^+$	C	4^-	$3^-,4^-$
	1407.67(9)	7	$E1, E2$	995	$4,2_1^+$	C		
2474.166(12)	1281.034(68)	10	$M1$	1193	$5,4_1^-$	1118	6^-	$5^+,6^+,7^+$
	1041.353(111)	3.6	-	1432	$7,2_1^+$			$6^-,7^-,8^-$
	653.879(63)	0.33	-	1820.1	$6,3_1^-$			
	472.218(12)[b]	0.81	-	2001	$5,4_2^-$			
2477.21(5)	1383.362(84)	5	-	1094	$4,4_1^-$		5^-	???
	1284.08(8)	7	$M1, E2$	1193	$5,4_1^-$			
	1165.653(98)	5.2	$M1$	1311	$6,4_1^-$			
2513.694(55)	1518.95(16)	9	$E1$	995	$4,2_1^+$		5^-	4^-
	1396.125(58)	11	-	1118	$5,2_1^+$	C		
	1617.75(10)[c]	11	$E1$	896	$3,2_1^+$	C		
2547.247(65)	2282.84(50)	4	-	264	$4,0_1^+$		(4^+)	$4^+,5^+,6^+$
	1997.88(30)	3	-	549	$6,0_1^+$			5^-
	1651.49(7)[b]	7	$M1$	896	$3,2_1^+$			
	1552.55(25)	6	-	995	$4,2_1^+$			
2561.55(4)	2297.43(10)	25	-	264	$4,0_1^+$		4^+	$4^+,5^+,6^+$
	2012.34(21)	5	-	549	$6,0_1^+$			5^-
	1665.74(8)	8	$M1$	896	$3,2_1^+$	995		
	1444.06(14)	4	-	1118	$5,2_1^+$			
	944.786(55)	2.4	-	1617	$6,0_2^+$			

[a] A C in this column indicates that the transition is observed in the corresponding coincidence spectrum. A number gives the gate in which the transition is seen in contradiction to the placement from Ref. [14] that is given in this table.

[b] Doubly placed in [14].

[c] Additionally γ ray depopulating this level based on the present coincidence data.

course, to test some of the γ-ray placements and spin assignments made in [14]. In the following paragraphs, assignments from [14] which are doubtful in the light of the new data will be discussed. Table VI summarizes the decay patterns of these states as deduced in [14].

2262.7 keV: In Ref. [14] the spin of 3^- for the *2262.7 keV* state was deduced from an extension of the analysis of the ARC data by the authors of Ref. [14] and from its decay to the 821 keV γ bandhead via a doubly placed 1441.4 keV $E1$ transition in [14]. This placement is shown to be incorrect by our coincidence information since there is a 1441.4 keV line in the 896 keV gate and *not* in the 821 keV gate. The remaining depopulating transitions allow both 3^- and 4^- assignments for the 2262.7 keV state, although 3^- was suggested in some transfer reaction studies [8].

2298.3 keV: The spin assignment in [14] of $I^\pi=5^+$ to the *2298.3 keV* state and hence its consideration as a $K = 5_2^+$ bandhead is solely based on the placement of the 986.938(50) keV transition connecting this level with the 1311.5 keV 6^- state. The sum of this transition energy and the 1311.458(2) keV level energy is 2.7 σ higher than the 2298.255(3) keV excitation energy, determined from the remaining depopulating transitions with smaller energy errors. However, it agrees (within 1 σ) with the energy sum of the 1180.868(24) keV γ ray and the energy of the 1117.568(2) keV 5_γ^+ state. Taking into account the unquestionable observation of a 1180.9 keV line in the 1118 keV gate, the existence of a second state at 2298.4 keV is very likely. Omitting the 986.9 keV transition from the decay of the 2298.3 keV level of Ref. [14] would now allow both 4^+ and 5^+ as possible spin assignments for the 2298.3 keV level of Ref. [14].

2303.1 keV: The $I^\pi=6^-$ assignment of the level at *2303.1 keV* is based on the placement of the 1185.5 keV $E1$ transition depopulating this state to the 1117.6 keV 5^+ member of the γ band. However, this γ ray is *not* observed in the 1118 keV coincidence spectrum. This is significant, since a neighboring line at 1180.9 keV with a smaller intensity than the 1185.5 keV γ ray is clearly visible in this gate. Removing this incorrectly placed transition leads to a somewhat modified level energy and therefore gives a new set of γ-ray placements but these are now based solely on the Ritz procedure. The 2303.1 keV level can no longer be considered as well established, nor is its spin any longer determined, and it cannot at all be assigned to a certain band.

2393.7 keV: The placement of an additional depopulating transition which has not been included in [14] is possible from energy sum considerations. This $M1$ 1176.4 keV γ ray populating the 1217.1 keV 0^+ level would lead to an $I^\pi=1^+$ assignment and is therefore inconsistent with the 2129.5 keV decay to the 4^+ member of the ground-state band. Since there are no further indications which of these two placements is incorrect both $I^\pi=1^+$ and 2^+ are possible spin values for the *2393.7 keV* state.

2402.4 keV: The level at *2402.4 keV* is defined by two depopulating $E1$ transitions which are both confirmed by the coincidence data. The final state spins 3^+ and 4^+ limit the possible spin assignments for the 2402.4 keV state to $I^\pi=3^-,4^-$. In Ref. [14] $I^\pi=4^-$ has been chosen. Furthermore the assignment of this state as a 4^- member of a $K = 3_5^-$ band is based on the argument that it decays exclusively to the 2_1^+ band. Since Ritz combinations suggest seven other possible decay branches for this state this band (K) assignment seems rather weakly founded.

2474.2 keV: The $M1$ 1281.0 keV transition is placed in [14] to depopulate the *2474.2 keV* 6^- state, feeding a level at 1193.0 keV. Our coincidence data show that this γ ray populates the 1117.6 keV 5_γ^+ state and therefore depopulates the new proposed level at 2398.6 keV instead (see above). Removing this placement from [14] eliminates all arguments leading to a unique spin assignment for the 2474.2 keV state. Decays to 5^-, 6^-, and 7^+ levels without multipolarity information allow $I^\pi=5^+,6^+,6^-,7^-$ values.

2477.2 keV: This level proposed in Ref. [14] was discussed above in connection with the newly disclosed level at 2479.1 keV. In addition to that discussion we note that, besides the three transitions placed in [14] to depopulate this state to the $K = 4_1^-$ band, two other decay branches to the 4^+ and 6^+ members of the ground-state band are also possible Ritz combinations. It is not clear how the selection of depopulating transitions was chosen in Ref. [14]. In particular, the decay energy to the 4^- level at 1094 keV differs by $\sim$ 3 σ from that expected on the basis of the other Ritz combinations. We conclude that no definite I^π assignment for this level can be currently made with confidence.

2513.7 keV: The *2513.7 keV* state has spin 5^- and is considered as a member of the $K = 3_5^-$ band in [14]. However, the observation of the 1617.8 keV $E1$ transition in the 896 keV gate adds a new γ ray depopulating the 2513.7 keV level and leads instead to an unequivocal assignment of spin $I^\pi=4^-$ for the 2513.7 keV state.

2547.2 keV: The 1552.6 keV γ ray is observed in the 821 keV gate and therefore depopulates the state at 2373.7 keV (see a discussion of this new level in the preceding section). The placement of this transition in [14] to depopulate the 2547.2 keV state is incorrect. Since the 1651.5 keV $M1$ transition is placed twice in Ref. [14], it should not be used in defining the spin of this state. From the remaining two depopulating transitions the values $I^\pi=4^+$, 5^+, 6^+, *and* 5^- are possible for the level at *2547.2 keV*.

2561.6 keV: The 4^+ spin assignment for the *2561.6 keV* level in [14] is based on the placement of the 1665.7 keV γ ray with known $M1$ multipolarity depopulating this state and feeding the 896 keV 3_γ^+. But this placement is not correct since this transition is observed in the 995 keV gate and *not* in the 896 keV gate. The remaining decay pattern leads instead to possible spin values $I^\pi=4^+,5^+,6^+,5^-$ for the 2561.6 keV state.

In contrast to the above levels, for which the present coincidence data cast doubt on the Ritz combinations proposed in Ref. [14], leading to altered I^π assignments, some of the depopulating transitions proposed by Davidson and Dixon [14] are confirmed by our results. In particular, specific γ-ray placements from the 2193, 2254, and 2336 keV positive-parity states and from the 2230, 2302, 2323, 2337, 2348, 2392, 2411, and 2451 keV negative-parity states are supported by the coincidence results summarized in Tables I–IV. We note of course, that confirmation of these *γ-ray placements* does not of necessity confirm the I^π or *band assignments* in Ref. [14].

IV. DISCUSSION

In the preceding section we established rather unambiguously 19 new states in ^{168}Er above 2.1 MeV on the basis of definite γ-γ coincidence relations (see Table V) and commented on a group of 10 states whose *definite* spin assignments in Ref. [14] need to be reexamined in light of the present coincidence data which show that some transitions used in Ref. [14] in limiting I^π choices (e.g., for the states at 2262.7, 2303.1, 2474.2, 2547.2, and 2561.6 keV) were incorrectly placed. In many cases, the I^π assignments of Ref. [14] for these 10 levels remain possible (amongst other choices as well) but the uniqueness of these I^π assignments is no longer tenable and, hence, band (K) assignments based on them become less reliable. The status of all levels in the new bands proposed in Ref. [14] where new information is provided by the present data is summarized in Fig. 3. All bands with bandheads above 2.1 MeV from [14] are shown. On the left, states for which our data support some coincidence relations implied by Ref. [14] are marked by thick lines, levels whose spins are modified as discussed above are given as dashed lines with the new spin given directly below the level, for comparison with the I^π assignments from Ref. [14] which are given above each level, and the

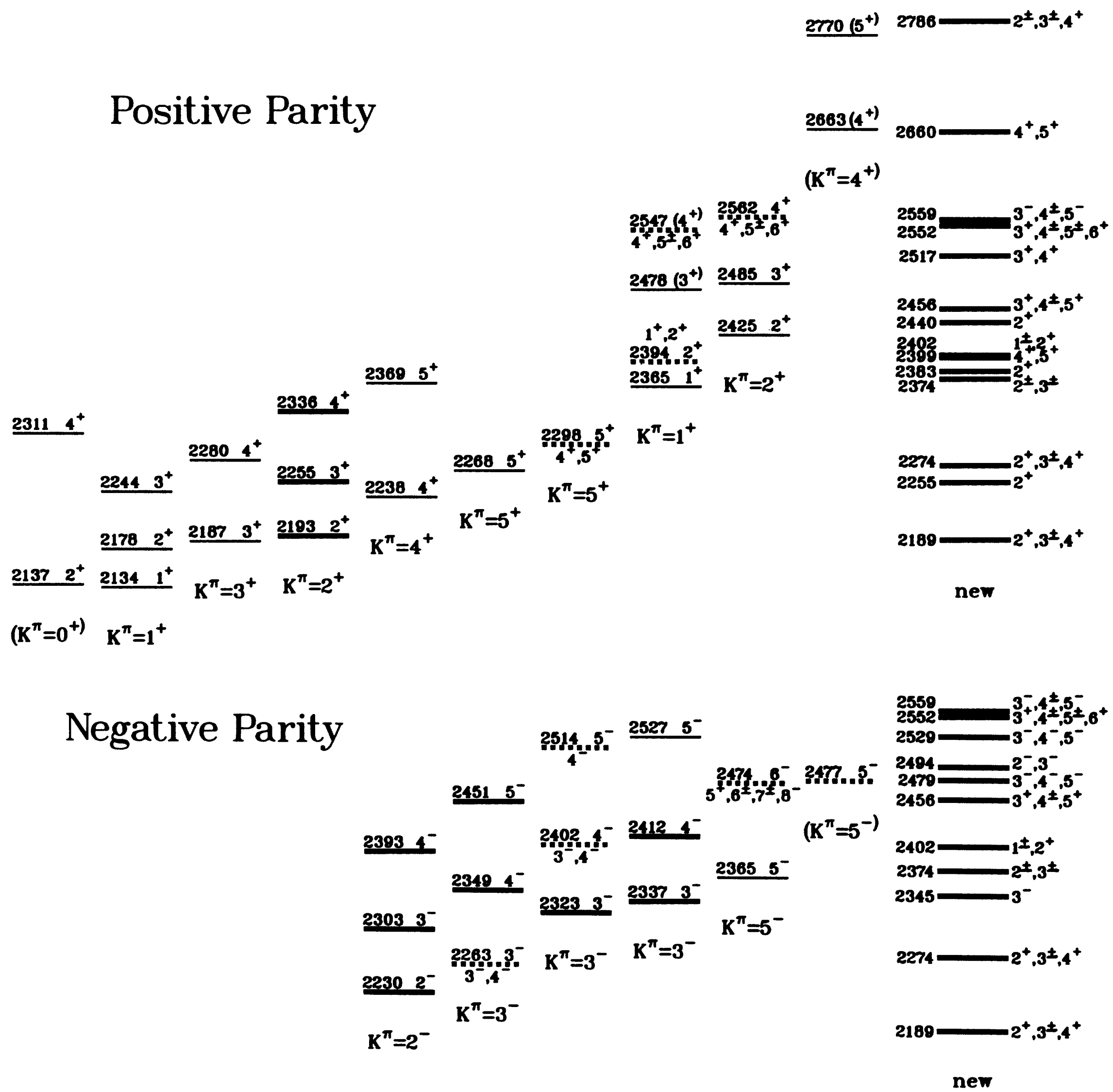

FIG. 3. All bands with bandheads above 2.1 MeV in ^{168}Er as assigned in Ref. [14]. States for which our data support some coincidence relations implied by Ref. [14] are marked by thick lines, levels whose spins are modified (see Sec. III B) are given as dashed lines with the new spin given below the level (for the 2394 keV level the new spins are exceptionally given above the level) and the states not accessible to our data are marked by thin lines. On the far right the new states proposed in this study in the same energy range are shown.

states not accessible to our data are marked by thin lines. On the far right the new levels found in this study in this energy range are shown.

In our experiment only levels which strongly decay to the γ band could be identified. Since the γ flux into the ground-state band and the γ band, respectively, have comparable strength the existence of a great number of additional states in the energy region between 2 and 3 MeV is very probable. This conclusion is further supported by the existence of many relatively strong transitions known from crystal spectrometer and Ge(Li) measurements (Table 1 of the second article of Ref. [14]) that are not yet placed in the deexcitation scheme. This is shown in Fig. 4 which compares the energies and intensities of (a) all known γ rays, (b) all transitions not placed in [14], and (c) the γ rays which depopulate the 19 new states discussed above. Clearly the new placements [Fig. 4(c)] only account for a small fraction of the remaining unplaced γ rays [Fig. 4(b)].

To summarize the experimental results of our study we found 19 new levels in the energy range of the level scheme extension proposed by Ref. [14], and also discussed that a number of γ-ray placements in Ref. [14] are contradicted by the γ-γ coincidence data, leading to revised or ambiguous I^π assignments for 10 of the levels proposed in Ref. [14]. Our level scheme extension, as noted, makes no pretence to completeness: it gives only

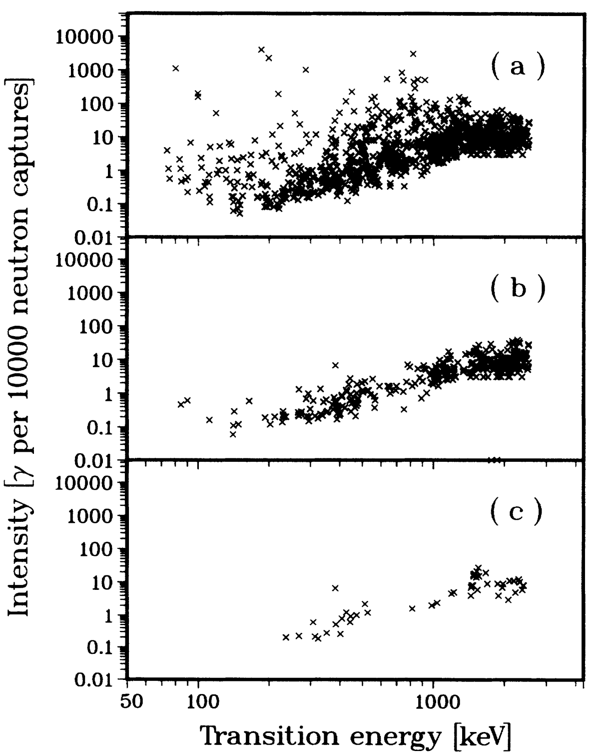

FIG. 4. Comparison of (a) all known γ transitions with $E_\gamma \leq 2.5$ MeV observed after thermal neutron capture in ^{167}Er (from Table 1 of the second entry of Ref. [14]), (b) all transitions not placed in the extended level scheme of Ref. [14], and (c) the not previously placed γ rays which depopulate the 19 newly proposed states.

a lower limit on the number of previously missed levels in this excitation energy range. The question now arises as to the implications of these results, in particular for the question of chaos vs order (mixing or relative purity) in the K quantum number at the neutron separation energy. Since the level scheme remains incomplete between 2200 and 2800 keV it is clearly imprudent to attempt to make revised band (and K) assignments. Indeed, perhaps the main point emerging from this study is that such assignments are explicitly *un*reliable in this energy region. Rather, we stress the impact of the new levels on the existing (Ref. [14]) band assignments. At the outset, it is abundantly clear from Fig. 3 that, with the revised I^π values for existing levels and the new levels, the band assignments proposed in Ref. [14] need to be seriously reconsidered. Of course, many may be correct. However, the important point is that they cannot be *relied* upon in an analysis, such as that of Ref. [15], which hinges on correct K assignments.

To give a couple of specific illustrative examples, the revision of the I^π value for the 2514 keV level (and the ambiguity for the 2402 keV level) eliminates all confidence in the 2323 keV $K = 3^-$ band they are assigned to. The newly disclosed 2345 keV 3^- level introduces a new state amongst the $K = 2^-$, 3^-, 3^-, and 3^- bands with bandheads at 2230, 2263, 2323, and 2337 keV, respectively. This new 3^- level must be accompanied, at slightly higher energies, by 4^- and 5^- rotational states. It is difficult to rule out the candidates at 2393, 2402, and 2412 keV. Hence, all these bands are shaky. Indeed, there are now at least four 3^- levels within 42 keV, implying at least four bands with $K \leq 3$ in this region.

Among the positive-parity states, the new 2^+ level at 2255 keV introduces a new band. So does the new level at 2255 keV which is very likely to have positive parity. The rotational excitations built above or below these states must either be chosen from the former levels (which is impossible since not enough levels of definite I^π are known) or it must be recognized that the existing band assignments need to be reexamined.

The 2^+ state at 2137 keV could now be a bandhead of a $K = 2$ band with the new states at 2274 keV (2^+,$3^\pm$,4^+) and 2399 keV (4^+,5^+) as 3^+ and 4^+ members, respectively, instead of belonging to a $K = 0$ band with unidentified bandhead as assigned in Ref. [14]. The 2311 keV 4^+ level can as well belong to the $K = 1$ band built on the 2134 keV level (as already pointed out in [14]). The change of I^π from 5^+ to 4^+, 5^+ for the 2298 keV level clearly raises doubts about the definite $K = 5^+$ assignment of Ref. [14]. The I^π changes in the energy region 2365–2562 keV also lead to ambiguities in band assignments. For example, the loss of any reliable I^π for the 2394 keV level means that the 2365 (1^+) state could now be a bandhead for the sequence of states 2425, 2485, 2562 keV, changing this group from $K = 2$ to $K = 1$. Also, the 2478 keV (3^+) and 2547 keV (4^+, 5^+, 6^+) states could be a new $K = 3^+$ band instead of belonging to the proposed $K = 1$ band. Perhaps most telling from the standpoint of the order-chaos question is the discovery of at least three new 2^+ levels — and possibly six — within 200 keV between 2250 and 2450 keV, necessarily implying at least that many new positive-parity bands with $K \leq 2$. Since, statistically, it is unlikely that all have $K = 2$, this implies the strong likelihood of some (up to 6) $K = 0, 1$ bands in this energy region. We stress that any band changes that potentially switch states from $K = 0, 1$ to $K = 2-5$ values, or vice versa, have significant impact on the order-chaos question since the distinction in intensity studied in Ref. [15] was between these two K groups.

Turning to the primary transitions themselves, we note that 5 of the 19 newly proposed levels (2254.7, 2401.9, 2479.1, 2528.7, and 2558.6 keV) are very close to existing states and the primary transitions are therefore unresolvable. This, in turn, implies that all these lines in the primary spectrum are now multiplets, and hence it is risky to use their intensities, or some fraction thereof, in a K intensity analysis. In addition 11 of the remaining new levels have known primary transitions. These range from very weak ($I_{\rm prim}$=47 rel. units for the 2273.6 keV level) to very strong ($I_{\rm prim}$=1020 rel. units for the 2969.7 keV level) and include moderately strong to very strong primaries to six levels between 2493 and 2786 keV. Since it is not known what bands (what K values) these states correspond to, the K-intensity distribution in Ref. [15] must be reexamined.

The present results can also be used to comment more directly on the claim of Ref. [15] that primary transitions to $K = 2-5$ states are stronger on average than to $K = 0, 1$ states which led the authors of Ref. [15] to conclude that K is incompletely mixed in the resonance region. Although the present I^π revisions and the disclosure of many new states cast doubt on the new band assignments — and hence the K quantum numbers — of Ref. [14], one could still ask what effect our newly disclosed levels would have, even if the band assignments of Ref. [14] were assumed (for the sake of argument) to be correct. Table VII lists all states above 2180 keV in ^{168}Er the primary feeding (thermal neutron capture) of which was used by Rekstad *et al.* [15]. Of these, the 2254.9 and 2402.4 keV levels must now be considered as doublets with the newly disclosed states at 2254.7 and 2401.9 keV, respectively. The 5425.28 keV primary transition assigned in [15] to populate the 2348.6 keV state populates more likely the new 2345.3 keV level ($E_{\rm cap}$-$E_{\rm prim}$=2346.1 keV). In the same way, the 5242.5 keV primary transition might populate the new 2528.7 keV level instead of the 2526.6 keV state ($E_{\rm cap}$-$E_{\rm prim}$=2528.8 keV). Therefore, the intensities of all these primary lines, which now are either parts of doublets or very probably assigned to the wrong level, must now be reduced (to accommodate the intensities to the new levels). Since all states discussed here are $K \geq 2$ levels, the *average* intensity of the primary transitions to $K \geq 2$ states must decrease, which goes in the direction of eradicating the claimed difference in primary intensities to $K = 0, 1$ vs $K = 2-5$ states.

V. CONCLUSION

Extensive new γ-γ coincidence data following thermal neutron capture in ^{168}Er cast doubt on the extension of the ^{168}Er level scheme proposed in Ref. [14] and recently used in the order-chaos analysis of Ref. [15]. The risks of extending γ-ray level schemes beyond regions of low-to-moderate level density (ca. 2 MeV in well-deformed rare earth nuclei) are highlighted by the present results, which show that the spins of 10 of the 39 new levels assigned by Ref. [14] cannot be relied upon — the present work either demonstrates that the I^π values are different or that other I^π values than those assigned in Ref. [14] are also possible. In addition, within the *same* energy region as the 39 levels in the extended scheme of Ref. [14], we now find definite evidence for 19 *additional* levels. Of course, there are surely more than this number of undetected levels: our aim was *not* to produce a complete excitation scheme — we believe, and we feel the

TABLE VII. States above 2180 keV in ^{168}Er which are used in Ref. [15] in the analysis of primary intensities. The states given in parentheses are members of multiplets, only used to extract the intensity of the strongest primary in Ref. [15].

E_x (keV)	I^π, K Ref. [14]	I^π Revised	E_x (keV) Present work	I^π Present work
2185.1	5^-, 1			
(2186.7)	3^+, 3			
(2188.4)	5^+, 2			
			2188.6	2^+,$3^\pm$,4^+
2193.2	2^+, 2			
2200.4	5^-, 3			
2238.2	4^+, 4			
2243.5	3^+, 1			
			2254.7	2^+
2254.9	3^+, 2			
2262.7	3^-, 3	3^-,4^-		
2279.6	4^+, 3			
2302.7	3^-, 2			
2323.2	3^-, 3			
(2336.2)	4^+, 2			
2337.1	3^-, 3			
			2345.3	3^-
2348.6	4^-, 3			
2365.3	5^-, 5			
(2368.6)	5^+, 4			
			2373.7	$2^\pm$,$3^\pm$
2392.6	4^-, 2			
(2393.7)	2^+, 1	1^+,2^+		
			2398.6	4^+,5^+
			2401.9	$1^\pm$,2^+
2402.4	4^-, 3	3^-,4^-		
2411.6	4^-, 3			
2425.4	2^+, 2			
2451.2	5^-, 3			
			2455.7	3^+,$4^\pm$,5^+
			2479.1	3^-,4^-,5^-
2484.5	3^+, 2			
2513.7	5^-, 3	4^-		
			2517.4	3^+,4^+
2526.6	5^-, 3			
			2528.7	3^-,4^-,5^-
			2558.6	3^-,$4^\pm$,5^-
2561.6	4^+, 2	4^+,5^+,6^+,5^-		

present data show this, that completeness in this energy region is not currently possible. Of course, that in itself does not mean that all band assignments in Ref. [14] are incorrect. Quite the contrary: undoubtedly many are correct. Our point is rather somewhat different. Given that the assignments for about 25% of the levels proposed in Ref. [14] are no longer unique and given our disclosure of 19 new levels, it is evident that, while a number of the detailed band assignments of Ref. [14] may be correct, it cannot be determined at this point *which* these are. Moreover, with the large number of new levels, there *must* be a considerable number of new bands and quite a few of the levels assigned to bands in Ref. [14] may actually belong to other bands with different K values. Hence, these band assignments can no longer be relied upon in analyses such as that of primary transition intensities and of the order-chaos concept which, per force, require a known-to-be reliable ensemble of states.

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[1] W. F. Davidson, D. D. Warner, R. F. Casten, K. Schreckenbach, H. G. Börner, J. Simić, M. Stojanović, M. Bogdanović, S. Koički, W. Gelletly, G. B. Orr, and M. L. Stelts, J. Phys. G **7**, 455 (1981).

[2] D. D. Warner, R. F. Casten, and W. F. Davidson, Phys. Rev. Lett. **45**, 1761 (1980).

[3] N. Yoshinaga, Y. Akiyama, and A. Arima, Phys. Rev. Lett. **56**, 1116 (1986).

[4] A. F. Barfield, J. L. Wood, and B. R. Barrett, Phys. Rev. C **34**, 2001 (1986).

[5] S. W. Yates, E. D. Kleppinger, and E. W. Kleppinger, J. Phys. G **11**, 877 (1985).

[6] H. G. Börner, J. Jolie, S. J. Robinson, B. Krusche, R. Piepenbring, R. F. Casten, A. Aprahamian, and J. P. Draayer, Phys. Rev. Lett. **60**, 691 (1991).

[7] W. Gelletly, P. van Isacker, D. D. Warner, G. Colvin, and K. Schreckenbach, Phys. Lett. B **191**, 240 (1987).

[8] D. G. Burke, B. L. W. Maddock, and W. F. Davidson, Nucl. Phys. **A442**, 424 (1985); D. G. Burke, W. F. Davidson, J. A. Cizewski, R. E. Brown, and J. W. Sunier, *ibid.* **A445**, 70 (1985).

[9] A. Bohr and B. R. Mottelson, Phys. Scr. **25**, 28 (1982).

[10] J. P. Draayer and K. J. Weeks, Ann. Phys. **156**, 41 (1984).

[11] M. K. Jammari and R. Piepenbring, Nucl. Phys. **A487**, 77 (1988).

[12] P. O. Lipas, P. Toivonen, and E. Hammarén, Nucl. Phys. **A469**, 348 (1987).

[13] V. G. Soloviev and N. Yu. Shirikova, Z. Phys. A **301**, 263 (1981).

[14] W. F. Davidson and W. R. Dixon, J. Phys. G **17**, 1683 (1991); National Research Council of Canada Report PIRS 0288, 1991.

[15] J. Rekstad, T. S. Tveter, and M. Guttormsen, Phys. Rev. Lett. **65**, 2122 (1990); J. Rekstad, T. S. Tveter, M. Guttormsen, and L. Bergholt, University of Oslo Report UiO Phys. 92-23, 1992; J. Rekstad, T. S. Tveter, M. Guttormsen, and L. Bergholt, Phys. Rev. C **47**, 2621 (1993).

[16] A. M. I. Hague, R. F. Casten, I. Forster, A. Gelberg, R. Rascher, R. Richter, P. von Brentano, G. Berreau, H. G. Börner, S. A. Kerr, K. Schreckenbach, and D. D. Warner, Nucl. Phys. **A455**, 231 (1986).

[17] B. R. Barrett, R. F. Casten, J. N. Ginocchio, T. Seligman, and H. A. Weidenmüller, Phys. Rev. C **45**, R1417 (1992).