threshold. Although not shown in this figure, the angular distribution data of Simmons[9] do indicate that K_0^2 rises again beginning with 3.0-MeV neutrons. The data represented by circles in Fig. 6, however, must be treated with some caution since a normalization (described earlier) is involved.

The pairing energy of nuclei decreases with increasing A.[17] It has been suggested[18,19] that the pairing effect is associated with a matrix element predominately in the nuclear surface. With increasing A, the surface-to-volume ratio ($\alpha A^{-1/3}$) decreases; and, hence, the pairing energy decreases as one goes from light to heavy nuclei.[18] This suggests that the pairing gap should increase for a particular nucleus as one goes from the equilibrium deformation to the much larger nuclear deformation of the transition nucleus.[19] The present experiments support an enhanced pairing gap in the more deformed Pu^{240} transition nucleus. The experimental magnitude of the enhancement is consistent with a recent calculation[20] which assumes that the pairing force strength in nuclei varies proportionally to the area of the nuclear surface. If the larger pairing energy is due to the influence of the nuclear surface, one expects even more pronounced differences in the pairing gap between equilibrium and transition nuclei in the vicinity of lead. These transition nuclei are deformed essentially to the scission configuration with very large surface-to-volume ratios. Preliminary results[21] in this region of the periodic table do indicate a large pairing gap consistent with the enhanced pairing energy for very deformed heavy nuclei presented here.

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PHYSICAL REVIEW VOLUME 174, NUMBER 4 20 OCTOBER 1968

Intensities and Angular Distributions of Ground-State Rotational Transitions Excited in (α,3n) and (α,4n) Reactions*

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(Received 17 June 1968)

Relative intensities measured for rotational transitions in the ground-state bands are reported for residual even-even rare-earth nuclei excited in (α,3n) and (α,4n) reactions. The incident α-particle energy was typically ~40.5 MeV, and the targets were isotopes of Gd, Dy, Er, and Yb. The angular distributions of the rotational radiations were found to be in accord with theoretical expectations. The relative intensities of the lines were, however, inconsistent with the implications of simple statistical models. More angular momentum is apparently carried away by photon transitions connecting higher-lying states than one might expect. Possible reasons for this discrepancy are briefly discussed.

I. INTRODUCTION

It has been known for some time that ground-state rotational bands of even-even distorted nuclei can be easily excited in bombardments involving the deposition of considerable angular momentum.[1–4] The purpose of the present measurements was to use the relative intensities of the lines excited in such bands to show how much of the initial angular momentum in the system remains at the end of the de-excitation, i.e., at the point of entry into the ground-state band of the final residual nucleus.[5] Such measurements therefore complement those of angular distributions of evaporated particles[6,7] and photons[8] which also give some information about the rate of loss of angular momentum during nuclear de-excitation. In the past, the relative intensities of low-lying isomers have sometimes been used as

* Work supported in part by the U. S. Atomic Energy Commission.

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indicators of the late-stage angular momentum content of cooling nuclei.[9,10] Rotational states have two important advantages over isomers in such studies. (1) Generally quite a few of the rotational levels in a band are excited instead of just two (seldom three) levels as in isomer excitation experiments. (2) All of the rotational states have the same intrinsic nuclear structure. Their relative yields are therefore less dependent on details of nuclear structure than those of isomers. Moreover, in very deformed nuclei, the rotational states are only little separated in energy. In a sense, they are a set of almost degenerate levels differing only in the parameter being investigated, the angular momentum.

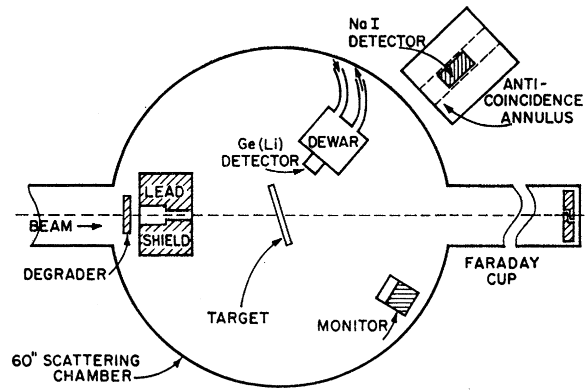

FIG. 1. A schematic view of the experimental arrangement in the 60-in. scattering chamber. The NaI and Ge(Li) detectors were not used in the same runs.

II. EXPERIMENTAL METHOD

A. General Experimental Arrangement

The measurements to be described were performed using the external α-particle beam from the University of Washington 60-in. fixed-frequency cyclotron. The beam energy was 42.0±0.2 MeV and could be reduced stepwise to 32 MeV by aluminum degraders located 24 in. from the target in a shielded rotating mechanism. The general experimental layout is shown schematically in Fig. 1.

The isotopically enriched rare earths used in the experiments were in the form of powdered oxides. A slurry of the powder and polystyrene was formed in a suitable solvent and allowed to dry into a "chip" about 1 cm^2 in area and typically 30 mg/cm^2 thick (i.e., about 3-MeV thick for 42-MeV α particles). This chip was then mounted on a thin nylon backing which was in turn clamped into a suitable target holder. Targets made in this way could be subjected to beam currents of 50 nA without visible deterioration.

The effective target thickness was monitored for each run by observing the elastically scattered α particles with a CsI(Tl) scintillation spectrometer placed at a laboratory angle of 30° with respect to the incident beam. This monitor was calibrated absolutely under conditions of low beam intensity by comparing its counting rate with that of a small Si(Li) solid-state detector placed at a sufficiently forward angle so that the elastic scattering was essentially purely Rutherford. The scintillation detector was used instead of the solid-state detector for general monitoring because the latter would have been quickly damaged by the high neutron and charged particle fluxes present in the experiment.

The beam current for each run was integrated by a split Faraday cup arrangement[11] which allowed continuous monitoring of the lateral beam position without loss of integration accuracy. A collimator was placed between the degraders and the target to make sure that no part of the degraded beam passed through the target frame. The targets used in the experiment were not thick enough to cause significant loss of beam from the Faraday cup by small-angle multiple scattering.

B. Ge(Li) Detector

The measurements of the intensities of the rotational band transitions were made with a 4-mm-thick Ge(Li) solid-state detector of about 0.5 cm^2 active area. In order to achieve a reasonably large solid angle, the detector had to be placed no farther than 10 in. from the target. This necessitated operating it inside the vacuum of the 60-in. scattering chamber. Two different cooling systems were developed for the detector and both were used during various phases of this experiment. The first system was designed around a miniature Joule-Thompson crysotat, and is described in detail elsewhere.[12] The second system made use of a 3-liter liquid-nitrogen reservoir that could be operated in a vacuum and filled from the outside through flexible metal lines.

The signals from the detector were fed into a charge-sensitive, field-effect transistor preamplifier. The preamplifier in turn drove a main amplifier having 1 μsec differentiating and integrating RC time constants. The usual experimental resolution was about 5-keV full width at half-maximum (FWHM). The dead time for each run was measured by a gated pulser technique developed by Bodansky.[13]

The effective area of the Ge(Li) detector used in these experiments was not known with precision, but it is the product of the effective area and the detector efficiency that is needed to determine absolute cross sections. This product was measured for the Ge(Li)

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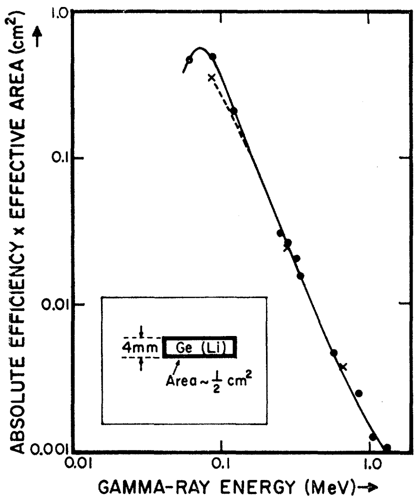

FIG. 2. Efficiency curves for the 4-mm-thick Ge(Li) detector systems used in this experiment. The ordinate is the product of the absolute full-energy efficiency and the effective counter area. The black dots represent measurements relative to a standardized 3 in. ×3 in. NaI(Tl) spectrometer for a system using a liquid-nitrogen Dewar. The crosses are for the same detector in a Joule-Thompson cryostat system and are measured relative to the absolute efficiency of a $1\frac{1}{2}$ in.×1 in. NaI(Tl) spectrometer. The statistical errors on all of the points are smaller than their size in these drawings. The low efficiencies of the Joule-Thompson system at low γ-ray energies are due to the thicker entrance window in this system. The smooth curves were drawn by eye through the data and were taken to be the responses of the detectors for purposes of data reduction.

detector by observing the counting rate of the full-energy peak from various natural γ-ray sources placed at known distances from the detector. These sources were standardized by observing the counting rates of the full-energy peaks with a $1\frac{1}{2}$ in.×1 in. or a 3 in.×3 in. NaI(Tl) spectrometer in a well-defined geometry. The full-energy efficiencies of both these NaI spectrometers are known as a function of γ-ray energy to relative accuracies of 3–5% and absolute accuracies of 5–8%.[14,15] The results of the (area)×(efficiency) determinations for the Ge(Li) detector used in these measurements are shown in Fig. 2. Here the product of the full-energy efficiency and effective area is plotted as a function of γ-ray energy. It is believed that this product is known throughout most of the energy range in the figure to accuracies of 5–7% (relative) and 8–11% (absolute).

To determine the intensities of the observed transitions, the photon intensities had to be corrected for internal conversion.[16] This was a very important correction for the transitions between the lowest-lying members of the rotational bands.

A typical photon spectrum observed in a 42-MeV α-particle bombardment of an even-odd rare-earth nucleus ^{167}Er is shown in Fig. 3. The peaks produced by ground-band rotational transitions are seen to stand out clearly above the background produced by the Compton distributions of higher-energy γ rays and by poorly resolved low-energy γ rays. The areas of the peaks were extracted by an iterative fitting procedure for which it was assumed that the spectrum in the neighborhood of a peak could be represented by the sum of a linear function representing the background and a Gaussian function representing the peak. The width of the Gaussian was constrained to be that expected on the basis of studies of natural γ-ray lines.

C. NaI(Tl) Spectrometer

It was thought to be desirable to complement the measurements of rotational line intensities with measurements of the higher-energy portions of the photon spectra. These measurements proved to be helpful in interpreting the results obtained for the rotational lines. Unfortunately, the γ-ray lines in the nuclei studied become so closely spaced above about 1 MeV that it was impossible to resolve them even with the Ge(Li) detector. This essentially destroyed the usefulness of this detector in this energy range compared with that of a large NaI(Tl) scintillation crystal. Mainly because of its greater thickness, the efficiencies of such a crystal are considerably larger than those of a Ge(Li) detector. Even more important a much greater fraction of incident γ rays deposit their full energy in the NaI(Tl) crystal than in the Ge(Li) detector. In short, for photons above 0.5 MeV, it was much simpler and safer to unfold spectra which were observed with a NaI detector because this detector had a better response function. This advantage of the NaI detector was augmented in the present experiment by placing it inside an anticoincidence annulus made of NaI.[17] The annular crystal was 12 in. long and 8 in. in outer diameter with a central hole just large enough to contain the detector crystal which was 6 in. long and 3 in. in diameter.

The rather high background of neutrons in the vicinity of the target generally produced many unwanted events in the central crystal. These were eliminated by requiring a time correlation between cyclotron beam bursts (~2 nsec wide) and pulses observed in the crystal. The γ spectra thus obtained were then corrected for the detector response to obtain the energy distribution of the photons. The details of the time-of-flight technique employed and the method of spectrum unfolding are described elsewhere.[18]

III. EXPERIMENTAL RESULTS

The photon spectra observed at the different angles and various bombarding conditions of the experiment all

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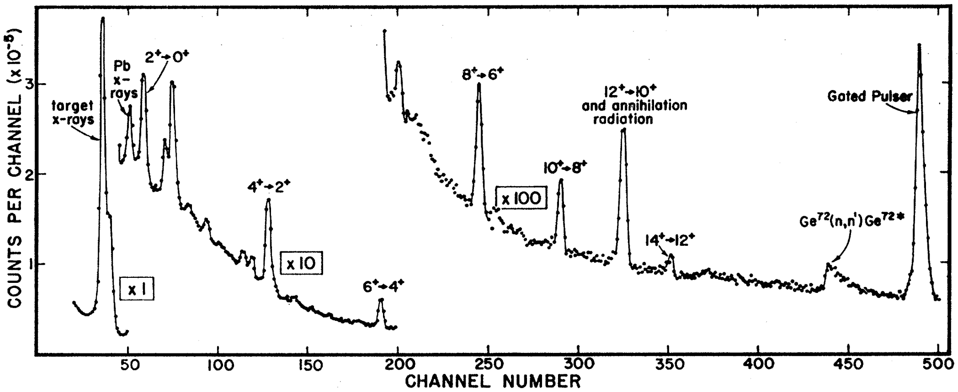

FIG. 3. The spectrum of γ rays from a 42-MeV α-particle bombardment of a 90% enriched $^{167}Er_2O_3$ target. The prominent rotational transitions in the ground-state band of ^{168}Yb are identified as well as several other lines observed in the spectrum. The calibration for the abscissa is about 1.6 keV/channel with channel zero corresponding to 21 keV. This run was for a total integrated charge 11.01 μC with an effective Er target thickness of 34.9 mg/cm^2. The detector was placed at 6.25 in. from the target at a laboratory angle of 20°.

showed strongly excited rotatonal lines as a conspicuous feature. These lines could always be identified with the transitions in an even-even residual nucleus and were often distinguishable up to the $14^+\rightarrow 12^+$ transition. The measured intensities of these lines and their angular distributions are given in the following three sections. This is followed by the corresponding information about the unresolved radiations.

A. Intensities of Rotational Lines for Different Targets

Figure 4 shows the relative intensities of rotational transitions in the ground-state bands of three even-even nuclei produced in (α,3n) reactions using 42-MeV incident α particles. The abscissa in this figure refers to the angular momentum of the radiating state. In all cases the targets were sufficiently enriched so that contributions to the yield were negligible from any isotopes in the targets other than the main isotopes (^{155}Gd, ^{161}Dy, and ^{167}Er). Because of target thickness, the mean energy of the α particles in the target was 40.5 MeV and the total energy spread of the interacting α particles was about 3 MeV.

The intensities shown in Fig. 4 have been arbitrarily normalized by passing straight lines through the data points and adjusting the ordinates so that the intensity at $J=0$ was unity. It must be emphasized that there is no theoretical reason to expect the intensity patterns to be linear. The normalization procedure is simply based on the empirical observation that for $J\geq 4$ the data seem to be reasonably well fitted with a straight line. Except for the residual nucleus ^{156}Dy it was unfortunately impossible to obtain reliable data for the $2^+\rightarrow 0^+$ transitions. This was because of the considerable background under these lines and the relatively large uncertainty in the values of the internal conversion coefficients for these lowest-energy rotational transitions.[19]

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For purposes of comparison with theory, it is convenient to extract from curves in Fig. 4 the median value of J at which the evaporation cascade first enters the ground-state band. If the intensity of the $J\rightarrow J-2$ transition is written $Y(J)$, the probability $P(J)$ of first entry at J is proportional to $Y(J)-Y(J+2)$. To define the median J at entry, J_M, we replace the histogram distribution for $P(J)$ with a continuous function, $P(J)\sim -(dY/dJ)_{J+1}$, and write

$$\tfrac{1}{2}=\int_0^{J_M+1}\frac{dY}{dJ}dJ\Big/\int_0^{\infty}\frac{dY}{dJ}dJ=\frac{Y(0)-Y(J_M+1)}{Y(0)-Y(\infty)}. \quad (1)$$

Hence $Y(J_M+1)=\frac{1}{2}Y(0)$. Thus, to obtain the median J one draws a smooth curve through the data and subtracts 1 from the J value at which the intensity is half what it is at $J=0$. In this procedure $Y(0)$ must be

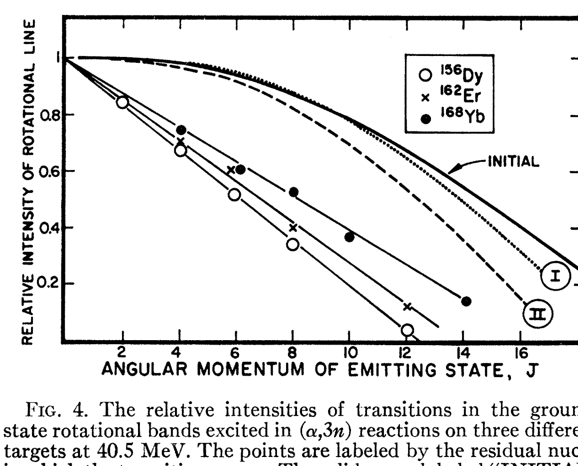

FIG. 4. The relative intensities of transitions in the ground-state rotational bands excited in (α,3n) reactions on three different targets at 40.5 MeV. The points are labeled by the residual nuclei in which the transitions occur. The solid curve labeled "INITIAL" gives the integral of the spin distribution of the initially formed compound nucleus determined according to the optical model. Curve I gives the expected distribution of ground-band rotational intensities according to a statistical model in which it was assumed that three dipole photons as well as the three neutrons were emitted before entry into the ground band. For curve II it was assumed that the three photons were quadrupole.

TABLE I. Values of J_M, the median angular momentum at entry of the evaporation cascade into the ground-state rotational band.

Reaction	Mean bombarding energy (MeV)	J_M
^{152}Sm$(\alpha,4n)^{152}$Gd	40	$5.2_{+0.5}^{-0.2}$ [a]
^{154}Sm$(\alpha,4n)^{154}$Gd	40	$7.1_{+0.6}^{-0.4}$ [a]
^{155}Gd$(\alpha,3n)^{156}$Dy	40.5	$5.1_{+0.25}^{-0.1}$
^{156}Gd$(\alpha,4n)^{156}$Dy	40.5	$5.6_{+0.5}^{-0.3}$
^{160}Gd$(\alpha,4n)^{160}$Dy	40.5	$5.8_{+0.25}^{-0.2}$
^{161}Dy$(\alpha,3n)^{162}$Er	40.5	$5.7_{+0.15}^{-0.1}$
^{167}Er$(\alpha,3n)^{168}$Yb	40.5	$7.1_{+0.1}^{-0.1}$
^{170}Er$(\alpha,4n)^{170}$Yb	40.5	$5.5_{+0.45}^{-0.35}$
^{176}Yb$(\alpha,4n)^{176}$Hf	40.5	$4.9_{+0.1}^{-0.2}$

[a] Data taken from Ref. 20.

obtained by extrapolation since no photon is emitted from the ground state.

Table I lists the values of J_M determined for the three targets mentioned above as well as for six enriched targets which lead to even-even final residual nuclei via the $4n$ reaction. Two of these latter targets were studied by Ejiri *et al.*[20] and the remaining four were studied in the present experiment.

The largest source of error in the determination of the median spins, J_M, is no doubt due to the method of extrapolation of the intensity distributions to spin zero. All theoretical treatments indicate that one must expect a leveling off of the intensity as one goes toward $J=0$. Since the tabulated values for J_M are determined by a simple linear extrapolation, they must be expected to be slightly smaller than theoretical estimates. For comparisons among themselves, the listed J_M values should probably be regarded as being less uncertain than for comparisons with theory. The errors listed in the table are just crudely estimated statistical errors. They were determined by drawing through plots like that in Fig. 4, the two straight lines which appeared visually to be the extreme credible fits to the data. One-half the difference between (the previously established) J_M and the median J of the extreme line having the higher median J was taken as the upward uncertainty. The downward uncertainty was defined correspondingly. It is seen that although the estimated errors on J_M are sometimes fairly large, they are not as large as the spread in J_M values for the bombardments studied.

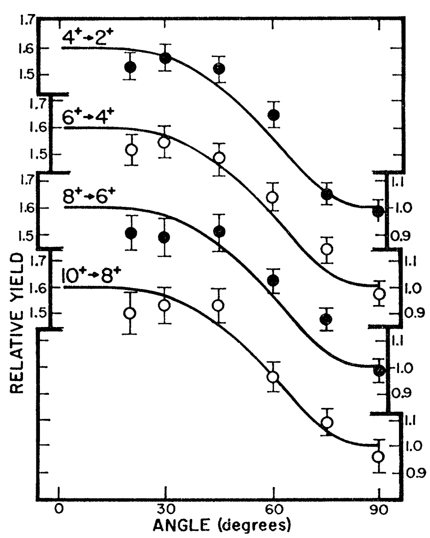

FIG. 5. Angular distributions of the rotational transitions for the reaction ^{167}Er$(\alpha,3n)^{168}$Yb for 40.5-MeV α particles. The curves drawn are all the same. They represent the expected quadrupole radiation pattern in the classical limit (see text).

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B. Intensities of Rotational Lines as a Function of Bombarding Energy

The ^{167}Er target was bombarded at three different energies covering a span of 10 MeV in order to observe possible changes in the J intensity pattern of the ground-state band in the $(\alpha,3n)$ reaction. In this part of the experiment, one is varying the angular momentum distribution of the initially formed compound nuclei as well as the total energy which must be removed by photons. The observed J patterns can once again be characterized by the median J values defined in the preceding section. These values for ^{167}Er$(\alpha,3n)$ at three incident energies are given in Table II. Similar results were also obtained for targets other than ^{167}Er.

C. Angular Distributions of the Rotational γ Rays

Angular distributions for each of the ground-state band rotational lines were measured for the reaction ^{167}Er$(\alpha,3n)^{168}$Yb at an (average) incident energy of 40.5 MeV. The results covered the range 20° to 90° and are displayed in Fig. 5. Separate measurements were made to check the expected symmetry of the angular distribution about 90°. The solid curves drawn through the data points are provided as comparison references for the observed distributions. These curves are all identical and represent the angular distribution expected for a set of classical electric quadrupole rotors whose rotating axes lie uniformly spread in azimuth about the beam direction. This distribution provides an asymptotic limit (in terms of anisotropy) for the distributions to be expected for the bombardments in this

TABLE II. Median values of angular momentum J_M, for the distribution of intensities of the rotational transitions for the reaction ^{167}Er$(\alpha,3n)^{168}$Yb for three different (mean) bombarding energies E.

E (MeV)	J_M
40.5	$7.1_{+0.1}^{-0.1}$
35.5	$5.5_{-0.3}^{+0.3}$
30.5	$4.9_{-0.4}^{+0.4}$

TABLE III. Differential cross sections (in mb/sr) for the ground-state band rotational transitions in the reaction ^{167}Er(α,3n)^{168}Yb. The indicated errors are combined statistical errors and estimated systematic errors between runs at the different angles. The over-all absolute error is approximately ±15%.

Transition[a]	Angle with respect to beam 90°	75°	60°	45°	30°	20°
$4^+ \to 2^+$	81.0±2.4	86.3±2.3	111.2±2.9	125.5±3.3	128.0±3.4	125.2±4.4
$6^+ \to 4^+$	65.0±2.0	76.5±2.1	89.0±2.5	98.7±3.1	102.0±3.1	100.2±3.8
$8^+ \to 6^+$	56.9±2.0	67.7±2.4	76.1±2.2	87.0±3.0	86.8±3.0	87.6±3.7
$10^+ \to 8^+$	37.7±2.0	43.7±2.4	52.9±2.5	63.2+3.0	63.3±3.1	60.7±3.6
$14^+ \to 12^+$	12.1±2.0	17.6±2.5	21.0±2.5	25.5±2.7	23.4±2.9	23.2±2.6

[a] The $2^+ \to 0^+$ cross sections were omitted because of normalization uncertainties in the intensities of this transition. The $12^+ \to 10^+$ cross sections were omitted because this line could not be effectively separated from the 511-keV annihilation radiation line.

experiment. The fact that the observed distributions resemble this limiting distribution so closely speaks for a relatively small amount of nuclear reorientation due to the evaporation of neutrons and photons. The smallness of this reorientation has been discussed before[2,18,21] and is briefly considered below (see Sec. IV A).

The absolute cross sections for the distributions plotted in Fig. 5 are recorded in Table III.

D. Intensity and Angular Distributions of Unresolved γ Rays

The angular distributions of γ rays of energy greater than $\frac{1}{2}$ MeV were measured using the NaI scintillation counter for 40.5-MeV α particles on ^{167}Er. These spectra were corrected for the oxygen contributions from the Er_2O_3 target and were unfolded as mentioned in Sec. II. The results are presented graphically in Fig. 6. It is seen that the photons of energy greater than about 1 MeV are emitted almost isotropically whereas the photons between $\frac{1}{2}$ and 1 MeV have an angular distribution similar to that of the rotational photons. The anisotropy is, however, somewhat smaller than those of the rotational photons.

If the absolute cross sections for the production of photons with $E_\gamma > 1$ MeV are compared with the expected total reaction cross sections[22,23] at this bombarding energy it appears that an average of about three such photons are emitted per reaction.

Because of the large yield of anisotropic photons between $\frac{1}{2}$ and 1 MeV, it was of interest to examine the yield and angular distribution of unresolved photons below $\frac{1}{2}$ MeV. This was done using the data obtained with the germanium detector in the ^{160}Gd(α,4n) reaction. From the observed spectra, corrected for background, we subtracted the observed rotational lines together with their estimated compton tails. The remaining spectrum showed some mild structure superposed on a smooth pattern which resembled that of the original unsubtracted spectrum. It is presumably produced by large numbers of relatively soft quanta which do not show up strongly enough to be unambiguously resolved. The total intensity of the remainder spectrum was about 2.4 times that associated with the ground-state rotational band. The angular distribution of this unresolved low-energy part of the spectrum was found to be anisotropic with the same sign of anisotropy as that of the rotational lines. The magnitude of the anisotropy was however much smaller; the 20°/90° ratio was about 1.15 compared with the value 1.6 typical of the rotational lines.

IV. DISCUSSION OF RESULTS

A. Unexpectedly Low Values of the J_M's

It is seen from Tables I and II that the median J values determined in a variety of bombardments between 30 and 40 MeV lie in the range from 5 to 7 units of angular momentum. To determine whether these values are in accord with theoretical expectations, a number of calculations based on a simple statistical model were carried out. The model, described in detail elsewhere,[21] consistently led to J_M values about twice as large as those observed. A discrepancy of this magnitude is too large to be accounted for in terms of the

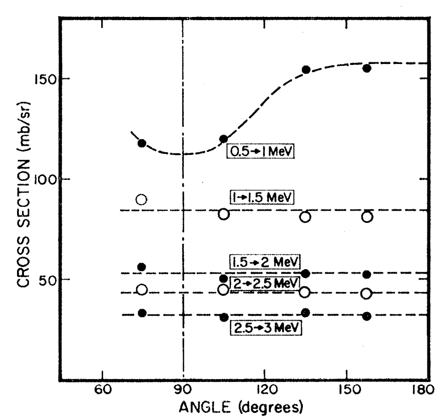

FIG. 6. The angular distribution of photons in the reaction ^{167}Er(α,3n)^{168}Yb for photon energies greater than $\frac{1}{2}$ MeV. For this presentation the spectra were corrected for oxygen contamination in the target and divided into energy bins $\frac{1}{2}$ MeV wide. The statistical errors are everywhere smaller than the data points. The absolute cross sections are estimated to have uncertainties of about 15%.

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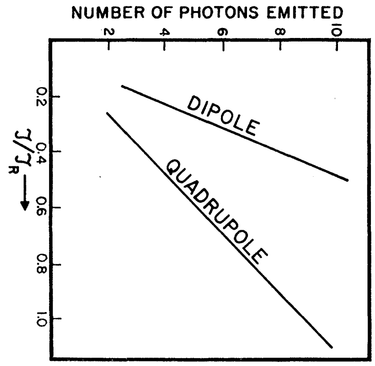

FIG. 7. A diagram to show which sets of values of the three critical parameters in the statistical theory lead to the predictions in accord with the J_M values observed in (α,3n) reactions. The three critical parameters are the multiplicity and multipolarity of evaporated photons and the ratio of the effective moment of inertia of the radiating nucleus to its rigid-body moment.

systematic underestimates of the experimental values for J_M that result from the use of linear extrapolations in their determination. (See Sec. III A.) The extrapolation procedure can be responsible for a downward displacement of the observed J_M of roughly 1 unit, but the discrepancy between statistical theory and experiment is about 7 or 8 units.

It is therefore necessary to scrutinize the theoretical calculations to see in what ways they might be reasonably modified to bring theory and experiment into better accord. In outline, these calculations proceed as follows: One estimates the spin distribution of the original compound nuclei formed upon absorption of the incident α particles by using an optical model.[22] Then one computes, in the framework of evaporation theory, the modification of the original spin distribution brought about by the emission of an appropriate number of neutrons and photons. These emissions leave the final residual nucleus in a low-lying state from which a transition takes place into the ground-state rotational band. The typical spin change associated with this last transition is expected to be small. For this reason, the distribution of entry probabilities into the ground band as a function of the J value of the state at entry is supposed to be a good copy of the spin distribution at the end of the evaporation cascade.

The easiest examination that one can carry out of the theoretical calculation is to see how the results depend on the assumed values of the critical parameters which enter the theory. These parameters are the assumed number of evaporated photons, the multipolarity of these photons, and the effective moment of inertia of the radiating nucleus. This last parameter is conventionally used to describe the spin dependence of the nuclear level density.[21,24] It determines the relative excess, in a statistical emission, of downward to upward transitions in nuclear spin.

[24] T. Ericson, Phil. Mag. Suppl. 9, 425 (1960).

Figure 7 shows the results of a calculation to determine which combinations of values of the critical parameters would reproduce typical observations. For example, if the effective moment of inertia were equal to the rigid-body moment it would require the statistical emission of about 20 dipole photons or 9 quadrupole photons to give J_M values in accord with observations. Such large numbers are consistent neither with observations (Sec. III D) nor with theoretical expectations. In our original theoretical computations, it was assumed that only 3 or 4 photons were emitted before the cascade reached the ground band.

One can reduce the number of photons required to match the observed J_M values by reducing the assumed ratio of the effective moment of inertia to the rigid-body moment. Although one can manage to bring the computed J_M values within range of the observed ones by making a considerable reduction in the assumed value of this parameter, such a reduction would be too severe to be taken lightly. At the very least, any large departure of $\mathcal{I}_{\text{eff}}/\mathcal{I}_R$ from unity raises basic questions concerning the meaning of the effective moment of inertia and whether its use in level density formulas remains appropriate when it is allowed to become very small.

A possible resolution of the J_M dilemma is suggested by the great difference between ordinary statistical photon cascades and those which take place within the ground-state band itself. In statistical emissions a state of spin J_0 decays about equally as often to states with spin $J>J_0$ as it does to states with $J<J_0$. This feature remains characteristic of statistical emissions unless the effective moment of inertia is assumed to be unacceptably small. In the ground-state rotational band, on the other hand, the emissions all decrease the J of the nucleus since there happen to be no opportunities to increase J while decreasing the energy. The average angular momentum loss per photon emission from a rotational state is orders of magnitude larger than that involved in a statistical emission. To account for the excessive emission of angular momentum before the evaporation cascade reaches the ground band, one is encouraged to suspect that some of the earlier emissions might be rotational in character. In particular it seems reasonable that some of these earlier radiations represent rotational transitions in bands built on excited intrinsic states. Because there are so many such bands, one may not expect to resolve individual rotational lines in experimentally observed spectra. Rather, one would expect to see them as an unresolved background.

If such transitions do indeed take place in relatively large numbers, they can be expected to remove considerable amounts of angular momentum from the nucleus.[5,20] In effect there would be, in these higher bands, an angular momentum short circuit.

Although this kind of behavior could be characterized within the framework of the usual statistical theory by assigning unusually small values to the effective moment of inertia, this would not be a very justifiable procedure. What is presumably occurring in these higher bands is a significant amount of nonstatistical emission. That is, although there may be a broad assortment of J values among the states which lie below any given state, it will often be true that there is an especially strong transition to some particular lower state whose J is smaller than that of the given state. Thus, in distinction to the assumptions usually made in statistical theory there is a correlation between the size of the matrix element in a transition and the sign of the spin change. Such a correlation reflects the fact that some specific nuclear structure features are playing a significant role in the decay patterns. In this event one must not expect purely statistical considerations of level densities to account for the observed patterns. To be sure, one can try to simulate this behavior by introducing into statistical theory abnormally small values for $\mathcal{I}_{\text{eff}}/\mathcal{I}_R$. However, the values that one would require would depend on the spin of the radiating state. When $\mathcal{I}_{\text{eff}}/\mathcal{I}_R$ is found to depend upon the angular momentum as well as on the excitation energy of a group of states, it is losing its usefulness as a parameter. Such behavior suggests that one try to treat that portion of the evaporation cascade which passes through higher-lying rotational states in a way that takes the preferred emissions more directly into account than does the usual statistical theory.[25]

It is possible to summarize some of the empirical evidences for the suggestion that there are important rotational transitions between higher-lying states.

(1) Such transitions have been observed in studies of slow neutron capture spectra. There are two reasons that individual lines in higher bands have been seen in slow neutron studies before they were seen in charged particle experiments like the one reported here.

(a) The resolution of the bent-crystal spectrometers sometimes used in such studies far exceeds that of photon detectors normally used in charged-particle studies. Good resolution is invaluable in sorting out decay schemes when many lines are involved.

(b) The low angular momentum input in neutron capture reactions results in the excitation of fewer rotational bands than in typical charged-particle reactions. The spectra are thus easier to unfold and interpret.

An example of the evidence for the importance of higher rotational transitions is afforded by the work of Koch[26] on ^{167}Er$(n,\gamma)^{168}$Er. He finds in ^{168}Er a $K=4^-$ band where the cascade, once it enters this band, tends to flow down through it instead of moving out of it and eventually reaching the upper levels of the ground band. According to Koch's measured branching ratios, the average J at entry into the ground band from transitions starting at the $K=4^-$ bandhead happens to be 2.6 and the corresponding averages for higher starting levels in this band (up to the 8^- level) are all within 0.2 of this value. It is likely that many such bands play a role in the experiments reported here and one can therefore begin to appreciate why the observed values of J_M are so low.

(2) There is a large background of soft quadrupole radiation in the present experiments (Sec. III D). It was seen that there were more unresolved photons below $\frac{1}{2}$ MeV than resolved photons which belong to the ground-state rotational band. Moreover, these photons and those immediately above $\frac{1}{2}$ MeV show anisotropies characteristic of rotational radiations whereas higher-energy photons which are presumably statistical are properly isotropic. Unfortunately, there is some ambiguity in the assignment of these background photons. Many of them must come from the even-odd nuclei which are produced along with the even-even nuclei in each of the bombardments. Rough estimates of relative production cross sections suggest, however, that there are more unresolved rotational photons than one could properly ascribe to these other products. It is clear that to be more definite about this point it would be desirable to study photon spectra in coincidence with the strong rotational lines due to transitions in the even-even residual nuclei.

(3) A comparison of the J_M values observed in ^{155}Gd$(\alpha,3n)^{156}$Dy and ^{156}Gd$(\alpha,4n)^{156}$Dy at the same bombarding energies supports the argument for an angular momentum short circuit in higher bands. The input angular momentum distribution must be virtually the same in these two bombardments. Since four neutrons are emitted in the second reaction compared with three in the first, it is clear that the average photon chain length in MeV or in numbers of photons must be much smaller in the $(\alpha,4n)$ reaction than in the $(\alpha,3n)$ reaction. It is found (Table I) that the J_M values are essentially the same. One may conclude that the reduction in nuclear angular momentum that takes place during the photon part of the cascade is very insensitive to the length of the photon chain. A strong role for higher-lying rotational bands in nuclear de-excitation would contribute to just such insensitivity since a cascade would, as we have seen, tend to leave the band close to the bandhead no matter at what level it first entered the band.

(4) The large anisotropies of the ground-state band radiations (Fig. 5) point to the importance of rotational transitions in the earlier stages of the nuclear de-excitation. It has been stressed that these anisotropies are as large as they can possibly be. That is, they correspond to quadrupole radiation from systems whose angular momenta are oriented perpendicular to the beam. This means that the distributions of orientations

[25] Such an attempt is described for example in H. Ejiri and I. Halpern, Bull. Am. Phys. Soc. **13**, 700 (1968).

[26] H. R. Koch, Z. Physik **192**, 142 (1966); H. T. Motz *et al.*, Phys. Rev. **155**, 1265 (1967); A. Bäcklin *et al.*, *ibid.* **160**, 1011 (1967).

of nuclear spins is about the same when the rotational radiations are being emitted as in the originally formed compound nucleus. Now, the statistical theory does indeed lead one to expect very little spin reorientation during evaporation,[21] but this theory also leads one to expect only a small change in the average J value during the evaporation cascade. As we have seen, this change is, however, quite large. The average J in the original compound nucleus in the reactions studied here is about 15 units, whereas the typical J_M at entry into the ground band is only about 6 units. With so small a value for J_M, it follows that if the evaporation cascade contributed only 2 or 3 units of angular momentum *transverse* to the orientation of the original angular momentum, it would visibly smear out the angular distributions of the rotational lines. The fact that these lines preserve their maximal anisotropies indicates therefore that the large amount of angular momentum carried off during evaporation is by no means randomly oriented as it would be in statistical emissions. On the contrary, it must be very nearly parallel to the angular momentum orientation in the original compound nucleus. Such behavior is characteristic of radiations in rotational bands.

In this discussion of the discrepancy between observed and statistically calculated values of J_M, we have emphasized the possible role of higher-lying rotational bands. It should be acknowledged here that there may be other mechanisms that contribute to the discrepancy. For example, Stephens *et al.*[27] suggest that one reason for reduced yields for the highest spin states in the ground-state band is that these states must compete for their yield with nearby states of comparable spin and energy. This is because these highest spin states ($J\sim14$) lie at energies approaching those of the lowest intrinsic excitations in even-even nuclei. This effect is likely to become quite important in reactions, like those involving incident heavy ions, where the angular momentum input is very large. It may also contribute to the J_M discrepancy in the present experiment. However, since the observed J_M values are so low, it is unlikely that it is here the major source of the discrepancy with the predictions of the conventional statistical theory.

B. Differences among the Measured J_M's

It is seen from Table I that the difference among the J_M values obtained in the various bombardments exceeds the typical experimental uncertainty in the determination of these values. The largest differences among the observed J_M's must therefore be regarded as physically meaningful and it is of interest to see whether these differences can be understood in terms of some simple considerations.

In trying to account for the J_M values observed in the $(\alpha,4n)$ reactions on Sm isotopes which lead to ^{152}Gd and to ^{154}Gd (first entries in Table I), Ejiri *et al.*[20] have emphasized the special role of the β and γ vibrational bands in determining the intensity pattern in the ground-state band. The γ bandhead lies lower than most excited bandheads, i.e., it is well below the first intrinsic excitation. Moreover, the transition probabilities from the γ band to the ground-state band are reasonably strong throughout the band. Thus the γ band serves as an effective stepping stone into the ground band from other bands. In deformed ^{154}Gd the ground-state rotational spacings are significantly compressed compared to those in more nearly spherical ^{152}Gd, whereas the γ bandheads are roughly in the same place. It follows that entry into the ground band through the γ band will occur at higher spins in ^{154}Gd than in ^{152}Gd. This is in accord with measurably different value of J_M observed in the identical bombardments of the two Sm iostopes (Table I).

To pursue this connection an investigation was made in order to see whether the J_M values of Table I for deformed nuclei could be correlated with the ratio of the energy of the γ bandhead to an energy difference characteristic of the rotational spacing. Although there were some mild evidences for such a correlation, there also appeared to be some significant failures. There apparently remain some features of the nuclear structure which have so far not been identified and which are important as regards the intensity distribution of ground-band rotational lines. Here again it would seem that coincidence studies would be very helpful in that they would help sort out some of the important details of the final stages of nuclear de-excitation by photon evaporation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the aid given by the staff of the University of Washington Nuclear Physics Laboratory in various phases of these measurements. Special thanks are due to Dr. R. Vandenbosch and Dr. D. Bodansky for many stimulating discussions and to D. Johnson and D. Chamberlin for assistance during runs. The authors are also much indebted to Dr. H. Ejiri for many enlightening conversations and for permission to refer to his data before publication. They would also like to acknowlegde their indebtedness to Dr. H. Motz and Dr. M. Bunker for providing very useful information about neutron capture spectra. One of the authors (CFW) would also like to acknowledge the hospitality and encouragement of the faculty and staff of the MIT Laboratory for Nuclear Science where a portion of the data analysis was performed.

[27] F. S. Stephens (private communication).