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Much of our information on states of high spin (30-60h) comes from γ-ray spectroscopy of their numerous de-excitation cascades. In such studies selection of particular (high) spin regions are made using multiplicity filters and total-energy spectrometers. The nuclei investigated so far, whether initially near-spherical or deformed, all appear to become deformed rotors at high spin, and effective moments of inertia can be obtained. A new technique of determining energy correlations among coincident transitions in the cascade offers great promise for the future.

I shall be discussing continuum spectra and states from a different point of view than most of the other speakers. I want to say something about their properties as determined from studies of the de-exciting γ-ray cascades. But first, I want to describe what we might expect to see.

In a heavy-ion compound nuclear reaction or in deep-inelastic collisions, product nuclei are made which are highly excited (50-100 MeV) and may have high spins (50-70h). These products very quickly lose energy by the emission of nucleons (α-particles also, if not too high in Z), but this is not an efficient process for the removal of angular momentum, so little of the latter is lost. When the excitation energy is within a neutron binding energy of the yrast line, particle emission stops and γ-emission takes over. The resulting γ-cascades are shown schematically in Fig. 1.
The heavy solid line indicates the approximate region of angular momentum (but not energy) populated in such a nucleus following an \((^{40}\text{Ar}, 4n)\) reaction. Lower spins lead mainly to 5n products, and the spins just above give a small amount of 3n product. The nucleus can decay vertically toward the yrast line by statistical transitions that "cool" the nucleus, carrying off energy, but little angular momentum, or by collective E2 transitions that carry off two units of spin as well as energy, and form bands parallel to the yrast line. There are many pathways, so that no single transition has enough intensity to stand out in the spectrum; this leads to the name "continuum" \(\gamma\)-ray spectrum. When the nucleus cools to near the yrast line there are fewer pathways, and then enough population goes through the individual transitions to make them appear as resolved lines.

The competition between vertical cooling and moving roughly parallel to the yrast line occurs at every step, and the result depends upon the nuclear structure of the particular case and upon where the nucleus is in the excitation energy—angular momentum space. At energies well above the yrast line the statistical transitions have the largest amount of energy available to them and so compete most favorably with the collective transitions. If the nucleus is oblate (or triaxial of dominantly oblate shape) and rotating around its symmetry axis, the
collective rotation is suppressed and the nucleus de-excites rather steeply into the yrast line, reaching it at a relatively high spin. Since the yrast line in this case is irregular, being composed of single-particle states, some of the states may be long-lived enough to be isomeric, the so-called "yrast traps."

But for a strongly deformed prolate nucleus (or triaxial nucleus favoring prolate shape) rotating around an axis perpendicular to its symmetry axis, the rotational bands are strongly enhanced and favor decay roughly parallel to the yrast line, though there is still a trend downwards both because of an occasional statistical transition and because of band crossings. The population intensity does not collect on the yrast line until a relatively low spin is reached, and so rather extensive continuum cascades are to be expected in this case.

It now appears that both of these types of behavior are observed experimentally. Near the closed-shell neutron numbers 82 and 126, there are a number of near-spherical or slightly oblate nuclei with high-spin states that appear to be made of high-j particles with large projections on the symmetry axis. These lead to high-$Q$ isomers and to the observation of discrete states to high spin in the de-excitation cascades. Two of the best examples studied are $^{152}$Dy and $^{154}$Er. Figure 2 shows the decay scheme for $^{152}$Dy; clearly the irregular spacing of the levels indicates a non-collective motion characteristic of the alignment of single particles as expected for a spherical nucleus, or a slightly oblate one rotating around a symmetry axis.

More will be said about such nuclei later, but now I would like to concentrate on the opposite situation, namely, the rotation of prolate deformed nuclei around an axis at right angles to the symmetry axis. As mentioned, these de-excite by collective rotational bands that run roughly parallel to the yrast line and do not decay into that line until spins of 20-30h or lower are reached. Although individual transitions cannot be resolved by present-day techniques, it might be expected that the moments of inertia of these bands would not differ greatly. Then the $I \rightarrow I-2$ transitions, though not identical, would be similar in energy and would occur in a limited region of the $\gamma$-ray spectrum as given by the rotational expression,

(1) \[ E_\gamma = (4I - 2) \hbar^2/2 \]
There is a definite correlation between $E_\gamma$ and the spin of the de-exciting state, in contrast to the situation with the statistical transitions or with the other nonrotational (e.g., vibrational) ones. Figure 3 shows an example of the deexcitation cascades from the 4n product of 181 MeV $^{40}\text{Ar} + \text{126Te} \rightarrow \text{166Yb}^*$, taken with a 7.6 x 7.6 cm NaI detector in coincidence with a Ge detector gated on the 4n lines. 5 The open squares are the raw pulse-height spectrum, and one can distinguish the high-energy exponentially-falling statistical tail and the lower-energy (below 1.5 MeV) yrast bump. The filled points are the same spectrum unfolded, that is, corrected for the NaI response function, to yield the primary $\gamma$-ray spectrum, and, in addition, divided by the NaI efficiency and the number of singles in the Ge counter to yield the absolute number of transitions per event per 40 keV interval. The sum of these points is $\langle M-1 \rangle$, the average multiplicity minus the one trigger $\gamma$-ray in the Ge detector ($\langle M \rangle - 24$ in this case). The angular anisotropy of the $\gamma$-rays is shown at the top of the figure. The large anisotropy observed between 800-1400 keV, the region of the yrast bump, indicates almost pure stretched E2 transitions in that bump. The high-energy tail is very similar in a number of nuclei, and for a number of bombarding energies, and likely corresponds to about half of the 3-4
statistical transitions involved per event. The bump, however, differs from nucleus to nucleus and with bombarding energy. Some evidence for these two statements is shown at the bottom of Fig. 3. The solid line is the locus of the unfolded points above for 181 MeV $^{40}$Ar bombardment. The dotted, short-dashed, and long-dashed lines are similar representations of the continuum spectra from the reactions (331 MeV $^{86}$Kr + $^{80}$Se, (87 MeV) $^{160} +$ 150Sm, and (157 MeV) $^{40}$Ar + $^{126}$Te, respectively, to

![Figure 3](attachment:figure3.png)

**FIGURE 3.** The raw (□) and normalized unfolded (·) $\gamma$-ray spectra from the reaction $^{126}$Te($^{40}$Ar,4n)$^{162}$Yb at 181 MeV. The larger dots are five-channel averages. At the top is the 0°/90° ratio for the unfolded spectra. At the bottom are schematic unfolded spectra for the same case (solid line) and for the reactions 331 MeV $^{86}$Kr + $^{80}$Se (dotted line), 157 MeV $^{40}$Ar + $^{126}$Te (longer-dashed line), and 87 MeV $^{160} +$ 150Sm (shorter-dashed line) to yield the same products (Ref. 5).
yield $^{162}\text{Yb} + 4n$. These three reactions involve about the same average angular momentum (25–30h) in the γ-ray cascade of the $^{162}\text{Yb}$ product, and the spectra are almost identical. In contrast, the higher energy (181 MeV) $^{40}\text{Ar}$ reaction brings more angular momentum to the cascade (~40h on average), and the additional γ-rays de-exciting these higher-spin states move the edge of the bump to a higher transition energy as expected for rotational bands. If we also know the spins of the highest states, we can determine their effective moments of inertia from the rotational formula, Eq. 1. We can, in fact, estimate the spins from the multiplicities, 

$$\langle I \rangle = 2(M - 6)$$

where 6 = 3–4 is the number of statistical γ-rays assumed to carry out no spin, and the rest of the γ-rays are stretched E2 transitions in the case of a good rotor. There are also other ways to estimate the moments of inertia of these continuum high-spin states, and all methods yield values within 10–20 percent of the rigid-sphere numbers. They are usually larger, suggesting deformation, but this is within the range of errors, both experimental and theoretical. However, just from the shapes (and changes in shape) of these spectra alone, we have thus obtained an indication of rotational bands, the average multiplicities, and estimates of the moments of inertia at high spin.

But can we observe the suggested rotational correlation between γ-ray energy and spin more directly? The development of γ-ray multiplicity filters has indeed made this possible. There are a number of multiplicity filter configurations, variously named hedgehog, porcupine, halo, etc., from the geometry of the NaI counters used, but all involve a number of detectors to determine the number of coincidence hits per event and thus statistically the γ-ray multiplicity distribution. A high γ-ray multiplicity corresponds in general to a large angular momentum, although the exact relationship (as given in the previous paragraph for rotors) may not always be clear. But because of this relationship, a measurement of average γ-ray multiplicity as a function of γ-ray transition energy gives direct information on transition energy—spin correlations in the continuum. Examples for two target-projectile systems at several bombarding energies are shown in Fig. 4. For $^{40}\text{Ar} + ^{124}\text{Sn} \rightarrow ^{164}\text{Er}^*$, there is a pronounced peak in the multiplicity spectrum at all bombarding energies, and it comes at the edge of the bump in the intensity spectrum, corresponding to the highest-energy and highest spin transitions. This peak moves to higher energy with increasing
FIGURE 4. Multiplicity vs $\gamma$-ray energy for (a) $^{40}$Ar + $^{124}$Sn and (b) $^{48}$Ca + $^{100}$Mo at the indicated bombarding energies. One $\gamma$-ray spectrum is also shown at the top for each system (Ref. 8).

bombarding energy and hence, higher angular momentum input, a nice confirmation of the collective rotation picture for this nucleus. Away from the deformed rotors, however, there may be more complex behavior. For the $^{48}$Ca + $^{100}$Mo $\rightarrow$ $^{148}$Sm* system the nearly semi-magic product nuclei do not show formation of a rotational peak until about spin 50h.

But all of the cases studied do appear to become rotational at some high spin, and so do $^{152}$Dy and $^{154}$Er, mentioned earlier as outstanding examples of non-collective decay from a weakly oblate nucleus rotating around its symmetry axis. A group at Orsay has recently studied $^{154}$Er in comparison with $^{160}$Er by bombarding targets of $^{119}$Sn and $^{124}$Sn with $^{40}$Ar beams of appropriate energy. The $^{159}$Er compound nucleus
gives a very different γ-ray spectrum from that of 164Er (Fig. 5a) showing two bumps below 1.6 MeV separated by a valley at 1 MeV. The low-energy one has a high intensity and contains all the discrete transitions around 0.7 MeV with spins up to 36h. The higher bump starts at ~1 MeV, and above its maximum at 1.3 MeV seems to resemble the upper part of the rotational bump in the 159,160Er product nuclei. This second bump develops very strongly with increasing fold number, showing that it comes from high-spin states.

The multiplicity spectrum for the 154,155Er products also shows two peaks. The multiplicity estimated for the upper peak, 31, again shows that it comes from the
highest-spin states in the cascade, and there is a remarkable similarity to the upper part of the $^{159,160}$Er multiplicity spectrum. The calculated spin at the top of the cascade is $-60\hbar$ and the moment of inertia is $-150\text{ MeV}^{-1}$. The evidence seems very strong that at about spin $40\hbar$ the products $^{154,155}$Er switch from weakly oblate (or spherical) nuclei, carrying angular momentum by alignment of their high-$j$ particles, to deformed rotors moving around axes perpendicular to their symmetry axes. The experimental results do not tell us whether these shapes are oblate or prolate, but the similarities with the heavier nuclei suggest the latter.

An important goal in studying continuum spectra is to try to select out those spectra coming from regions of particular (high) spin. One of the best ways to do this at present is to make use of a total-energy spectrometer in coincidence with the $\gamma$-ray spectrometers. Continuum spectra may then be obtained as a function of excitation energy (slices) as can be seen in Fig. 6. A total-energy spectrometer consists of a large NaI crystal, or two of them, with the target at the center and only narrow holes letting the beam in and a small fraction of the emitted $\gamma$-rays out to the coincident spectrometers. Thus nearly all the de-excitation $\gamma$-ray energy is absorbed in the sum spectrometer event-by-event. Examples of the spectra obtained are shown in Fig. 7 where the $0^0$ NaI spectra from the $185$ MeV $^{40}$Ar + $^{124}$Sn $\rightarrow ^{164}$Er$^*$ system in coincidence with $-4$ MeV-wide slices of the sum energy are given. These spectra are normalized to the number of transitions per event per $200$ KeV, that is, to the measured multiplicity for each slice. It can be seen that on successive slices the upper edge of the bump moves to higher energy. This is the expected rotational behavior for these deformed Er product nuclei. By subtracting the spectrum of one slice from the next, we obtain the curves in Fig. 7 (bottom), which show the very regular behavior of the additional transitions up to slice 8. If we integrate the difference spectrum for slice 7-slice 6, and take its centroid, we find 3.4 transitions were added having an average energy of $1.40$ MeV. Similarly, slice 6-slice 5 gives 4.0 transitions with an average energy of $1.20$ MeV. From the difference in energy, $0.20$ MeV, and the average number of transitions, 3.7, we determine the moment of inertia to be $2/\hbar^2 = 150\text{ MeV}^{-1}$ for $E_\gamma = 1.30$ MeV. These values correspond to a spin of about $50\hbar$, and this is for states of slice 6. This is surely the simplest and clearest view we have had yet about the transitions at such spins in any nucleus.
Finally, I would like to mention a new technique that has been developed to separate energy-correlated cascades from a background of uncorrelated events in the γ-ray continuum. Consider a nucleus de-exciting through a rotational cascade with a fixed moment of inertia, a true rigid rotor. Then by Eq. 1, the γ-ray spectrum is a set of transitions, evenly spaced at $\hbar^2/2$, as shown in Fig. 8a. If this cascade is looked at by two γ-counters, and the first one is gated on a particular transition, the
FIGURE 7, (Top) Number of transitions per 200 keV per event for consecutive slices in the total-energy spectrum as a function of \( \gamma \)-ray energy in a \( 0^\circ \) NaI detector. The ordinal numbers of the slices are shown. (Bottom) Differences in the pairs of spectra from consecutive slices in the total-energy spectrum as a function of \( \gamma \)-ray energy (Ref. 11).

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FIGURE 8. (a) The evenly spaced (at $8^{2}/2$) transitions from the state indicated for an idealized rigid rotor. (b) The spectrum observed in counter 2 in coincidence with a gate on the $I \rightarrow I-2$ transition in counter 1. (c) Same as (b), but there are three rotational bands with slightly different values of $\hbar$, although all have the same effective value for the $I \rightarrow I-2$ transition.

two-dimensional array, the gap becomes a valley at $45^\circ$, with parallel ridges at each side for the neighboring transitions. But, of course, the real situation is more complicated; the detectors do not yield the original $\gamma$-spectrum, but a pulse-height spectrum with many lower-energy Compton events, and this, as well as the imperfect counter resolution, fuzzes out the detail. And then nuclei do not have a single, constant moment of inertia; especially at low spins the value increases with spin as the pairing correlations are lost. An actual experiment involving the $\gamma$-ray cascades de-exciting the reaction products from $80$ MeV $^{160}$O on $^{64}$Ni was performed using four $12.7$ cm x $15.2$ cm NaI detectors as well as a multiplicity filter of three smaller NaI counters. The main product (75 percent) is $^{74}$Se which has a vibration-like structure to spin $10\hbar$, where it then changes to a rotor. After the two-dimensional data array was treated to remove
non-correlated events, a valley clearly appeared from 800 to 1500 KeV, and its average width corresponded to 
\[ 2 / h^2 = 53 \text{ MeV}^{-1} \]. This value agrees with that obtained from the discrete transitions of the ground band above the structure change at spin 10h, and an additional change in structure at I = 22, not yet seen by more conventional studies, was indicated.

In collaboration with the Copenhagen group, we have undertaken to extend this type of study to larger projectiles, namely \(^{40}\text{Ar}\) from the 88\(^{\text{m}}\) cyclotron, so that the maximum amount of angular momentum possible can be given to the reaction products. In our first experiment we looked at a good rotor, our old friend \(^{40}\text{Ar} + ^{124}\text{Sn} \rightarrow ^{159,160}\text{Er}^* + 5,4n\), using four Ge(Li) detectors, four NaI detectors, and a multiplicity filter. The data analysis has not been completed yet, but a preliminary look at the \(^{159,160}\text{Er}\) results, Fig. 9, does show the valley from ~500 keV to 1 MeV. Above ~1 MeV the valley gets shallower. There are bridges at 0.52 MeV and at ~0.8 MeV and ~1.0 MeV, suggesting structural changes or band crossings. The bridges at 0.5–0.6 MeV can be correlated with the known backbends in \(^{156,160}\text{Er}\) at spins 14\(^+\), 16\(^+\), but the higher ones correspond to features not yet known. Especially intriguing is a plateau from above 1 MeV to about 1.4 MeV, the end of the yrast bump.

It is clear that a whole new type of spectroscopy will be opened up by such a technique and the future improvements on it. Use of far more complex and sophisticated devices such as the "crystal ball" will add a new dimension to these studies, and we can look forward to learning about exciting new properties of nuclei at very high spins.

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FIGURE 9, Two-dimensional contour coincidence array for detector 1 vs detector 2 for 185 MeV $^{40}$Ar $+^{124}$Sn, using Ge(Li) counters. The origin is at 400 keV and there are 24 keV per channel. Non-correlated events have been subtracted by the formalism of Ref. 12.

REFERENCES