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CONTINUUM GAMMA RAYS FOLLOWING (HI, xny) REACTIONS*

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ABSTRACT

The continuum γ-ray spectrum following neutron emission in a (HI, xny) reaction consists of two parts: a high-energy component whose intensity decreases exponentially with γ-energy, the initial statistical cascade; and a low-energy bump which usually contains most of the intensity and consists predominantly of stretched E2 transitions, the yrast cascade. The latter cascade carries away most of the angular momentum of the product nucleus, and so there is a good correlation between the average angular momentum of the initial compound nucleus leading to a particular product and the average gamma-ray multiplicity in that reaction. The measured values of the γ-ray multiplicity show a variation of a factor of ten and have dependencies on the projectile mass and energy which can be explained with simple considerations. Determination of the moment-of-inertia of the nucleus at spins as high as 60h involves difficulties and is not yet accurate, but is very interesting to do and seems possible of better accuracy.

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CONTINUUM GAMMA RAYS FOLLOWING (HI, xny) REACTIONS

R. M. Diamond

I. Introduction

In the last few years (HI, xny) reactions have been much used for the study of the nuclear properties of high-spin states. Today, much is known about low-lying states with spins up to \( \sim 20h \), and interesting phenomena have been uncovered such as "backbending", angular-momentum induced shape changes, and rotation alignment.

But from simple considerations one can estimate the angular momentum brought to the reaction by heavy ions,

\[
\lambda_{\text{max}} = \left[ 2\mu (R_p + R_t)^2 \frac{(E-V)}{\hbar^2} \right]^{1/2}
\]  

where \( \mu \) is the reduced mass of the system, \( E \) and \( V \) are the energy and Coulomb barrier in the center-of-mass system, and \( R_p \) and \( R_t \) are the projectile and target radii, respectively,

\[
R(\text{fermis}) = 1.16 (A^{1/3} + 1).
\]

To estimate the angular momentum actually retained in the compound nuclear system, and to what extent it is formed, requires a model-dependent approach. But whether compound nucleus formation is limited by entrance channel restrictions or by fission, compound systems with up to
60-70h are expected in the mass region 100-180 with Ar or Kr projectiles of the appropriate energy. Such a value is far more than can be accounted for by the discrete γ-ray transitions observed in even the most careful studies of the γ-ray cascades de-exciting the compound-nuclear residues. Clearly large amounts of angular momentum must be carried off by the continuum of γ-rays that precede the discrete transitions. The subject of this paper is the study of these continuum γ-rays, and of what information they yield about the reaction mechanism and about the nuclear structure at high spins. The first figure gives two examples of (high resolution) Ge-counter spectra of de-excitation γ-ray cascades, showing the discrete transitions of the ground-state band at low energies superimposed upon a broad continuum of γ-rays that, above 2 or 3 MeV, fall exponentially in intensity.

Early attempts to study the γ-rays following particle evaporation in a (HI, xny) reaction were made by Mollenauer at Berkeley and Oganesyan and others at Dubna. The Dubna experiment was, and the Berkeley study essentially was, a singles γ-ray measurement using a 7.5 × 7.5 cm NaI spectrometer. Mollenauer used mainly 4He and 12C beams, and the Dubna group used principally 16O ions. Both experimental groups found that with the heavy ions the average cascade γ-ray energy was between 1 and 1.5 MeV, and that of the order of a dozen transitions were involved in the de-excitation cascade. In addition it appeared that more than a neutron binding energy could be tied up in a collective motion of the nucleus, and so not be available for particle evaporation.

More than ten years passed before this topic became of interest again to experimenters. Then a few years ago, der Mateosian, Kistner, and Sunyar used two Ge counters in coincidence to study the continuum γ-rays
following \((^{12}\text{C}, \text{x}\gamma)\) reactions mainly, and were able to pick out the spectrum of a particular \((\text{xn})\) reaction channel by setting windows on known discrete transitions in the ground band of the desired compound-nuclear product. They determined the number of \(\gamma\)-rays in one counter in coincident cascade with known discrete ground-band transitions in the other detector; that is, they determined the \(\gamma\)-ray multiplicities for several \((^{12}\text{C}, \text{x}\gamma)\) reactions. A somewhat similar Ge-NaI coincidence technique has been used by Hagemann, Broda, Herskind, Ishihara, Ogaza, and Ryde\(^9\) to determine the average \(\gamma\)-ray energies and multiplicities of the transitions produced in \(^{159-162}\text{Er}\) by \(^{148,150}\text{Nd}(^{16}\text{O}, \text{x}\gamma)\) reactions, and has also been used by Fenzl and Schult\(^10\) in a similar study. The Copenhagen group has also performed measurements using additional NaI detectors in higher-order coincidence to yield information on the distribution of the \(\gamma\)-ray multiplicities around the average value determined in the simpler Ge-one NaI coincidence system. Tjøm, de Boer, Meyerhof, Banaschik, Simon, Colombani, Soroka, Stephens, and Diamond\(^11,12\) have also used a Ge-NaI coincidence arrangement in a series of studies on the continuum \(\gamma\)-ray cascade of a number of product nuclei; their experimental arrangement will be discussed in the next section. A somewhat different technique employing a liquid scintillation counter-NaI coincidence arrangement with careful adjustment of the bombarding energy to maximize a particular reaction product was used by Newton, Lisle, Draconlis, Leigh, and Weisser\(^13\) to distinguish between the initial "statistical" \(\gamma\)-ray transitions following particle evaporation and the subsequent "yrast" cascade. (These terms are defined in the following paragraph.)
The second figure, a modification of one given by Grover in his series of papers\textsuperscript{14} discussing the de-excitation of compound nuclei, indicates what we believe happens in the \( \gamma \)-ray cascade after particle evaporation in a \((\text{HI}, xn\gamma)\) reaction.\textsuperscript{15} The initial compound nucleus has a relatively sharp excitation energy, but a distribution of angular momentum. On a simple sharp-cutoff model of the nucleus, this distribution is triangular, \( P(\ell) \propto (2\ell+1) \). The emission of a few neutrons takes away large amounts of excitation energy but relatively little angular momentum, so that a similar angular momentum distribution, but with a broadened energy distribution, results after emission of enough nucleons to bring the high end of the angular momentum distribution to less than one neutron binding energy above the yrast line. But for nuclei with lower angular momentum, there may still be enough excitation energy left to emit another neutron. So we might expect some fractionation of angular momenta in the product nuclei with the number of neutrons emitted; the more neutrons emitted, the lower the average angular momentum. After emission of the last particle, the product nucleus is left with thermal excitation above the yrast line of up to one neutron binding energy, and so decays to near that line by a few \( \gamma \)-rays in a statistical cascade (with little change in angular momentum). Decay then proceeds by many paths along the yrast region until a band is reached (usually the ground band) which concentrates the total intensity of the cascades in the discrete transitions observed below \( \sim 20\text{h} \).

In their experiments, Oganesyan et al.\textsuperscript{7} set limits of \( <2.5 \times 10^{-9} \) seconds for the time taken by the nuclei they studied to decay to the discrete ground-band transitions observed. A few years ago we set still
smaller limits using the recoil-distance Doppler-shift technique\textsuperscript{16}) for seven reactions involving projectiles from Ne to Ar and resulting in product nuclei from the rare earths to Os. Ward and his co-workers\textsuperscript{17}) have likewise determined the upper limits to the feeding times in \textsuperscript{130}Ce, \textsuperscript{158}Er, and \textsuperscript{184}Hg, and Kutschera et al.\textsuperscript{18}) have done this for \textsuperscript{120,122}Xe produced by \((^{16}\text{O}, xny)\) reactions on \textsuperscript{108,110}Pd. In general the mean feeding times were < 10 ps, and so an individual transition, on the average, takes a fraction of a picosecond. With an average energy of ~ 1 MeV, only a dipole or a 10- to 100-fold enhanced electric quadrupole transition is fast enough to satisfy this requirement. Hence, if E\textsubscript{2} transitions are involved, they must be part of a collective band. Since the individual members are not observed, there must be of the order of ten such bands carrying the intensity, so that no one set of transitions stands out. For the same reason, the inter-band matrix elements must be quite small to prevent concentration in the lowest band. The only type of collective motion that seems to us to fit the necessary conditions is the rotation of (quadrupole) deformed nuclei. The strong Coriolis mixing that occurs at high spin provides for the rotation alignment of pairs of nucleons, and for such a situation the model of Stephens and Simon\textsuperscript{3}) explains quite naturally the grouping into parallel cascades with vanishing interband transition matrix elements. Mottelson has suggested even a more detailed model, the rotation of an asymmetric rotor,\textsuperscript{19}) in which the degree of wobbling of the angular momentum provides the differentiation in the rotational sequences.

What more can we learn about these transitions and the states they connect? Instead of measuring the gross \(\gamma\)-ray multiplicity, the average number of \(\gamma\)-rays in all the cascades for all exit channels, as did references
6, 7, one can determine the average \( \gamma \)-ray multiplicity of the cascades leading to a specific reaction product, say the \((\text{HI}, 4\text{n})\) or \((\text{HI}, \alpha 3\text{n})\) product. A. Sunyar and his colleagues at Brookhaven\(^8\) did this using two Ge detectors in coincidence; by setting a gate in one counter on one of the discrete transitions in the ground band of a particular reaction product (the \( 12^\text{C}, 4\text{n} \)), they could determine the number of \( \gamma \)-rays in coincidence with it in the other Ge detector, essentially normalized to the low-spin members of the ground band in that counter.

We have pursued our studies on the continuum gamma rays employing a slightly different technique.\(^{11,12}\) We use a Ge-NaI coincidence system, specifying the reaction product by gates on the discrete lines in the Ge detector. After studying the behavior of the neutrons emitted during the reaction with the use of a liquid scintillation counter, we developed the setup shown in Fig. 3. An \( \sim 8 \text{cc} \) intrinsic Ge detector is placed 5 cm from the target, a \( \sim 1 \text{mg/cm}^2 \) foil on a 25 \( \mu \text{m} \) Pb backing. The Ge counter is at 125° or 135° to the beam and is in coincidence, pairwise, with three 7.5\( \times \)7.5 cm NaI(Tl) detectors at 0°, 45°, and 90° to the beam and 60 cm back from the target. This distance allows the pulses generated by the \( \gamma \)-rays and neutrons to be separated by their time-of-flight, as shown in the TAC spectra in Fig. 4. Note that with \( ^{16}\text{O} \), and more so with \( ^{40}\text{Ar} \)(and still more so with \( ^{84}\text{Kr} \)), the neutrons are concentrated in the 0° detector due to the center-of-mass motion of the product. The Kr and Ar beams were furnished by the SuperHILAC, and Ar, O, C, and H beams by the 88-Inch Cyclotron. Typical spectra are shown in Figs. 5-7: a \( ^{84}\text{Kr} + ^{82}\text{Se} \) singles and an \( ^{16}\text{O} + ^{150}\text{Sm} \) singles spectrum in the Ge detector are given in Figs. 5 and 6, the corresponding coincident \( ^{16}\text{O} + ^{150}\text{Sm} \) spectrum in the NaI counter,
II. Gamma-Ray Multiplicities

Dividing the integrated counts in the coincident NaI spectrum gated by a particular photopeak in the Ge spectrum by the number of counts in the same photopeak in the singles Ge spectrum, we can obtain the average number of $\gamma$-rays in the cascades passing through the particular gate peak chosen. That is, we can determine the average $\gamma$-ray multiplicity, $N$, for the cascades passing through that gate. If we let $I_s$ and $I_c$ be the background-corrected singles and coincident intensities of the particular peak,

$$I_s = C \varepsilon$$  \hspace{1cm} (3)

$$I_c = C \varepsilon [1 - (1 - \Omega)^{N-1}] \approx C \varepsilon \Omega (N-1)$$  \hspace{1cm} (4)

where $C$ is the true number of singles gate transitions, and $\varepsilon$ and $\Omega$ are the photopeak efficiency of the Ge detector and the average total efficiency (including solid angle and $\gamma$-ray efficiency) of the NaI counters, respectively, and $N$ is the average $\gamma$-ray multiplicity for the photopeak chosen. Then

$$\frac{I_c}{I_s} \approx (N - 1)\Omega$$  \hspace{1cm} (5)

and the value of the gamma-ray multiplicity, $N$, can be determined once the average NaI efficiency over the energy range of interest is known. The efficiency at a few energies was determined through the use of sources with known cascade populations, e.g., $^{24}\text{Na}$, $^{207}\text{Bi}$, and $^{60}\text{Co}$; with the 7.5×7.5 cm
NaI detectors, Ω is only a slowly varying function of the γ-ray energy from 500 keV to several MeV, and so a fixed value, usually of the order of 0.04%, was used for a particular set of experimental conditions. Because there are expected to be few low-energy continuum transitions (and few were observed), and to help keep the value of the efficiency nearly constant, a lower cutoff of 600 keV was placed on the NaI spectrum. The arrangement was also tested with a 252Cf fission source, by using fission fragments as the gate trigger, and agreement with previous results20) was obtained for the number of γ-rays per fission. It should also be mentioned that corrections must be made for summing of pulses in all the NaI detectors and for Doppler shifts in the 0° and 45° counters.

Results of our early measurements11) on the 166Yb compound-nuclear system are shown in Table 1. The choice of Yb was made because we already knew from another study the characteristic γ-ray transitions of many of the possible light Yb reaction products. Mass 166 represented the heaviest Yb it was convenient to make with a variety of projectile-target combinations, 16O + 150Sm, 40Ar + 126Te, 84Kr + 82Se, and a nucleus with as high a neutron number as possible was desirable in order to minimize charged-particle emission and the onset of fission. In Table 1 the first two columns indicate the gate transition in the Ge detector, and the third and fourth columns give the experimental average multiplicity values for γ-rays above 600 keV in the NaI counter, N > 0.6, for the reactions of 347 MeV 84Kr + 82Se and of 88 MeV 16O + 150Sm to yield the various compound nuclear products listed. For the total average γ-ray multiplicity, N, one must add the number of coincident γ-rays below 600 keV, which in the present case means essentially adding the average number of discrete transitions observed in the ground-state band.
The striking feature of Table 1 is the great variation in the value of $N_{>0.6}$ for different reactions, a factor of 10 overall. This is not likely to be caused simply by the difference in excitation energy remaining when different numbers of neutrons are evaporated, as the $(^1\text{H}, 2\text{n})$ and $(^1\text{H}, 3\text{n})$ reactions show a difference in multiplicity of less than two $\gamma$-rays but have about the same neutron-binding energy difference. However we think the variation in $N_{>0.6}$ is a natural result of angular momentum considerations, as discussed in what follows.

We assume for simplicity that the yrast energy of the product nuclei is that of a rigid rotor,

$$E_{\text{yrast}} = \frac{\hbar^2}{2J} \ell(\ell+1)$$  \hspace{1cm} (6)$$

With $\hbar^2/2J \approx 0.009$ MeV around mass 160, we obtain the situation shown in Fig. 8, and since the number of neutrons emitted depends upon the thermal energy available, namely the difference between the total excitation energy and the yrast line, it is clear that only products involving a small number of emitted neutrons can come from the high-spin states and that the products with the largest number of evaporated neutrons come from the low-spin states. There is a fractionation of the final $xn$ product depending upon the initial angular momentum of the nucleus. Furthermore, since it takes, on average, a nearly constant amount of energy, $E_n = \text{neutron binding energy} + \text{average neutron kinetic energy} \approx 10-11$ MeV, to emit a neutron, this fractionation corresponds to dividing the original angular momentum distribution into bins of nearly constant width in $\ell(\ell+1)$ or $\ell^2$; at mass 160 with $\ell^2 = E_{\text{yrast}}/0.009$, $\Delta\ell^2 = \Delta E/0.009 = 10/0.009 \approx 1100$. For example, if a bin starts at $\ell=0$, it
can hold all angular momenta up to $33\hbar$, and the bin starting at $\ell=33$ corresponds to the evaporation of one less neutron. But such bins in $\ell^2$ also correspond to bins in the cross section, for on the sharp-cutoff model,

$$\sigma_\ell = \pi \lambda^2 (2\ell+1) T_\ell$$

T_\ell = 1 \quad 0 \leq \ell \leq \ell_{\text{max}}

T_\ell = 0 \quad \ell > \ell_{\text{max}}

Summing the partial cross sections,

$$\sigma_n = \pi \lambda^2 \sum_\ell (2\ell+1) T_\ell = \pi \lambda^2 \ell_n (\ell_n + 1)$$

$$\sigma_{\text{total}} = \pi \lambda^2 \ell_{\text{max}}(\ell_{\text{max}} + 1)$$

and substituting for $\ell_{\text{max}}$ from eq. (1),

$$\sigma_{\text{total}} = \pi R^2 (1 - V/E)$$

where $V$ and $E$ are the Coulomb barrier and initial energy in the c. of m. system. Thus a constant value of $\Delta \ell^2$ corresponds, via eq. (8), to a constant value of $\Delta \sigma$ at a fixed bombarding energy,

$$\Delta \sigma = \pi \lambda^2 \Delta (\ell^2) / 2\mu E$$

where $\Delta \sigma$ and $\Delta (\ell^2)$ are per neutron emitted. With $\Delta (\ell^2) \approx 1100$, this becomes for $A \approx 160$,

$$\Delta \sigma \text{ (barns)} = 740 / \mu E$$

Consider the reaction of $87 \text{ MeV} \, ^{16}O + ^{150}\text{Sm} \rightarrow ^{166}\text{Yb}^*$ shown in Fig. 8. The 4n reaction has the largest cross section, $540 \pm 100 \text{ mb}$, and that compares
with the value 650 mb calculated from eq. (10a). For the 327 MeV $^{84}$Kr + $^{82}$Se $\to ^{162}$Yb + 4n case, eq. (10a) gives $\Delta \sigma = 110$ mb, compared with a measured value of 105±25 mb. Thus, the equation seems grossly correct, and we may consider Fig. 8 in greater detail. Going back to the $^{16}$O + $^{150}$Sm case, we can use the measured cross sections for the 5n, 4n, and 3n reactions to determine the 5n-4n boundary, the 4n-3n boundary, and a value of $\ell_{\text{max}}^2$ from the sum of the three cross sections. Neglecting charged-particle emission (which would probably raise the value of $\ell_{\text{max}}$ by $\approx 10\%$), we obtain $\ell_{\text{max}} = 35$. This is in good agreement with the estimate from

$$\ell_{\text{max}} = [2\mu (E-V)]^{1/2} R/h = 0.219 R [\mu (E-V)]^{1/2}$$

(1a)

which gives $\ell_{\text{max}} = 37$ for this case (using $R$ in fermis and $(E-V)$ in MeV). For the $^{84}$Kr + $^{82}$Se case, we can consider the 4n cross section as a full bin and find from the 5n and 3n cross sections 0.34 and 0.65 bins respectively. Since the 2n plus the 6n cross sections add less than 0.15 bin, this places the upper limit for compound nuclear xn products at $\ell_{\text{max}} = 2360$ or $\ell_{\text{max}} \approx 49$. Addition of the cross sections for the $\infty n$ products (measured) and the pxn products (estimated) only increases $\ell_{\text{max}}$ to 55, far smaller than the value $\ell_{\text{max}} = 79$ calculated from eq. (1a). However, it is now well known that with heavy ion projectiles the cross section for evaporation residues may not increase with bombarding energy above a certain value, and may in fact decrease, and there are at least two mechanisms to account for this difference. Firstly, with an increase in angular momentum the fission barrier drops, so that when it reaches the order of the neutron binding energy, fission can compete with neutron emission and may become an important process at
high angular momentum.\textsuperscript{5,22}) Secondly, with heavy-ion projectiles there may be entrance-channel effects that limit the amount of angular momentum brought to the compound nucleus,\textsuperscript{4,23}) and the observation of the deep inelastic scattering reactions is an important example.\textsuperscript{24}) Figure 9 taken from ref. 4 shows these two types of limitations on the angular momentum left to a compound-nuclear system calculated in particular ways.

For each bin in Fig. 8, whether full or only partially so, one can calculate an average angular momentum, $\overline{l}$,

$$\overline{l} = \frac{2}{3} \frac{l_f^2 + l_f l_i + l_i^2}{l_f + l_i}$$

(11)

where $l_i$ and $l_f$ are the angular momentum values at the initial and final boundaries. From the discussion about Fig. 2, we might suspect that there should be some correlation between the average angular momentum of a bin and the length of the de-excitation $\gamma$-ray cascades for that reaction product. In Fig. 10 the values of $N_{>0.6}$, the experimentally determined $\gamma$-ray multiplicities for pulses over 0.6 MeV, are plotted vs. these $\overline{l}$. These are all points for the xn products of the $^{166}$Yb compound nucleus, and there is a clear correlation between the average multiplicity and the average angular momentum. The three points at $N_{>0.6} \approx 10$ and $\overline{l} \approx 30$ are particularly illustrative; they correspond to an ($^{160}$O, 4n) an ($^{40}$Ar, 5n) and a ($^{84}$Kr, 4n) reaction, showing that neither the nature of the projectile nor the number of neutrons emitted is an important factor governing the value of the multiplicity, but that the average angular momentum in the compound systems at the start of the $\gamma$-ray cascade is decisive.
We believe that this conclusion is the most important one to come out of this first study, and admittedly in hindsight it seems most reasonable. A secondary conclusion is that there does appear to be some fractionation by angular momentum into the different $\alpha n$ reactions, although the lines separating the bins are surely not as rigid as in the simple model used.

III Gamma-Ray Multipolarities

We might also consider whether the measured multiplicities allow for enough $\gamma$-rays to carry off the angular momentum corresponding to $\overline{\mathcal{E}}$, remembering that only dipole and E2 transitions are fast enough to be consistent with the (few) feeding times that have been measured. For example, in Fig. 10 the points at $\overline{\mathcal{E}} = 30$ have $N_{\mathcal{E}_2 > 0.6} \approx 10$. If they are all stretched E2 transitions, they remove $20\hbar$, leaving $10\hbar$ to be accounted for. But for these doubly-even Yb nuclei, there are on the average 5 or 6 additional discrete E2 transitions in the ground band that are below 600 keV and must be included. In the $\gamma$-ray cascades leading to odd-mass Yb nuclei, fewer discrete stretched E2 transitions are usually observed, on the average, but they are from a cascade built on a $13/2^+$ bandhead rather than the ground state, so that at least as much additional angular momentum is carried off by the low energy discrete transitions as in the doubly-even nuclei. In addition, the neutrons emitted first may carry off one or two units of angular momentum a piece, though their contribution is at least partially compensated for by the fact that the first 2 or 3 $\gamma$-rays are probably not stretched E2 transitions (see below). But
it appears that the values of $N_{>0.6}$ and $\bar{l}$ shown in Fig. 10 are consistent if the majority of the continuum $\gamma$-rays are stretched E2 transitions.

To check this point, we have measured the angular correlation of the $\gamma$-rays absorbed in the NaI counters that are in coincidence with the entire spectrum in the Ge counter. This is a beam-$\gamma$-gamma-gamma triple correlation, but with the Ge detector at $125^\circ$, the $\gamma$-ray anisotropy, $W(0)/W(90^\circ)$ is almost the same as for a beam-$\gamma$-gamma angular distribution, namely $\sim 1.4$ for stretched quadrupole transitions and $\sim 0.7$ for stretched dipole transitions.\textsuperscript{26) The results for three product nuclei made by irradiating the listed targets with 183 MeV $^{40}$Ar are shown at the top in Fig. 11. The ratio $W(0^\circ)/W(90^\circ)$ for the raw pulse-height spectra is given as solid lines, but a number of corrections must be made. First, since we want to measure the anisotropy of the true $\gamma$-ray distribution and not that of the pulse-height spectrum from the detector, the raw data must be unfolded. We have used for this purpose a computer code originally developed by Mollenauer,\textsuperscript{27) and have modified it, and in particular the response function, to suit our arrangement of NaI detectors. After unfolding, the $0^\circ$ spectrum must be corrected for the fact that the products are moving forward with 2-3% the speed of light when they emit the continuum $\gamma$-rays, so that the latter are Doppler-shifted. In addition the effective solid angle in the $0^\circ$ counter is increased relative to the $90^\circ$ one, and this must be corrected for also. The unfolded and corrected $0^\circ$ spectra are shown in the main part of Fig. 11 (open triangles), and the ratio $W(0^\circ)/W(90^\circ)$ for the unfolded and corrected spectra are also plotted as open triangles above. The process of unfolding worsens the statistics, and hence the errors on the
individual points, but it can be seen in these examples, and in a number of other cases that have been unfolded, that at γ-ray energies below ~ 2.5 MeV the anisotropy rises to ~1.3, and at higher energies the ratio falls to ~1. At the lower energies, where most of the γ-ray intensity is concentrated, (note that the counts scale is logarithmic), the anisotropy indicates predominantly stretched E2 transitions. At the higher energies the few transitions appear to be mixed dipole-quadrupole. So the expectation of the previous paragraph that the majority of the continuum γ-rays in these (HI, xnγ) reactions are stretched E2 transitions when $\langle E \rangle$ is large appears to be confirmed.

IV. Gross Structure in the Continuum Spectra

Figure 11 also illustrates that there appears to be a gross structure in the continuum spectra, namely, a division into a high-energy, nearly exponential tail, and a low-energy bump containing most of the intensity and consisting predominantly of stretched E2 transitions. It seems most natural to associate the exponential tail with the first 2-4 transitions that follow neutron emission and constitute a statistical gamma-ray cascade. This sequence is called statistical because the nucleus does not yet feel the angular momentum pinch but has a high density of states below it to decay into by dipole and quadrupole transitions. But after a few such γ-rays, of a few MeV each, the yrast region is reached and now the nucleus is hard-pressed to lose angular momentum with a minimum loss in excitation energy. So the nature of the transitions changes to stretched E2 γ-rays of moderate (~ 1 MeV) energy; this is the yrast cascade. If only a single sequence of γ-rays were involved they would have enough intensity to be seen
as discrete lines so, as mentioned earlier, there must be a number of such sequences. And because of the short de-excitation times for the whole cascade, the E2 transitions must be enhanced and form numbers of (several) collective bands.

The division of the continuum spectrum into a statistical and an yrast cascade has also been noted by Newton and his colleagues\textsuperscript{13} by a somewhat similar, but not identical, set of experiments using \textsuperscript{16}O projectiles on Sm targets. We believe this is an important result of these studies. We have made preliminary studies of the dependence of the yrast bump on the projectile size, projectile energy, and compound-nuclear mass number. In some cases, such as the \textsuperscript{40}Ar + Cu \rightarrow Ag reaction shown in Fig. 11, the yrast bump is small. Arbitrarily extending the exponential slope of the high-energy tail to low energies (not a correct subtraction of the statistical cascade, as it is expected to have few low-energy transitions) allows rough comparisons to be made between the different compound-nuclear product systems. For example, the ratio of intensities of the bump to the exponential tail so defined is \( \sim 0.5 \) for the products found by \textsuperscript{183}-MeV \textsuperscript{40}Ar irradiation of Cu, and even less for \textsuperscript{183} MeV \textsuperscript{40}Ar on Al. For \textsuperscript{183} MeV \textsuperscript{40}Ar on \textsuperscript{82}Sc and \textsuperscript{126}Tc, the ratio is \( \sim 2.8 \) and \( 3.3 \), respectively. We do not as yet understand this dependence on product mass, nor the other examples we have found.

The projectile energy dependence is easier to explain. At low energies, little angular momentum is brought in over the Coulomb barrier, so there is only a short yrast cascade, and hence a small bump. With increasing energy, increasing angular momentum is brought in, and the yrast cascade involves more low-energy E2 transitions, the \( \gamma \)-ray multiplicity
increases. So the bump grows relative to the exponential tail until the bombarding energy is high enough to open new decay channels such as fission, direct reactions, deep inelastic scattering, etc., which use up the high-angular-momentum collisions, and may even cause the gross γ-ray multiplicity to fall.

Somewhat similar is the explanation for the projectile dependence. Small ions, such as $^{12}\text{C}$, cannot bring in very much angular momentum to the compound nucleus at moderate energies above the Coulomb barrier, and so the bump is not as pronounced as with larger ions. At higher energies, where $^{12}\text{C}$ might be expected to bring in as much angular momentum as a larger ion at more moderate energy, other reactions occur to drain away the high-angular-momentum collisions, and so the bump never becomes as pronounced as with Ar and Kr beams.

V. Moments-of-Inertia of High-Spin States

Although much is yet to be learned about the dependencies described in the previous section, more information of another type can be extracted from the present data to give some clues as to the nature of the high-spin states that are at the top of the yrast cascade. Consider Fig. 12 which shows spectra from the reactions $^{82}\text{Se}(^{40}\text{Ar}, x\gamma)^{116,118}\text{Te}$ and $^{126}\text{Te}(^{40}\text{Ar}, 4\gamma)^{122}\text{Yb}$. Coincidence requirements in the Ge detector allowed selection of the four lowest ground-band transitions from each reaction as gates. The sums of the resulting NaI spectra have sharp edges at the upper boundary of the yrast bump; they are visible already in the raw pulse-height spectra, but are enhanced in the unfolded spectra. These breaks come at
different energies for the different product nuclei, at about 2.4 MeV for the 4n Te product and 1.7 MeV for the 6n one. That is, the break comes at a higher energy for the channel associated with the higher angular momentum values. We can estimate the average angular momentum involved in these two reactions with 183 MeV $^{40}$Ar from the corresponding average γ-ray multiplicities. Since the discrete ground-band transitions in these two cases have energies greater than 600 keV, they are already included in $N_{>0.6}$ so $2N_{>0.6}$ is a good estimate for $\bar{\epsilon}$, yielding 58h and 26h for the 4n and 6n reactions, respectively. From these average values we can now deduce the "highest" spin value involved in each reaction, namely, the angular momentum at the upper boundary of the bins as illustrated in Fig. 8. For the 4n reaction with 183 MeV $^{40}$Ar, this value will be only slightly higher than $\bar{\epsilon}$ itself, 58h. We will take the value calculated by the Bass model$^{28}$ for the limiting angular momentum for this case, 64h, which should be good to better than 15%. For the 6n reaction, the value for the upper boundary should be somewhere near the average of the values of $\bar{\epsilon}$ for the 6n and 5n reaction bins, so we shall take 34h, with an error of ±20%. With the assumption that the energies of the yrast cascade transitions go up monotonically with spin, the upper edge of the bumps in Fig. 12 involves the state of highest angular momentum and the transitions of highest energy. Substituting these values in the rotational formula

$$E_t = \frac{\hbar^2}{2J} (4I-2)$$

(12)

where $E_t$ is the transition energy and $I$ is the spin of the upper state, we can determine the value of an effective rotational constant, $\frac{\hbar^2}{2J}$, or
of an effective moment-of-inertia, $\mathcal{J}$, for the highest state in the yrast cascade for that reaction. For the state in $^{116}$Te with $I = 34$ (the $6n$ reaction) $h^2/2\mathcal{J} \approx 12.7$ keV, and for the state in $^{118}$Te with $I = 64$ (the $4n$ reaction), $h^2/2\mathcal{J} = 9.1$ keV. For comparison, the experimental value of $h^2/2\mathcal{J}$ for the $8^+ \rightarrow 6^+$ ground-band transition in $^{118}$Te is $\approx 26$ keV, and the value calculated for a rigid sphere is 11.8 keV. Liquid-drop estimates which allow for a small amount of deformation with increasing spin are $\approx 11$ keV for $I = 34$ and 9.6 keV for $I = 64$.

The two values of $h^2/2\mathcal{J}$ deduced from the two Te spectra in Fig. 12 carry the uncertainties of the spin estimates, but it is difficult to see how they could be grossly incorrect. Within their 15-20% uncertainties they agree with the rigid-sphere value and possibly somewhat better with the more realistic liquid-drop estimates.

One of the assumptions made in deducing these values of the effective rotational constant was that the increase in energy of the transitions was monotonic with increasing spin. Liquid-drop model calculations for nuclei in this region of the Periodic Table indicate that just at, or above, the region of spin reached in these experiments, the nucleus undergoes a rapid and marked increase in deformation due to centrifugal forces which leads to superdeformed triaxial nuclei, and ultimately to fission. Indeed, single-particle Nilsson potential calculations in the rare earths yield very much the same behavior at almost the same range of spins. The agreement of these two types of calculations in such a prediction makes it very interesting to try to observe this sudden deformation at high spin. As a result of this shape change, the moment-of-inertia may increase so rapidly that the transition energies no longer increase with spin, but decrease,
and the nuclear levels backbend. Independent evidence from fusion and
fission cross sections\textsuperscript{31} does indeed suggest that the $^{118}\text{Te}$ produced by
$^{40}\text{Ar}$ of the appropriate energy on a $^{82}\text{Se}$ target will have angular momenta
up to this very interesting region. The very sharp drop in the unfolded
$^{118}\text{Te}$ spectrum (there is even a hint of a peak) may indicate that we are
close to just such a phenomenon, and attempts to observe such behavior are
continuing.

The edge of the yrast bump is sharper in the unfolded spectra than
in the raw data, and can also be made more obvious by subtracting the 90°
spectrum from the 0° one. The reason for this is that the stretched E2
transitions, the collective yrast ones of interest here, show a maximum
intensity at 0° and a minimum at 90° to the beam, and so are intensified
in the difference spectrum. This can be seen in Fig. 13 for 168 MeV $^{40}\text{Ar}$
on $^{126}\text{Te}$; the 0° raw spectrum and the 0°-90° difference spectrum are shown
for the 3n reaction (top) and the 4n one (bottom). Similarly in Fig. 14
the 0° and the 0°-90° spectra are shown for the 4n reaction product $^{162}\text{Yb}$
(top) and the 5n product $^{161}\text{Yb}$ (bottom). It can be seen that in all cases
the yrast bump edge is pretty well defined. Again, associating the energy
of this edge with the angular momentum of the upper boundary of the reaction
channel leads to a determination of an effective rotational constant or
moment-of-inertia at that spin for these Yb nuclei. In Fig. 15 the ener­
gies of the bump edges, the highest yrast transition energies, are shown
plotted against the spin of the (initial) state. The solid points are for
$^{162}\text{Yb}$ and the known low-spin discrete transitions in this nucleus are also
shown. The open points are for neighboring nuclei, the squares and triangles
being the $3n$ as $5n$ reactions measured under the same conditions, and the
circles are the discrete low-spin transitions in the isotone $^{160}\text{Er}$.
More states are known $^{32}$ for it than for $^{162}\text{Yb}$, and it shows backbending
behavior, as $^{162}\text{Yb}$ might well do also if known to higher spin. The dashed
line gives the rigid-sphere value for mass 162. The same data are shown
on the more usual type of plot to illustrate backbending in Fig. 16. The
high-spin points are probably all consistent with the rigid-sphere value
within the present error limits. Since the liquid-drop estimates differ
from the rigid-sphere value by only $\sim 10\%$ at $I = 50$, and by less at lower
spins, the data are also consistent with liquid-drop shapes.

Better statistics in the continuum spectra will help decrease the
present uncertainties in the position of the high-energy edge of the yrast
bump. But better statistics may also permit another approach to the deter-
mination of effective moments-at-inertia at high spins from continuum spec-
tra. Consider an unfolded spectrum, corrected for Doppler shift, solid
angle, and efficiency, as given for example in Figs. 11 and 12, but with
the ordinate scale normalized so that the integral under the spectrum yields
the value of ($\mathcal{N}-1$), the $\gamma$-ray multiplicity minus 1. Then each point on the
flat part of the yrast bump gives the number of cascade gamma rays per
energy interval, if all the population in that reaction channel passes
through the energy interval of interest. The reciprocal of this quantity is
the average change in the transition energy between successive transitions,
$\Delta E_t$. If we again assume that the transition energies, $E_t$ increase mono-
tonically with spin, than $\Delta E_t$ (related to the slope of the curve in Fig. 15)
can be converted into local effective moment-of-inertia values in the follow-
ing way. From eq. (12),
\[ \Delta E_t = \frac{\hbar^2}{2J} 4\Delta I - \frac{\hbar^2}{2J^2} (4I-2) \Delta J \] (13)

where \( J \) is the equilibrium value of the moment-of-inertia at any spin \( I \).

Since the yrast transitions are predominantly stretched E2 \( \gamma \)-rays, \( \Delta I = 2 \) and

\[ \Delta E_t = \frac{8\hbar^2}{2J} - 2E_t \frac{d\ln J}{dI} \] (13a)

From Fig. 16 it is apparent that for these Yb nuclei \( J \) is nearly constant above \( (h\omega)^2 \approx 0.2 \), corresponding to \( I \geq 25 \), (provided it behaves smoothly). On this assumption the last term in eq. (13a) will be small for this case, and a first approximation to \( \frac{\hbar^2}{2J} \) is \( \frac{\Delta E_t}{8} \), where \( \Delta E_t \) is the reciprocal of the number of gamma rays per energy interval on the flat part of the bump. Using this first approximation in the case of \(^{162}\text{Yb}\) gives \( \frac{2J}{h^2} \approx 125 \) in the applicable region of \( 25 < I < 35 \) or \( 0.2 < (h\omega)^2 < 0.3 \). Taking into account the second term with a value of \( \frac{d\ln J}{dI} \) derived from Fig. 16 reduces the value of \( \frac{2J}{h^2} \) to \( \approx 110 \text{ MeV}^{-1} \), and we feel the correct answer is probably not far from this range.

Even when the second term on the right-hand side of eq. (13a) is not small, it should still be possible to solve eqs. (12) and (13a) for \( \frac{h^2}{2J} \) and \( I \) by an iterative procedure, as long as the primary assumption is valid that the intensity of the cascade for that particular reaction channel is unchanged in passing through the region of interest. Although insuring this means working below the lower boundary of the angular momentum bin for a particular reaction, and so is not applicable for the highest spins, the method should be able to contribute to the determination of the shapes of the curves in Figs. 15 and 16.
Summary

By recording the continuum γ-ray spectra received in one detector in coincidence with a high-resolution spectrum in a Ge counter, it is possible to study the continuum spectra emitted by individual reaction products. One can determine the average γ-ray multiplicity, the average γ-ray energy, and the average γ-ray multipolarity. It appears that most continuum spectra have two parts: a high-energy component of mixed dipole and E2 multipolarity, whose intensity falls off exponentially with γ-ray energy; and a lower-energy bump that is mainly E2 in nature and usually contains most of the γ-ray intensity. The first component can be associated with the initial statistical cascade of a few transitions following neutron evaporation and leading to the yrast region. The second component is the cascade by a number of parallel paths along the yrast line, and removes most of the angular momentum of the product, ending, for an even-even nucleus at levels in the ground-state band with spins between 10h and 20h.

There are very large variations in the γ-ray multiplicities observed, and these seem to correlate well with the initial angular momentum of the compound nucleus. If this proves to be true in general, it provides a means of determining the average angular momentum of the nucleus at the start of the de-excitation cascades. In addition there are interesting dependencies of the γ-ray multiplicity on the projectile energy, projectile mass, and compound nuclear mass.

Finally, these studies appear to be able to yield values of the effective moments-of-inertia of the high-spin states at the top and along
the γ-ray cascade. They may be able to prove or disprove the existence of a rapid and marked increase in deformation at spins above $60\hbar$ predicted for middle-weight nuclei by both liquid-drop and Nilsson-potential single-particle calculations. Such deformations would result in such large increases in the nuclear moments-of-inertia that backbending would take place followed by fission at still higher spins. Certainly we can hope for, and expect, interesting results from such studies.

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References


26. We would like to thank Drs. P. C. Simms and K. S. Krane for helping us with their correlation program.


Table 1. Average number of continuum $\gamma$-rays above 0.6 MeV.

<table>
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<tr>
<th></th>
<th>347 MeV $^{84}$Kr+$^{82}$Se</th>
<th>88 MeV $^{16}$O+$^{150}$Sm</th>
<th>25 MeV $^1$H+$^{165}$Ho</th>
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<tr>
<td>E(keV)</td>
<td>$I_i + I_f$ $N_{&gt;0.6}$ $N_{&gt;0.6}$</td>
<td>$I_i + I_f$ $N_{&gt;0.6}$ $N_{&gt;0.6}$</td>
<td>$I_i + I_f$ $N_{&gt;0.6}$ $N_{&gt;0.6}$</td>
</tr>
<tr>
<td>162Yb(4n)</td>
<td>163Er(3n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>166</td>
<td>2 $\rightarrow$ 0 11 8</td>
<td>127 $13/2^+ \rightarrow 9/2^+$ 1.2</td>
<td></td>
</tr>
<tr>
<td>320</td>
<td>4 $\rightarrow$ 2 14 10</td>
<td>165 $15/2^+ \rightarrow 13/2^+$ 2.2</td>
<td></td>
</tr>
<tr>
<td>437</td>
<td>6 $\rightarrow$ 4 12 9</td>
<td>171 $13/2^- \rightarrow 11/2^-$ 2.3</td>
<td></td>
</tr>
<tr>
<td>521</td>
<td>8 $\rightarrow$ 6 12 9</td>
<td>190 $9/2^- \rightarrow 7/2^-$ 1.3</td>
<td></td>
</tr>
<tr>
<td>579</td>
<td>10 $\rightarrow$ 8 9</td>
<td>213 $15/2^+ \rightarrow 11/2^+$ 1.3</td>
<td></td>
</tr>
<tr>
<td>163Yb(3n)</td>
<td>218 $17/2^+ \rightarrow 13/2^+$ 1.7</td>
<td></td>
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</tr>
<tr>
<td>202</td>
<td>$17/2^+ \rightarrow 13/2^+$ 20 14</td>
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<tr>
<td>345</td>
<td>$21/2^+ \rightarrow 17/2^+$ 19 9</td>
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<td>$164$Er(2n)</td>
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<td>232</td>
<td>$17/2^+ \rightarrow 13/2^+$ 10 5</td>
<td>410 $8 \rightarrow 6$ 3.2</td>
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Figure Captions

Fig. 1. Singles Ge spectra of $^{166}$Yb made by $^{11}$B+$^{159}$Tb (upper curve) and $^{40}$Ar+$^{130}$Te (lower curve).

Fig. 2. Schematic figure showing the energy levels in a nucleus of mass $\approx 160$ vs. angular momentum.

Fig. 3. Diagram of the counter arrangement used.

Fig. 4. Time-to-amplitude converter spectra of the Ge counter and indicated NaI counter (60 cm from target) for $^{16}$O- and $^{40}$Ar-induced reactions.

Fig. 5. Singles Ge spectrum of 345 MeV $^{84}$Kr on $^{82}$Se, showing ground-band transitions in $^{162}$Yb and Coulomb-excited 2+0 transitions in $^{82}$Se and $^{84}$Kr.

Fig. 6. Singles Ge spectrum of 88 MeV $^{16}$O on $^{150}$Sm, again yielding ground-band transitions in $^{162}$Yb.

Fig. 7. NaI-counter spectrum in coincidence with 166 keV 2$^+_\pi$-0$^+_\pi$ photopeak of $^{162}$Yb in Ge detector. Reaction is 88 MeV $^{16}$O + $^{150}$Sm.

Fig. 8. Plot of excitation energy vs. angular momentum squared for a nucleus with $A \approx 160$. The yrast line is drawn as that of a rigid rotor with $E = 0.009\hbar^2$. The angular momentum ranges calculated for the products of the reactions 25 MeV $^1$H+$^{165}$Ho, 87 MeV $^{16}$O+$^{150}$Sm, and 327 MeV $^{84}$Kr+$^{82}$Se are shown. The projectile energies have been corrected to mid-target values.
Fig. 9. Critical angular momenta vs. Z of the compound system. The dashed line shows the limits of angular momentum for a fission barrier of zero from reference 22; the solid lines are the calculations of ref. 4. This figure has been taken from ref. 4.

Fig. 10. Average number of continuum γ-rays with $E_\gamma > 0.6$ MeV coincident with the lowest observed discrete transition ($2^+ \rightarrow 0^+$ or $17/2^+ \rightarrow 13/2^+$) vs. the initial average angular momentum of the compound nucleus leading to that reaction. The cross is for the reactions $^{165}$Ho($^1$H,xnY)$^{163,164}$Er, and the circles, triangles and squares are for the 5n, 4n, and 3n reactions from $^{16}$O+150Sm (open), $^{84}$Kr+$^{82}$Se (closed), $^{40}$Ar+$^{126}$Te (half-closed). The parentheses on the $^{84}$Kr data indicate that considerable uncertainty in the values of $\bar{x}$ is introduced by the target thickness in this case.

Fig. 11. The raw (dots) and unfolded (triangles) continuum spectra in coincidence with the full Ge-detector spectrum for 183 MeV $^{40}$Ar projectiles on Cu, $^{82}$Se, and $^{126}$Te targets. The straight lines are fitted to the unfolded spectrum between 3.2 and 6.2 MeV (solid portion) and extrapolated to lower energies (dashed portion). The upper plots show the $0^\circ/90^\circ$ intensity ratios for the raw data (dots) and for the unfolded data corrected for recoil motion (triangles). The error bars indicate statistical errors only.

Fig. 12. The histograms show the raw continuum spectra in coincidence with the (background-corrected) γ-ray lines from the specific reaction products indicated. Negative or zero counts are plotted at the bottom of the figure. The dots show the unfolded spectra in the lower-energy regions where the statistical variations are not too large.
Fig. 13. NaI spectra of 168 MeV $^{40}$Ar on $^{126}$Te in coincidence with sum of the four lowest discrete ground-band lines in the Ge detector for the 3n product (upper figure) and the 4n product (lower figure). The squares give the $0^\circ$ spectrum, and the points give the $0^\circ$-$90^\circ$ difference spectrum. The straight lines are drawn through the averaged higher-energy points.

Fig. 14. NaI spectra of 183 MeV $^{40}$Ar on $^{126}$Te in coincidence with sum of the lowest discrete ground-band lines in the Ge detector for the 4n product (upper figure) and the 5n product (lower figure). Again the squares give the $0^\circ$ spectrum, and the points give the $0^\circ$-$90^\circ$ difference spectrum. The straight lines are drawn through the averaged higher-energy points.

Fig. 15. Plot of the transition energy vs. the spin of the decaying state for $^{162}$Yb. The open points are for neighboring nuclei, the squares and triangles belong to the 3n and 5n reactions, determined as described in the text, and the circles are the low-spin transitions in the isotone, $^{160}$Er. More levels are known in $^{160}$Er, and it backbends; it seems probable that $^{162}$Yb will also backbend at higher spin. The dashed line is the rigid-sphere value.

Fig. 16. The same data shown in Fig. 15, but plotted in the more usual coordinates to show backbending, $2J/\hbar^2 = (4I-2)/E_t$ vs. $(\hbar\omega)^2 = (E_t/2)^2$. 
Fig. 1

\[ ^{11}\text{B} + ^{159}\text{Tb} \rightarrow ^{166}\text{Yb} + 4\text{n} \]

\[ ^{40}\text{Ar} + ^{130}\text{Te} \rightarrow ^{166}\text{Yb} + 4\text{n} \]  

(background subtracted)
Population following $^{40}\text{Ar}, 4n$

A $\sim 160$

Excitation energy (MeV)

Quasi-particle states

Statistical cascade

Yrast cascade

No levels

Fig. 2
Beam

Ge
125°

Target on Pb backing

NaI
90°

3 x 3" NaI
0°

NaI
45°

Fig. 3
Fig. 4

\[ 126\text{Te} + 40\text{Ar} \ (162\text{MeV}) \]
\[ 162\text{Yb} + 4\text{n} \]
Coinc. with \( \gamma_d = 2 \)

\[ 150\text{Sm} + 16\text{O} \ (91\text{MeV}) \]
\[ 162\text{Yb} + 4\text{n} \]
All coincidences
Fig. 5

Number of counts

1.5 \times 10^4
2 \times 10^4

Energy (keV)

100 200 300 400 500 600 700 800 900 1000

82\text{Se} + 345 \text{MeV} \ 84\text{Kr}

82\text{Se}
84\text{Kr}

2 \rightarrow 0 \ 3n
5n
4 \rightarrow 2
3n
6 \rightarrow 4
8 \rightarrow 6
10 \rightarrow 8
Fig. 7

\[ ^{150}\text{Sm} + 88\text{MeV} \rightarrow ^{160}\text{O} \rightarrow ^{164}\text{Yb} \]

NaI 0° Ge 90°
Gate 166 keV 2^+ - 0^+

Number of counts

Energy (MeV)

Logarithmic scale: 10^1, 10^2, 10^3
327 MeV $^{84}$Kr + $^{82}$Se

4n

5n

3n

$\ell_{\text{max}} = 79$

87 MeV $^{16}$O + $^{150}$Sm

$\ell_{\text{max}} = 38$

25 MeV p + $^{165}$Ho

$\ell_{\text{max}} = 8$

Yrast line, $E = 0.009 \ell^2$

Fig. 8
Fig. 9

- Krypton (■)
- Neon (○)
- Oxygen (●)
- Carbon (△)
Fig. 10
Fig. 11
Fig. 12
Fig. 13
Fig. 14
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