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Submitted on 1 Jan 1980

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EXPERIMENTAL STUDIES OF VERY HIGH SPIN STATES

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Introduction.

Detailed spectroscopy studies of high spin states are limited to the band structures close to and along the yrast line up to I~35. As discussed in previous talks, these studies have in previous few years given good insight and understanding of how the nuclear coupling schemes are influenced by the interplay of quadrupole and coriolis forces. The success of the cranked shell model calculations as the one described by Bengtsson and Frauendorf for the quasiparticle energies in deformed nuclei and the shell model type calculations as e.g. by Dudek or those by Dissing, Neergaard and Sagawa for nuclei near closed shells where not only the energies, but even the static quadrupole moments are reproduced extremely well, is very satisfying.

It would be exciting to extend such studies, both theoretical and experimental, up to the highest spin, nuclei can accommodate, a limit which is found to be $\sim$65 $\hbar$ for nuclei with $A=150$. The study of discrete band structures in this spin region has so far not been possible, and it has therefore been necessary to develop new methods by which one can evaluate at least the gross average properties of high spin states from the so-called $\gamma$-ray continuum. Most of this work is based on measurements of correlations in the $\gamma$-ray transition energy spectrum ($E_\gamma$) with i) spin by excitation functions, $\gamma$-ray multiplicity or/and total energy of the $\gamma$-cascade $E_\gamma$, ii) multipolarity by angular correlation or/and conversion coefficient measurements, iii) collectivity by Doppler shift attenuation measurements on reverse reaction products slowed down in fast stopping material.

Recently a series of second generation correlation experiments has been initiated by studying the transition energy $E_\gamma-E_\gamma$ correlations. These measurements have shown how one in a unique way can extract detailed nuclear properties from average values over many bands built on similar particle configurations. Experiments are in progress by a Berkeley-Copenhagen-GSI collaboration, in which the techniques developed for the 1. generation experiments are incorporated into the $E_\gamma-E_\gamma$ correlation measurements to study the spin-, multipolarity- or lifetime-dependence of the structures observed in the two-dimensional $E_\gamma-E_\gamma$ spectra.

The development of large counter arrays approaching $4\pi$ geometry promises to add yet another dimension to the study of the $\gamma$-continuum from the high spin region. It will be possible with these "Crystal Balls" when com-
<table>
<thead>
<tr>
<th>Correlation parameters</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FIRST GENERATION</strong> Correlation with $E_\gamma$</td>
<td></td>
</tr>
<tr>
<td>$E_\gamma$ vs. $E_{\text{in}}$ + $l_{\max}$</td>
<td>Excitation function</td>
</tr>
<tr>
<td>$E_\gamma$ vs. $&lt;M&gt;$</td>
<td>$\gamma$-multipolarity as function of $E_\gamma$</td>
</tr>
<tr>
<td>$E_\gamma$ vs. $E_2$</td>
<td>Selection of total $\gamma$-ray cascade energy</td>
</tr>
<tr>
<td>$E_\gamma$ vs. $E_{\text{pol}}$</td>
<td>Angular correlation geometry to select multipolarity</td>
</tr>
<tr>
<td>$E_\gamma$ vs. $W(0,\phi)$</td>
<td>Conversion coefficient</td>
</tr>
<tr>
<td>$E_\gamma$ vs. lifetime</td>
<td>Ge(Li) polarimeter</td>
</tr>
<tr>
<td>$E_\gamma$ vs. $(T_{\text{dec}} + T_{\text{feed}})$</td>
<td>Comparison $E_\gamma$ spectrum for recoil in vacuum and stopped</td>
</tr>
</tbody>
</table>

| **SECOND GENERATION** Correlation with $E_\gamma$ | |
| $E_\gamma$ vs. $E_{\gamma}$ | $E_\gamma$ correlation between two $\gamma$-rays |
| $E_\gamma$ vs. $E_{\gamma}$ - angular momentum | |
| $E_\gamma$ vs. $E_{\gamma}$ - $\gamma$-ray multipolarity | |
| $E_\gamma$ vs. $E_{\gamma}$ - lifetime | |

| **THIRD GENERATION** Large fraction of $\gamma$-rays are recorded in individual detector, crystal ball | References |
| Count detectors that fired - small correction | 26, 27 |
| Directly if eff = 1.0 | 1, 28 |
| All available | 11, 18, 29 |
| All available | 6, 20 |
| All available | 30, 31 |
| All available | 32, 33, 34 |
| All available | 35 |
| All available | 20, 21, 22 |
| All available | 23 |
| All available | 36 |

References: 1, 38)
energy. Most of the excitation energy is removed through particle emission $< 10^{-18}$ sec. and the nucleus can in the cases where neutron emission is dominant be produced in bound states (no particle emission) with energies 0-10 MeV above the yrast line and with very high angular momentum. The slower ($>10^{-16}$ sec.) $\gamma$-emission removes the rest of the excitation energy and angular momentum through $\gamma$-cascades. A typical decay process is illustrated in fig.1 and fig.2.

Statistical calculations and the study of continuum $\gamma$-ray spectra are consistent with the hypothesis that the $\gamma$-cascades consist of two parts, namely a few statistical $\gamma$-rays which remove predominantly excitation energy from the nucleus (verified by an exponential tail of high energy transition in the $\gamma$-spectra) and a long series of yrast-like stretched quadrupole and dipole transitions which remove both energy and angular momentum with a $\Delta E/\Delta I$ which in average is roughly equal to the slope of the yrast line, reflected in the observed low energy bump. The flow pattern is illustrated in fig.2.

Several systematic studies$^{4,5,6}$ of continuum $\gamma$-ray spectra performed on many nuclear systems with very different structures in the low spin regions have shown that the statistical transitions are relatively structureless and similar in all cases, only reflecting the temperature of the nucleus at higher excitation energies whereas the yrast-like transitions form a low energy bump of high intensity which shows different characteristics, depending on the nuclear structure of each particular nuclear system.

This is illustrated in fig.3 taken from ref.$^7$, where fig.3b shows a typical spectrum as a result of a $^{124}$Sn + $^{40}$Ar reaction leading to evaporation residues of well deformed $^{158,159,160}$Er nuclei. Excitation functions$^6$ and the sum-spectrometer experiment by the Berkeley group discussed later show that this collective low energy bump of stretched E2 transitions increases in energy with increasing $I_{max}$ as expected for a good rotor. In fig.3a, in contrast to this very smooth bump observed in general for good rotors, a distinctly different structure of the bump is observed for the $^{40}$Ar + $^{119}$Sn reaction leading to evaporation residues close to the $N=82$ neutron shell. For these nuclei it is known from discrete spectroscopy up to $I \sim 35$ that the single particle aspect of the nuclei is dominating. The analysis of this type of spectrum given by the Orsay-Stockholm group$^7$ shows that the upper part of the collective bump originates from stretched E2 transitions probably emitted from a prolate fast spinning nucleus. These data as well as other systematic studies may indicate that the spherical-like nuclei become rotational-like at high spins. More detailed information is needed before clear conclusions can be made, but such data indeed point at the interesting regions for further study. Other regions where irregularities have been observed$^{3,15}$ are $^{50}$Ti + $^{40}$Ar + $^{90}$Zr, $^{50}$Ti + $^{50}$Ti + Ru, $^{82}$Se + $^{40}$Ar + Te, $^{110}$Pd + $^{40}$Ar + Gd, $^{122,130}$Te + $^{48}$Ca + Hf.
Fig. 1. Statistical model calculation\(^1\) for the decay of the \(^{164}\text{Er}\) nucleus from a 147 MeV \(^{40}\text{Ar} + ^{124}\text{Sn}\) reaction. The angular momentum distribution given by the reaction is shown in the top portion of the figure. The depopulation is indicated as function of excitation energy and angular momentum for the evaporation residues after emission of 1-5 neutrons. The shaded region of the 3n-5n population shows the portion in which \(\gamma\)-emission competes. The entry populations for the residues are projected on the energy and angular momentum axis to display the channel overlap to the left and bottom part of the figure. The predicted entry lines are shown for each \(\gamma\)-ray emitting region.

Fig. 2. Schematic diagram of the visualized \(\gamma\)-ray cascades following the particle decay of the \(^{164}\text{Er}\) shown in fig. 1. The contours indicate the \(\gamma\)-ray emitting regions of the 3n-5n evaporation residues predicted from the statistical model calculations of ref.\(^1\).

Fig. 3. Continuum \(\gamma\)-ray spectra (\(E_{\gamma}\)) from \(^{119}\text{Sn}\) and \(^{124}\text{Sn}\) targets bombarded\(^1\) by 185 MeV \(^{40}\text{Ar}\) ions. The spectra are collected in coincidence with at least 4 out of a 6-NaI detector multiplicity filter. The data are obtained by the Orsay-Stockholm group\(^7\).
Fig. 4. The yrast diagram giving all the known even spin states in $^{160}$Yb from the rather complex level scheme of ref. 9). The alignment of the $v(113/2)$ neutron states and the $\pi(111/2)$ proton states is indicated.

The two Moments of Inertia, $J_{\text{coll}}$ and $J_{\text{eff}}$.

A typical example of data from a detailed $\gamma$-spectroscopy experiment is shown in fig. 4 for $^{160}$Yb taken from ref. 8).

Essentially all discrete lines in the spectra down to a level of $\approx$2% of the most intense lines are used in the construction of the present level scheme. The level structure observed is surprisingly well explained by rather simple cranked shell model calculations, which both reproduce the level order, the alignment of several different particle configurations and the rotational frequencies at which the band crossings occur, as well as the interaction strength of the individual crossings. A detailed discussion of this type of data and the interpretation is given in refs. 8, 9, 10).

One may note here that the second backbend observed at a frequency $\hbar \omega \approx 0.42$ MeV is discussed in a contribution to this conference 10) to be experimentally verified via a study of the level scheme of $^{161}$Yb to originate from the alignment of $h_{11/2}$ protons as earlier predicted by Faessler et al. 11).

From these studies it is quite evident that the level schemes for good rotational nuclei show many band crossings in the spin region $\Gamma \approx 10-30$ which can be characterized according to the band crossing frequency, $\hbar \omega_c$, spin alignment, $i$, and interaction strength, $V$, in the vicinity of the crossing.

An interesting question now is whether this type of structure of intermediate coupling strength continues to exist also at higher spins or the bands interact even stronger over larger regions for more extreme rotations under influence of the strong Coriolis force and thereby form a "parallel" strongly coupled band structure as illustrated in fig. 5 by S. Björnholm 10).

Let us take a closer look at a single band crossing and the resulting $\gamma$-ray cascade passing through it, as shown in fig. 6, and try to visualize how an average over many of these bands and band crossings would be detectable in $\gamma$-correlation experiments.

The energy of the levels in each separate band can be written:

$$E_{\text{rot}} = \frac{\hbar^2}{2 J_{\text{coll}}} R^2 + \frac{\hbar^2}{2 J_{\text{coll}}^2} (I-I_a)^2 + E_p(j_s)$$

(1)

where $J_{\text{coll}}$ is characteristic of the in-band
transitions, and \( j_a \) represents the aligned angular momentum, \( E_p \) the energy of the quasiparticle configuration, and \( R \) the collective angular momentum.

For constant \( \delta_{\text{coll}} \) and \( j_a \) within a band the transition energies are:

\[
E_Y = \frac{\hbar^2}{2\delta_{\text{coll}}(1)} \cdot 4R = \frac{\hbar^2}{2\delta_{\text{coll}}(1)} \cdot 4(I-j_a) = 2\hbar \omega \tag{2}
\]

and the curvature of the band related to the change in \( E_Y \) for successive transitions are:

\[
\frac{dE_Y}{dt} = \frac{\hbar^2}{2\delta_{\text{coll}}(2)} = 4 \frac{d\omega}{dt} \tag{3}
\]

where the subscripts (1) and (2) indicate when the 1. or 2. difference in the transition energy is used.

In the continuum \( \gamma \)-ray spectra one can not resolve the individual bands, but if many bands have a similar \( \delta_{\text{coll}} \) and \( j_a \), one may observe such bands in the \( \gamma-\gamma \) correlation spectrum and an average \( \delta_{\text{coll}}(2) \) may be extracted.

The effective moment of inertia \( \delta_{\text{eff}} \) which is usually extracted from "1. generation" \( \gamma \)-spectra, may be visualized as represented by the transitions which could have passed through the envelope of the band crossing (see fig. 6). The transitions through this fictive envelope can be written:

\[
E_R = \frac{\hbar^2}{2\delta_{\text{eff}}} \cdot I^2; E_Y = \frac{\hbar^2}{2\delta_{\text{eff}}(1)} \cdot 4I; \Delta E_Y = \frac{8\hbar^2}{2\delta_{\text{eff}}(2)} \cdot \frac{dE_Y}{dt} \tag{4}
\]

From eqs. (2) and (4) we derive the ratio of the two different moments of inertia

\[
\frac{\delta_{\text{coll}}(1)}{\delta_{\text{coll}}(2)} = \frac{I-j_a}{I} \cdot \frac{\delta_{\text{coll}}(2)}{\delta_{\text{eff}}} \tag{5}
\]

which is an important consequence of the above discussion.

Since these rules are rather simple, it is useful to discuss and compare the experimental data from the \( \gamma \)-continuum in this frame. The \( \gamma \)-ray flux measured by an \( \gamma \)-ray detector in "singles mode" (1. generation experiment of table 1) represents the average over many different bands and band crossings. This means, that only average quantities can be measured. It is seen from fig. 6 that 3 different quantities are equal for the decay either through the crossing bands or through the fictive envelope band, namely:

\[
\frac{<M>_{\text{band}}}{\text{keV}} = \frac{<M>_{\text{env}}}{\text{keV}} \tag{6}
\]

\[
E_{\gamma,\text{band}}(I_{\text{max}}) = E_{\gamma,\text{env}}(I_{\text{max}}) \tag{7}
\]

\[
\frac{<E_{\gamma}>_{\text{band}}}{\text{keV}} = \frac{<E_{\gamma}>_{\text{env}}}{\text{keV}} \tag{8}
\]

Therefore, the effective moment of inertia, \( \delta_{\text{eff}} \), of the envelope band may in principle be extracted from the \( E_{\gamma} \) "singles" spectra in 3 independent ways:

1) According to eq. (6) the height of the yrast bump in the \( E_{\gamma} \) spectra normalized to \( <M>/\text{keV} \), the number of transitions per keV, is linearly proportional to \( \delta_{\text{coll}}(2) \).

2) The energy of the upper edge of the yrast bump (or the more sharp multiplicity bump) is in average proportional to \( I_{\text{max}} \) and since eq.(7) is valid in average one may use the approximation that

\[
E_{\gamma,\text{max}} = \frac{\hbar^2}{2\delta_{\text{eff}}(1)} \cdot 4I_{\text{max}} \tag{9}
\]

\( I_{\text{max}} \) is usually evaluated from the experimental \( f_{\text{max}} \) of the reaction or from measured multiplicity values.

3) The difference in average transition energy for selected spin intervals (which can be approximately measured in a sum spec-
Fig. 5. Two different possibilities for band structures along and above the yrast line. It is in principle possible to determine $J_{\text{eff}}$ and also $J_{\text{coll}}$ which will be different in the two cases.

Fig. 6. Schematic illustration of one band crossing and the implication on the sequence of energy ($E_Y$) distribution from the $\gamma$-ray cascade shown in the left lower part of the figure. The $E_Y-E_Y$ correlation experiment discussed later determines the band curvatures of the upper and lower band as function of $E_Y=2\hbar\omega$ whereas the $l$-generation "singles" measurements of $E_Y$ can determine the envelope curvature in the 3 different ways discussed in the text from the average quantities given in the right lower frame of the figure.
trometer-multiplicity (I-M) setup discussed later) is

\[ \Delta \langle E_\gamma \rangle = \frac{8 \ h^2}{2\pi^2} \ \text{eff} \]  

(10)

Many measurements have been performed and analyzed according to these approximations, and the different evaluations of \( \text{eff} \) give remarkable agreement, although so far no attempt has been made to distinguish between \( \text{eff}^{(1)} \) and \( \text{eff}^{(2)} \). I shall first discuss one of the more general methods, the (I-M) method which has been used to measure \( \text{eff} \) and later the \( \gamma-\gamma \) correlation method which can be used to study in more detail the \( \gamma \) coll.

The Sum Spectrometer.

The principles of the I-M method are given in ref.\textsuperscript{13}), where also the possibility for channel selection is discussed. This latter point can be appreciated from a look at fig.1 where the projected entry regions on the energy and spin axis are shown. Since the binding energy is larger than the kinetic evaporation energy of the emitted neutrons, one expects small overlap between the \( \gamma \) channels on the energy axis and a good channel selection in the total energy of the \( \gamma \)-ray cascades measured in the sum spectrometer. This effect is very useful for the study of discrete lines in particular if many particle channels are open.

For the study of continuum \( \gamma \)-ray spectra where one so far only has looked at bulk properties in different mass regions, the channel selection power is less important, and one may rather use the spectrometer as a "pseudo" spin selector. In the following discussion we have mostly taken this view point.

The principles for the spin selections and the subtraction technique are shown in fig.7. If we assume that the statistical transitions first remove a large fraction of the energy in a given \( \gamma \)-ray cascade, then the decay corresponding to successive selected high window gates (W5-W4) on the sum spectrum of fig.7a can be constructed. This is shown in fig.7b and 7c. The area of the arrows is made proportional to the number of transitions \( \langle M \rangle \). If the multiplicity normalized \( E_\gamma \) spectrum corresponding to window 4 is subtracted from the \( E_\gamma \) spectrum of window 5, then the resulting spectrum (W5-W4) will correspond essentially to only yrast-like transitions as illustrated in fig.7d. It is seen that the sharply selected sum windows \( \Delta E > 20\% \) result in transitions from a fairly wide spin interval, but still with a half width of \( \Delta T \sim 20\% \), due to the steep slope of the yrast line.

A typical setup is shown in fig.8. The target is bombarded with heavy ions in the center of the large NaI crystal (here 20 cm x 25 cm\(^2 \)) in which the major part of the \( \gamma \)-ray cascade is collected. Two (12.5 x 15 cm\(^2 \)) NaI detectors are placed in 0\(^\circ \) and 90\(^\circ \) with respect to the beam at a distance of 60 cm from the target such that the \( E_\gamma \) spectra can be clearly separated from the neutron background by TOP. The effect from the neutrons can not be removed from the sum spectra, but it is less important here, since only few MeV are added to the total energy of the cascades which can be considered as a positive bias. Furthermore the shape of the sum spectra is not used directly.
Fig. 7. A principle diagram to show the spin selection and subtraction technique. Fig. 7a shows a typical sum spectrum (C) with two window gates W4 and W5. Fig. 7b and 7c show a typical decay flow corresponding to the respective window gates W5 and W4, and fig. 7d the expected γ-flow along the yrast line only when (W5-W4) are formed.

Fig. 8. A typical sum spectrometer setup. The experimental details are given in ref. 18.)
With this setup one can study the $E - \gamma$ distributions, the $\gamma$-ray multiplicity $<M>$ and the anisotropy of the transitions as function of the total sum energy of the cascade.

For the ideal sum spectrometer with a $4\pi$ geometry and 100% efficiency including the 2 $E_\gamma$ detectors, the coincidence to "singles" ratio for counts in the sum crystal with one of the transition detectors can be written:

$$N_C/N_S = 1 - (1-\omega)^M \tag{11}$$

where $\omega$ is the solid angle of the $E_\gamma$ detector used for the multiplicity measurement.

If a coincidence with the second detector is required, which is often done to clean the spectra for low multiplicity events, such as transfer reactions, the $M$ has to be replaced by $(M-1)$.

In a more realistic case there will be a loss due to imperfect summing ($\Omega < 4\pi$), and the multiplicity will depend on the actual energy collected in the sum crystal. This effect can be eliminated if both the "singles" and the coincidence rates are treated separately, both with the $E_\gamma$ detector solid angle $\omega$ included into the large $\Omega$, (the energy signals $E_\gamma$ and $E_\Sigma$ added in one spectrum $(N_C/N_S)_{\Omega+\omega}$) and with the $E_\gamma$ detector excluded from $\Omega$, ($E_\gamma$ and $E_\Sigma$ not added in another spectrum $(N_C/N_S)_{\Omega}$).

The average multiplicity $<M>$ can then be obtained by eliminating the parameter $x$, the number of transitions actually collected out of $M$ possible, in the two expressions:

$$\left(N_C/N_S\right)_{\Omega+\omega} = 1 - \left(1 - \frac{\omega}{\Omega+\omega}\right)^M \cong \frac{(M-x)\omega}{1-\omega} \tag{12}$$

which is approximately the same as evaluating $(M_{\Omega+\omega})$ from the added and $(M_{\Omega})$ from the non-added spectra and then find $<M>$ from the equation:

$$<M> = \frac{M_{\Omega+\omega} \cdot (\omega+\Omega) + M_{\Omega} \cdot (1-\Omega)}{\omega+\Omega} \tag{13}$$

In a similar way, the $E_\gamma$-spectrum corresponding to different values of sum energy has to be corrected by the approximate relation:

$$E_{\gamma,\text{true}} \cong E_{\gamma,\Omega+\omega} \cdot (\omega+\Omega) + E_{\gamma,\Omega} \cdot (1-\Omega) \tag{14}$$

If the spectra are measured by sum spectrometers with $\Omega > 0.5$, the errors in these approximations are negligible.

If one is particularly interested in the data originating from the high spin region, it is an advantage to subdivide the sum crystal into several sectors and then require that all the sectors have been activated before an event is stored in the computer. In this case the formulae become more complicated and require a numerical solution for $<M>$. The following equation may be used:

$$\left(N_C/N_S\right)_{\Omega+\omega} = 1 - \left(1 - \frac{\omega}{\Omega+\omega}\right)^M \cong \frac{(M-x)\omega}{1-\omega} \tag{13}$$

and

$$\left(N_C/N_S\right)_{\Omega} = 1 - \left(1 - \frac{\omega}{\Omega}\right)^M \cong \frac{(M-x)\omega}{1-\omega} \tag{14}$$

with $n$ being the number of separated segments. A more detailed discussion of the sum spectrometer technique is given in refs. 14 and 15.

We shall here only concentrate the discussion on two typical examples of this type of experiments. In a case where the nucleus behaves as a good rotor $\gamma$ may be reliably
extracted as a function of \( I \), whereas the analysis is not so straightforward when the nuclear structure is more complicated, perhaps due to large changes in the deformation.

The Berkeley group\(^{16}\) applied the method to the well studied case of \( ^{40}\text{Ar} + ^{124}\text{Sn} \) at a bombarding energy of 185 MeV ensuring that the highest spin states in the evaporation residues of \( ^{160}\text{Er} \) were populated. In this experiment several external \( E_\gamma \) detectors were placed in the vicinity of \( 0^\circ \), and it was therefore also possible to extract the width of the multiplicity distributions. In fig.9 the measured multiplicity \( M \) and width \( \sigma_M \) are shown as functions of total energy measured in the sum spectrometer. It is seen that the expected proportionality between sum energy and multiplicity is obtained. It is noted also that the \( \sigma_M \) seems rather wide at higher multiplicities, indicating that the entry states have a large spread in spin and excitation energy in accordance with hypotheses shown in figs.1 and 8. This spread in \( I \) for definite sum energy windows may be smaller for lower mass nuclei with smaller \( J_{\text{eff}} \) since it depends on the slope of the yrast line.

In fig.10a the \( E_\gamma \) spectra are shown for different gates (windows) on the sum energy spectrum (see fig.9a). It is seen that the number of transitions per 200 keV does not change much from window 5 to 8 which indicates an only slowly increasing \( J_{\text{eff}} \) as function of spin according to eq.(6).

The edge of the bump increases almost linearly with window number, as expected from eqs.(7) and (9). Because of various background considerations, it is only feasible to consider the center region of the sum spectrum. In the lower end the transfer reaction channel will contribute significantly, and in the upper end pile-up effects can be important and therefore have to be evaluated with precaution. The subtraction technique discussed earlier is applied to obtain the result shown in fig.10b. It is seen how the \( \langle \Delta E_\gamma \rangle \) increases linearly with the sum energy as expected for constant moment of inertia (see eqs.(8) and (10)) and how both the low and higher energy transitions subtract out.

A numerical evaluation of these data according to eqs.(8), (10), (12) and (13) is shown in fig.11 where the effective moment of inertia \( J_{\text{eff}} \) is plotted as function of \( h^2\omega^2 \) as frequently used for backbending plots. The data are in very good agreement with the liquid drop predictions\(^{17}\). This was also found earlier from studies using the \( \gamma \)-multiplicity technique on the same reaction channels (see fig.12).\(^4\)

The apparent agreement between the two different experimental methods as well as with the theoretical predictions is a strong indication that the \( J_{\text{eff}} \) can be determined reliably from such data on good rotational nuclei. It should be emphasized, however, that the nuclear systems studied in this case are expected to behave like good rotors over the entire angular momentum range with only small changes in the deformation. With this in mind it would therefore be particularly interesting to apply the technique to nuclei which are not expected to
Fig. 9. The upper part shows the experimental sum spectrum and the xn channel components obtained by gating on known lines in the coincident Ge-spectrum. The middle part indicates the windows used for the multiplicity evaluation and for the subtraction technique discussed in the text. The lower part shows the measured multiplicities <M> and width σM as function of the total γ-ray energy. The points on the dotted line correspond to the measured multiplicity by means of a 0° Eγ-counter and no angular correlation correction, whereas the points on the solid line have been corrected for angular correlation effects assuming an 80% stretched quadrupole and a 20% stretched dipole composition of the γ-rays.

behave so regularly.

The NBI-GSI group has performed a similar type of experiment on the 50Ti + 50Zr + 109Ru* and 50Ti + 110Pd + 160Er* giving evaporation residues, 96Ru - 92Mo and 154,155,156Er in the vicinity of the closed shells N=50 and N=82. In fig.13 two sets of Eγ spectra are shown for the 0° and 90° counters corresponding to 5 window gates on the sum energy spectrum with increasing energy. These data have been used to evaluate the multiplicity and anisotropy as functions of Eγ as shown in figs.11a and 11b. If the assumption is made that the major part of the low energy transitions (Eγ<2.8 MeV) is stretched the Eγ spectrum can be decomposed into a (l=1,Δl=1) dipole and a (l=2,Δl=2) quadrupole part. This is shown in the lower part of fig.14. It is clearly seen that the upper part of the bump consists of almost pure stretched quadrupole transitions in both cases, whereas the lower energy part contains both stretched dipole and quadrupole transitions. It is noted that the multiplicities are especially high at the outermost edge of the quadrupole bump.

A more complete set of the decomposed data
Fig. 11. The $I_{\text{eff}}$ moment of inertia obtained by means of eq. (10) from data as shown in fig. 10, plotted as function of $h^2\omega^2$ for points above $h^2\omega^2=0.2$. For comparison the $\epsilon_{\text{coll}}$ obtained from the yrast band in $^{158}\text{Er}$ is shown as black dots labeled with I for (I+I-2).

Fig. 12. The same as fig. 11, except that the data used is from the multiplicity measurements of ref. 4, evaluated by means of eq. (9) for all the points in the right part of the figure. The dashed line shows the prediction from rotating liquid drop calculations.

is shown in fig. 15.

The dipole component is in both cases showing an increase in the number of transitions per 60 keV for higher windows which strongly indicates that a dipole component is present also in the decays between the windows corresponding to the highest spin interval which of course as seen from fig. 7 can have rather wide tails in the spin distributions.

The quadrupole part is quite different in the two cases. For the $^{50}\text{Ti} + ^{110}\text{Pd}$ case there are a low and a higher energy component which both increase with increasing spin, whereas for the $^{50}\text{Ti} + ^{50}\text{Ti}$ case only the high energy part increases in number of transitions for increasing spin intervals.

The spectra are in principle very different from those observed for the good rotors. The increasing number of transitions per energy interval and the almost constant average $<E_X>$ for different windows may be understood as due to an increasing $I_{\text{eff}}$ for increasing spin. If the data for $^{50}\text{Ti} + ^{50}\text{Ti}$ are analyzed numerically in the different ways by use of the formulas (6), (7),
Fig. 13. $E_x$ spectra taken at $0^\circ$ and $90^\circ$ for 5 different window gates on the total energy spectrum for the $^{50}\text{Ti} + ^{50}\text{Ti}$ reaction. The spectra taken with $(5'' \times 6'')$ NaI detectors have been unfolded and normalized to average multiplicity of corresponding windows on the total energy.

Fig. 14. The multiplicity $\langle M_x \rangle$, the anisotropy $N(0^\circ)/N(90^\circ)$, and $E_x$ spectra decomposed into $(J=1, \Delta J=1)$ and $(J=2, \Delta J=2)$ components as functions of $E_x$ are shown in the upper, middle and lower part of the figure, respectively, for two different reactions.

(8), (9) and (10) the result is consistent with the most simple explanation namely that for $^{50}\text{Ti} + ^{110}\text{Pd}$ the $J_{\text{eff}}$ increases linearly with spin up to $J_{\text{rig}}$ at the highest spin interval. The 3 narrow energy distributions of both dipole and quadrupole transitions may indicate triaxial shapes with relatively small changes in particle alignment along a possible axis of collective rotation.

For the $^{50}\text{Ti} + ^{50}\text{Ti}$ reaction there are one increasing dipole and only one increasing quadrupole component with again almost constant $\langle E_x \rangle$, but with a large energy spread in the quadrupole bump. The low quadrupole bump is probably due to the low spin vibrational states through which the decay has to pass before reaching the ground state. This component disappears in the subtracted spectra just like most of the statistical tail. The numerical analysis shows that the $J_{\text{eff}}$ increases linearly with spin but in this case up to $J_{\text{eff}}=1.3$ $J_{\text{rig}}$ indicating that some of the nuclei populated in the highest spin interval may...
Fig. 16. The average decay flow of the γ-cascades is shown in this yrast diagram. The entry points corresponding to the 5 window gates on the total energy of the cascades and the measured multiplicity are shown as open circles connected by the entry line. From the entry points the direction and length of the vertical lines indicate how much statistical γ-rays remove of angular momentum and energy in average for each window. The thick (λ=2, ΔI=2) lines roughly parallel to the yrast line indicate the amount of angular momentum and energy removed by the stretched quadrupole transitions measured for each window interval by the subtraction method, and the thin continuous lines indicate the dipole (λ=1, ΔI=1) parts for the same intervals. The dashed lines indicate the slopes corresponding to the energy spread observed for the quadrupole bump of each window interval. The yrast line corresponding to a rotating liquid drop is shown to be steeper at the highest spin than the measured slope of the average flow of the yrast-like transitions.

be superdeformed with a ratio of axis as high as 2:1. This has been anticipated from theoretical calculations of a rotating liquid drop with a possible stabilization due to shell effects \(^{19}\). The wide distributions of the stretched E2's could be due to the fact that many particle channels are open, but this is not very likely, since the overall shape seems unchanged. The spread could also indicate several different alignment mechanisms present in the same nuclei. In other words, if the spread should be explained by an ensemble of different particle aligned configurations it would mean that at least half of the spin in some of the states is created by alignment of individual particles \(j_a > I/2\) and other states have almost pure collective rotation.

It would be interesting to try to construct a decay path which would be consistent with the above given discussion and
see if the many check points on the energy relations in the data are consistent. This is tried in fig.16. The five entry points are given by the measured sum energy and multiplicity for each energy window, where the measured anisotropies are taken into account in translating M to I. From the highest entry point we then mark the loss in energy and angular momentum consistent with the measured subtracted E\gamma spectra, and the measured anisotropies. It is interesting to note that the internal energy balance and multiplicity evaluations are accurate to within few percent from a comparison of the entry points and sum windows 4, 3 and 2, and that only the endpoint of the constructed decay flow deviates slightly from the position of W\gamma.

The limits of the large spread observed in the E2 bump of ~1.2 MeV are indicated with thick dashed lines. Some other experiment performed by the Orsay group is reported as a contribution to this conference.

It has been the purpose of this section of the paper to demonstrate that it is possible to understand the observed bulk properties of the \gamma-continuum spectra from simple pictures of the nuclear decay from high spin states. On the other hand it is also clear that the underlying structures may be much more complicated than assumed above and more refined methods have to be developed.

Second Generation Correlation Experiments.

In the previous section we used the rotational model as a frame for the analysis of the continuum \gamma-ray spectra. It may be interesting to go a little step further with this idea and ask how the transition energies in one cascade would be correlated if this underlying rotational picture is roughly correct.

For a perfect rotational nucleus with constant moment of inertia the

$$\Delta E_\gamma = 8 \frac{\hbar^2}{2J_{\text{coll}}}$$

is constant for all \gamma-cascades, and the pattern shown in fig.17 may be the result of a \gamma-\gamma coincidence experiment if an ideal detector with no Compton scattering were used. One would expect a clean valley along the 45° diagonal corresponding to $E_{\gamma 1} = E_{\gamma 2}$ since in perfect rotational cascades no \gamma-ray has the same energy as any other. It is noted that the distance between the 1. ridges along the valley corresponds to $16 \cdot \frac{J_{\text{coll}}^2}{2J}$ where $J_{\text{coll}}$ is the moment of inertia of the intraband transitions (see fig.6).

If we further introduce 10% spread in the moment of inertia for the bands used in fig.17 and add one extra transition in each band as a typical example of a backbend, the picture shown in fig.18 can be constructed. It is even more clear from this picture that if rotational structures are dominating in real nuclei, one should be able to detect it by such a simple \gamma-\gamma coincidence experiment. There is, however, one serious experimental difficulty, namely that the (photopeak/total) efficiency for large collimated NaI detectors is ~50% and for GeLi detectors only ~15%. That means that only ~20-25% and 2-3% of the events in a NaI or GeLi coincidence spectrum, respectively, would be due to photopeak x photopeak coincidences, or in other words ~98% of all events in the GeLi spectra will
Fig. 17. $E_Y-E_Y$ coincidence pattern for four rotational bands of constant moment of inertia. The spacings of adjacent ridges and ridges on each side of the equal energy valley are $8A$ and $16A$ respectively, where $A = h/2\xi_{\text{coll}}$.

Fig. 18. $E_Y-E_Y$ coincidence pattern corresponding to the 4 bands shown in fig. 17, plus 4 additional bands with moment of inertia 10% greater and 4 with 10% smaller moment of inertia than those shown in fig. 17. The pattern indicated by solid dots corresponds to non-rotational features (backbending) shown as black peaks in the cascade spectra.

Fig. 19. A typical arrangement for $E_Y-E_Y$ correlation experiments. Since large photopeak/total efficiency is important, the NaI detectors are collimated such that only the center portion of the detector sees the target.

Fig. 20. $E_Y-E_Y$ correlation 2-d spectra taken with NaI detectors for the reaction of $^{118}$MeV $^{12}$C with $^{12}$Sn populating residues of the $^{136}$Ba compound system$^a$.)
be background due to Compton scattering.

To overcome this problem a data reduction technique has been developed to isolate the truly correlated photopeak events from the uncorrelated background of Compton scattered events.

If the number of truly correlated events is small compared to the number of uncorrelated events, the probability of obtaining an uncorrelated event at energies \((E_i, E_j)\) in the two-dimensional plane is

\[
\frac{\sum_k N_{ik}}{\sum_{kk} N_{kk}} \times \frac{\sum_k N_{kj}}{\sum_{kk} N_{kk}}
\]

The number of uncorrelated events \(N_{ij}\) in the spectrum \(N_{ij}\) is then these probabilities times the total number of counts \(\sum_{kk} N_{kk}\) and the number of uncorrelated events is therefore

\[
N_{ij} = \frac{\sum_k N_{ik}}{\sum_{kk} N_{kk}} \sum_k N_{kj}
\]

The "correlated spectrum" \(\Delta N_{ij}(E_i, E_j)\) is then given

\[
\Delta N_{ij}(E_i, E_j) = N_{ij} - N_{ij} - \frac{\sum_k N_{ik}}{\sum_{kk} N_{kk}} \sum_k N_{kj}
\]

By this procedure one finds a correlation spectrum which gives the deviation from the average and in this way enhances the local structures in the spectra.

The subtracted background is too large, however, since the projections \(\sum_k N_{ik}\) and \(\sum_k N_{kj}\) contain also the correlated events. It is possible to improve the spectra towards the absolute number of correlated events by an iteration procedure. The projections of the absolute values of the correlated spectrum \(\sum_k |\Delta N_{ik}|\) and \(\sum_k |\Delta N_{ik}|\) give a good approximation to the number of correlated events in the spectrum and can therefore be used to correct the background subtraction. The next step in the iteration procedure is therefore given by:

\[
\Delta N_{ij}(E_i, E_j)_{p+1} = N_{ij} - \frac{\sum_k (\Delta N_{ik})_p \sum_k (\Delta N_{kj})_p}{\sum_{kk} (\Delta N_{kk})_p}
\]

In the following we shall use the correlated spectra \(\Delta N_{ij}(E_i, E_j)_p\), mostly because it particularly enhances the strongest local structures over the background, whereas the iterated spectra are useful when an absolute number of counts should be extracted, but are more difficult to look at. It is generally true for the typical spectra we have studied so far that the absolute number of correlated events are 3-4 times larger in the iterated spectra after \(\sim 20\) iterations compared to the positive correlations in the 1. order correlation spectra. Since the errors usually are proportional to the square root of the counts in the raw spectra, the relative errors become significantly better (3-4 times) in the iterated spectra.

A typical experimental arrangement is shown in fig.19. Since it is important to avoid "true" pile-up from several \(\gamma\)-rays in the same cascade, which may have a high multiplicity, the solid angle of each counter must be kept < 0.5\%, and since many events
are needed (>50 mill.) it is necessary to use many counters to obtain sufficient statistics especially in the high energy region.

The result of one of the first experiments with NaI counters made at the Stockholm cyclotron\(^{21}\) for the reaction 118 MeV \(^{12}\text{C}\) on \(^{124}\text{Sn}\) target populating the residues of the \(^{136}\text{Ba}\) compound system is shown in fig.20. The general patterns of this spectrum are as expected with a deep valley along the equal energy diagonal and with pronounced inner 1. ridges, and with outer ridges which become less well defined farther away from the valley. The more detailed analysis of this spectrum is given in a contributed paper to this conference by M.A. Deleplanque et al.\(^{21}\).

We shall only here emphasize the very intense bridge observed to fill the valley at \(E = 1120\) keV. This bridge contains as many transitions as the adjacent ridges, indicating that a large fraction of the many rotational-like cascades in the continuum must contain at least two transitions of this energy. It is interesting to note that no discrete lines have been observed at this high energy, although the bridge structure observed in the 2-d spectrum is very pronounced. This is believed to be caused by the fact that many band crossings occur at the same rotational frequency \(\hbar \omega = E_\gamma/2 = 560\) keV.

To understand this multi-band-crossing (MBC) effect it is useful to look at a theoretical calculation where more levels can be systematically included. Let us look at the cranked shell-model calculation performed for \(N=90\) nuclei which we later also can compare to experimental data for \(^{160}\text{yb}\). Fig.21 shows only the positive parity levels based on the \(i_{13/2}\) neutrons of the Nilsson configurations \(|660|1/2\) and \(|651|3/2\) which because of signature splitting give 4 different levels as functions of \(\hbar \omega\). A detailed discussion of these diagrams is given in refs.\(^{1,8,9}\) and by Bengtsson on this conference.

The four neutron levels labeled here as A, B, C and D can be combined to give the 6 possible 2-quasiparticle levels AB, AC, BC, BD and CD. The energy of these levels is obtained as functions of \(\hbar \omega\) by simply adding the energy \(e'\) of the individual particle levels in the rotating frame as given in fig.20. For the purpose of illustration the levels have been smoothed through the crossings.

The energy in the rotating frame of the resulting six 2-quasiparticle states is plotted as thin fully drawn lines in fig.22. (The ground state band and its continuation above the first backbend has 0 energy in this frame - shown as the 0 line). It is f.ex. seen how the aligned particle state AB crosses the ground state band (the vacuum) at \(\hbar \omega_{AB} = .23\) MeV, and the AB configuration thereafter continues as the high spin members of the yrast band. The 4 neutrons can again combine to a 4-quasiparticle state ABCD which is given as a thin dashed-dotted line in fig.22. Since the energy of the particle states is additive in the rotating frame, the rotational band ABCD will cross the band CD at the frequency where AB goes through 0 namely \(\hbar \omega = .23\) Mev (labeled \(\omega_{AB}\)
Neutron quasiparticle energies calculated in the rotating frame as function of rotational frequency $\hbar\omega$ for the 4 lowest positive parity configurations in $^{160}\text{Yb}$. In the text the levels are referred to as the labels A, B, C, D.

**Fig. 21.**

**QUASIPARTICLE ROUTHANS**

- 2qp neutrons
- 4qp neutrons
- 2qp protons
- 4qp neutrons-protons
- possible bandcrossing (not blocked)

**YRAST STATES**

<table>
<thead>
<tr>
<th>Energy of the Quasiparticles in the Rotating Frame (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
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<tr>
<td>3</td>
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**Fig. 22.** The levels shown in fig. 21 are combined to give the 2-qp. neutron levels shown as thin lines with labels AB, AC, BC, AD, BD, and CD on the figure. Similarly the lowest lying 2-qp. proton levels (shown as thick line labeled 2p) are combined with the neutron levels to give the 4-qp. (neutron-proton) levels indicated by thick dashed lines. The black dots indicate the energy and frequency where the various levels possibly may interact.

**Fig. 23.** $E_{\gamma}-E_{\gamma}$ correlation spectra for the $^{147}\text{Sm} + ^{14}O + ^{160}\text{Yb} + 3\text{n}$ reaction at 80 MeV taken with Ge(Li) detectors. The data is the same as used earlier by Riedinger et al. for discrete line spectroscopy. The energies for the different band crossings identified in ref. are indicated on the figure. The channels have been binned together to give 20 keV/channel to obtain better statistics, and then quadratically smoothed by the plotting code.

In fig. 22, the frequency of the first backbend. The ABCD also crosses all the other 2-quasiparticle bands at characteristic frequencies for the pairbreaking of the other five 2-quasiparticle states ($\omega_{AC}, \omega_{BC}, \omega_{AD}, \omega_{BD}, \omega_{CD}$). If we further combine two highly aligned $\frac{1}{2}^+\text{protons}$, labeled (2p) in the figure, into the diagram, a complicated set of band crossings occur. Many of these crossings will be blocked, and only the bandcrossings where possible interaction can take place are marked on the figure with black dots. It is seen that all the allowed crossings line up on specific frequencies $\omega_{AB}, \omega_{BC}$ etc. which
are all characteristic for the breaking of specific pairs of particles like f.ex. the first backbend discussed above. It is interesting to realize that although one is not able to resolve the individual bands in the continuum of γ-rays, one may still be able to identify the highly aligned configurations as bridges in the 2-d spectra and in this way systematically study the details of the nuclear structure which influences the characteristic frequencies for breaking of the particle pairs, as f.ex. the deformations $\varepsilon_2$ and $\varepsilon_4$.

Fig.23 shows the data earlier used for detailed spectroscopy studies of $^{160}$Yb by Riedinger et al.\textsuperscript{8)}, resorted into a two-dimensional spectrum which has been background reduced and binned to 20 keV/channel to obtain better statistics. The position corresponding to the $\omega_{AB}$, $\omega_{AD}$, $\omega_{BC}$ and $\omega_{2p}$ crossings found in ref.\textsuperscript{5)} for the individual bands is marked, and it is seen that bridges (or stepping stones) occur in the valley exactly at those places. The AB crossing is however not so clear because the interaction for this crossing is weak and results in a very sharp backbend. The intensity observed in the valley is not caused by the successive transitions, but rather by those corresponding to the second ridge, in the present case the $8^+\rightarrow6^+$ (589.5 keV) and the $12^+\rightarrow10^+$ (586.8 keV) transitions. The second backbend (2p) is only weakly observed because only states of $I<30$ $\hbar$ are populated in the present reaction. Therefore only a few bandcrossings above the yrast crossing can be populated since many of the possible configuration crossings will occur at $I>30$ $\hbar$ due to the high alignment of f.ex. the 6-gq. states.

A numerical analysis of the number of transitions in the bridges is in progress, but it is evident from the preliminary analysis that the intensities in the bridges are more than twice the values which can be accounted for by discrete lines from the experiment of Riedinger et al.\textsuperscript{8)}. We can therefore conclude that the effect of MBC enhances the bridge structures and that we have a new and interesting possibility of a systematic study of the effect of MBC.

Since we in principle understand the structures observed in the lower spin region, it would also be interesting to extend the experiments to the highest spin regions as well. Such experiments were performed by the NBI-Berkeley-GSI collaboration at the 88° cyclotron in Berkeley\textsuperscript{22}). $^{124}$Sn was bombarded with 170 and 185 MeV $^{40}$Ar ions leading to evaporation residues of $^{158,159,160}$Er, the same systems which earlier were studied in detail by the I-M method discussed in the previous section.

4 GeLi detectors were used to collect 6 pairs of coincidences added into the same matrix and a multiplicity filter of NaI detectors ensured that low spin components were suppressed in a similar arrangement as shown in fig.19.

The result of the 170 MeV run is shown in fig.24. It is seen that the valley extends up to at least 1.2 MeV, but a general filling of the valley is observed to
Fig. 24. $E_\gamma - E_\gamma$ correlation spectrum for $^{124}$Sn($^{40}$Ar, xn)$^{164-x}$Er. $E (^{40}$Ar) = 170 MeV. The transition energies for MBC's in $^{164}$Er and those assumed to occur in $^{165}$Er from the corresponding $^{165}$Yb isotones are indicated.

Fig. 25. $E_\gamma - E_\gamma$ correlation spectrum as fig. 24 except for the higher bombarding energy 185 MeV. The cross hatched areas b, c and d indicate where the projected cuts perpendicular to the valley are made for the data shown in fig. 26.
The known crossings can immediately be identified in the lower energy range as given on the figure, from discrete line studies and cranking calculation, but several more bridges corresponding to unidentified crossings at higher energies can also be seen. A more systematic study of these upper bridges is in progress, but it seems evident that the general structure of band crossings found and studied up to $\sqrt{1\text{MeV}}$ corresponding to $I \approx 40$. The general filling of the valley is more clearly verified in the 185 MeV data shown in fig. 25. Many other cases have been investigated, although not finally analyzed, in the regions around $^{118}$Te, $^{136}$Nd, $^{155}$Er, $^{166}$Yb, and it is seen in all these cases that the valley becomes less pronounced at $E_\gamma$ energies larger than $\sqrt{1\text{MeV}}$. It is not clear yet what the cause of this filling is. It may be connected to the loss of pairing above $I \approx 40$, and/or with $\Delta N=2$ couplings to the higher lying shells which are being strongly aligned and thereby lowered in energy. One really strong more distinct bridge is observed in the 185 MeV data (fig. 25) at $\hbar \omega = 0.55$. Calculations show that this may be connected with the $h_9/2$ proton orbit, but systematic studies on neighbouring nuclei are necessary before more definite conclusions can be made about the details in the high spin region.

As pointed out earlier the distance between the ridges is a measure of the collective moment of inertia $J_{\text{coll}}$ which can then be compared to the measured $J_{\text{eff}}$ discussed in the sum-spectrometer section.

Fig.26b, c and d show projections across the valley for selected energy interval slices $(E_1+E_2)/2$ equal to 750-820 keV, 900-950 keV and 1160-1240 keV, respectively. A tentative location of possible ridges is shown by dashed arrows. The location of a ridge corresponding to a moment of inertia of 150 MeV$^{-1}$ as found for $J_{\text{eff}}$ for these nuclei (see figs. 11 and 12) is also indicated. The width of the valley is clearly 25-50% larger than this, indicating an $J_{\text{coll}}$ smaller than $J_{\text{eff}}$ and an average particle alignment $j_a$ of around 10-20, whereas $I$ is around 45. The general filling of the valley can also be observed in fig. 26a, where projections of slices along the valley and along the ridge are shown. More detailed theoretical calculations are performed by the Lund-group and discussed in ref. 24.

As the last point we will like to discuss the possibility for identifying the lower members of the quasiparticle bands which are, f.ex. crossing the ground state band at higher spin. One may say that these bands will form a second quasi-continuum starting just above the pairing gap as illustrated in fig. 27. The states in this "second" continuum should be predominantly fed by the $(6n)$ channel which has the highest number of neutrons. In the figure this is shown as a $(6n)$ channel in contrast to the $(5n)$ channel which predominantly will feed higher spin states first.

Fig. 28 shows the low energy part of an iterated 2-d spectrum after a $^{40}$Ar +
Fig. 26. Projected cuts on the spectrum shown in fig. 25. The left side of the figure shows cuts along the 1. ridge (squares) and along the valley (open circles). The position of the second back-bend (2bb) is indicated. The right side of the figure shows cuts perpendicular to the valley for the shaded areas in fig. 25. The positions corresponding to $J_{\text{eff}} = 150 \text{ MeV}^{-1}$ and $J_{\text{coll}} = 95 \text{ MeV}^{-1}$ and 110 MeV$^{-1}$ are indicated with arrows.

$^{130}$Te + $^{164,165,166}$Yb reaction with a bombarding energy of 185 MeV. The advantage of the iterated correlation spectra is that photopeak x photopeak correlated events are enhanced and compton scattered events as well as statistical photopeak events which are randomly distributed over the entire 2-d spectrum are suppressed.

A series of ridges parallel to the two axes can be observed. It is believed that they represent a continuum of photopeak coincidences feeding the discrete low spin levels of the ground state bands (gsb) in the $^{164,165,166}$Yb nuclei. Some of the most pronounced ridges are marked with the transitions in the gsb they are in coincidence with. It is seen that all the ridges which belong to the 6n channel feeding the gsb of $^{164}$Yb do not extend as high up in energy as those belonging to $^{165}$Yb. Fig. 29 shows some typical projections on one energy axis when narrow gates are set on the discrete lines on the other axis. The pattern of the continuum $\gamma$-rays is very different in shape for the (6n) and the (5n) channel. The continuum $\gamma$-rays in $^{164}$Yb are concentrated in the low energy region up to 500 keV, and may even show a regular oscillating structure (indicated by cross-hatched areas) which would be characteristic of a series of parallel
Fig. 28. The low-energy part of a GeLi \( \text{Er-Ey} \) correlation spectrum, iterated 20 times, for the reaction \( ^{130}\text{Te} + ^{89}\text{Ar} \rightarrow ^{165,164,166}\text{Yb} \) with 185 MeV. The figure is a Xerox copy of a colour plot, but it is still possible to see the ridges parallel to the axis corresponding to photopeak coincidences with discrete transitions in the ground state bands of \( ^{165,164,166}\text{Yb} \). The strongest ridges are indicated and reflect e.g. coincidences with \( (2^++0^+) \), \( (4^++2^+) \), \( (6^++4^+) \) and \( (8^++6^+) \) in the gsb of \( ^{166}\text{Yb} \).

Fig. 29. Projected spectra corresponding to window gates on discrete transitions \( (2^--0^+) \), \( (4^--2^+) \), \( (6^--4^+) \) and \( (21/2--17/2) \) in the gsb of \( ^{164}\text{Yb} \) and \( ^{165}\text{Yb} \) respectively. The shaded areas indicate the continuum (low-spin) \( \gamma \)-ray transitions, which feed the gsb and are believed to be from rotational bands mainly above the pairing gap.
bands with an $\mathcal{I}_{\text{coll}} \sim 90 \text{ MeV}^{-1}$. If this is the case the broad peaks at 180, 270 and 360 keV would then correspond to $6^+4$, $8^+6$ and $10^+8$ intraband transitions in this "second" quasi-continuum above the pairing gap. At the moment, however, we do not know the multipolarity of the transitions, and much work has to be done before this explanation becomes more than just plausible.

In an experiment by Jin Gen-Ming et al. ref. 25), it has been possible to identify the low spin ($4^+$, $6^+$ and $8^+$) members of the $(113/2)^2 S$-band in $^{160}\text{dy}$ by a ($^3\text{He},\alpha$) reaction. According to the authors, the energy relations in this band are consistent with $\mathcal{I}_{\text{coll}} = \mathcal{I}_{\text{rig}}$. The gsb on the other hand has $\mathcal{I}_{\text{coll}} = 80 \text{ MeV}^{-1}$ at the lowest spins. It is therefore not unlikely that one should find an average $\mathcal{I}_{\text{coll}}$ of $90 \text{ MeV}^{-1}$ for the low spin members of this quasi-continuum. We may hope that a more detailed study of this region will shed more light on the coriolis attenuation effect, since the band structures at low spin are expected to experience particularly strong changes in the alignments due to the coriolis force. Also the structure should be more sensitive to recoil effects in this region.

**Summary.**

It has been the purpose of this talk to show that we in the last few years have come far closer towards the understanding of the bulk properties of high spin states, but also to show that many inspiring problems remain to be solved before a more complete insight into the details of the nuclear phenomena of these states is encountered.

We have shown that one can speak about **two** different moments of inertia, the effective moment of inertia $\mathcal{I}_{\text{eff}}$ which expresses the envelope of the decay pattern and relates to the slope of the yrast line and thereby the shape of the nucleus, and a collective moment of inertia $\mathcal{I}_{\text{coll}}$ deduced from the second derivative of the rotational energy directly related to collective rotations of the core of the nucleus. The ratio of these $\mathcal{I}_{\text{eff}}/\mathcal{I}_{\text{coll}}$ gives the average alignment of the many particle configurations on which the rotations are built at high spin. We have shown that there recently have been developed methods by which one experimentally can determine these values from the $\gamma$-ray spectra. We have also seen how the $E_\gamma - E_\gamma$ correlation method reveals a new way to study the details of the nuclear configurations, namely by determining the characteristic rotational frequencies $\hbar \omega$ at which the individual particle pairs break up and align their spins.

A more systematic study and mapping of this effect is in progress in different laboratories. In principle there is also information about the alignment of the individual particle configurations in the 2-dimensional spectra, but further experiments using more parameters have to be made before we will learn how to extract this information.

As a final point, we discussed the possibility of extracting information from the iterated correlation spectra about the low-
spin quasi-continuum above the pairing gap. An average $T_{\text{coll}} \approx 90$ MeV$^{-1}$ is found for these bands, although very speculative, since f.ex. no spin determination has been made yet.

Acknowledgements.

The work discussed above, much of which is not published yet, has been made in collaboration with colleagues and visitors at the NBI-Risø, LBL-Berkeley, GSI-West Germany and AFI-Stockholm. In particular I would like to thank G.B. Hagemann, J.D. Garrett, F.S. Stephens, O. Andersen, M.A. Deleplanque, R.M. Diamond, C. Ellegaard, Th. Lindblad, S. Ogaza, R.S. Simon, and P.O. Tjøm. Many stimulating discussions with colleagues in Copenhagen and Lund have been most helpful, and I would like especially to thank Aa. Bohr, B.R. Mottelson, S. Bjørnholm, S.Frauendorf, G. Leander, and B.S. Nilsson for help and encouragement.

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