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Gamma-Ray Energy Correlations from Nuclei at Very High Spins

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Abstract: A detailed study has been made of the correlation between two (unresolved) γ ray energies emitted by nuclei at very high spins. The data can be explained as a superposition of γ rays coming from: (1) a high-temperature region where the rotational motion is heavily damped ($\Gamma_{rot} \gtrsim 250$ keV); and (2) a low-temperature region where there is little or no damping ($\Gamma_{rot} \lesssim 50$ keV). This is in qualitative agreement with theoretical expectations; however, the predicted motional narrowing of the damping width is not found.

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Heavy-ion fusion reactions can easily provide as much angular momentum as any fused system can sustain without subsequent fission--about 70$\hbar$ in the rare-earth region. Following particle evaporation, the bulk of this angular momentum is carried off by a cascade of many (up to ~30) γ rays. At the bottom of the cascade, these γ rays consist of strong resolved lines (of energy E_γ) between states in the lowest (few) pathway(s). But with increasing spin, the population spreads out over progressively more and more pathways, so that, typically, above ~40$\hbar$ there are essentially no resolved lines, only a relatively smooth unresolved spectrum. Nevertheless, the average properties of the unresolved γ rays can be studied, and the present indications (based on angular distribution, E_γ-spin correlation, and lifetime measurements) are that the highest spin transitions in all nuclei are basically rotational. However, the rotational behavior in this higher-spin region has special properties, [1,2] which have been interpreted to indicate that the rotational motion is damped [3]. The present work is a study of some of these special properties.

A rotational state deexcites by a series of γ rays, roughly equally spaced in energy. The spectrum in coincidence with one of these γ rays will contain all the rest, but will have the one at the position of the gate missing. The unresolved spectrum is presumably a superposition of many such bands whose properties (moments of inertia, etc.) vary sufficiently to make a smooth spectrum. A gate on such an unresolved spectrum must also produce a coincident spectrum that has a hole or "dip" at the position of the gate transition. The area missing in the dip must be one transition (the gate) but the shape of the dip (width, depth and steepness of sides) carries more detailed information about the rotational behavior. The present work represents the first high-resolution study of the dip with sufficient statistics to say something about its detailed shape. Our conclusion is that the observed dip is not a manifestation of the main damping (which comes at higher temperatures), but is rather a residue from the lower temperature region that has little (or no) damping.

We have studied three reactions, 1) ^{48}Ti (215 MeV) + ^{124}Sn → ^{168}Hf +, 2) ^{40}Ar (180 MeV) + ^{124}Sn → ^{160}Er +, and 3) ^{40}Ar (176 MeV) + ^{100}Mo → ^{136}Nd +, using beams from the LBL 88" Cyclotron. In each case the main (4n) product is given, but there are two or three others made in sizeable yield. However, it seems unlikely that the different products of a given reaction behave very differently at the highest spins. The data were taken on HERA, our array of 21 Compton-suppressed germanium detectors, each of which subtends 0.75% of 4π and has a peak-to-total ratio of about 0.5 for the ^{60}Co γ rays. Between 3 and 7 x 10^8 three-fold and higher events were taken in each of the three cases, which, for the present purposes, were broken down into 1-2 x 10^9 independent pairs of γ rays. These were sorted into a 1000 x 1000 matrix (4 keV per channel) which was symmetrized and then unfolded to correct for the response function of the detectors. Finally a statistical γ-ray spectrum, having a shape, $E_\gamma^3 \exp(-E_\gamma/T)$, for temperature T, was fitted to the high-energy part of the full-projection spectrum and then normalized and subtracted from each row and column of the matrix, thus removing, to a good approximation, the effects of the (largely uncorrelated) statistical γ rays.

Two additional procedures were used to study the detailed shape of the dips. First, in order to remove the large-scale variations in the spectrum, as well as most of the resolved lines, we subtracted a comparison spectrum from each gated spectrum. The comparison spectrum was, in all cases, the full projection of the matrix, normalized to the same number of counts as the gated spectrum. Second, the gates were always 4 keV wide, but, in order to improve statistics, a number of gated spectra (with consecutive and contiguous gates) were shifted in energy, to align the gates, and added. This had the additional effect of smearing out features, like most of the resolved lines, that were not correlated with the gate, but preserving the structures that were correlated with the gate energy. In all cases, the spectra added appeared to be similar except for resolved-line effects.

Three gate-energy regions for the ^{136}Nd data are shown in fig. 1, and similar regions are shown for the other data in fig. 2. In all cases the dip is clear as are peaks or "ridges" on either side of the dip. The first ridge corresponds to the rotational transition adjacent to that in the gate, and in some cases additional ridges (rotational transitions) can be seen. The overall unevenness in the spectra has to do with how well the comparison spectra matched the gated spectra, and is not otherwise significant. Without the subtraction, such variations would be much larger.

As discussed above, the area of the dip should equal one transition (the gate). However, the observed dip areas vary from about 20% of one transition at the low gate energies down to about 5% at the highest gate energies shown. This implies that most of the cascades at these gate energies already have the dip smeared out (i.e., involve a large damping width), and they all do at still higher gate energies. Since higher γ ray energies are associated with higher temperatures, this "broad smearing" is likely to be a high-temperature effect; whereas, the dip itself is probably a lower-temperature phenomenon, as has been discussed elsewhere [4]. The present objective is to determine more precisely the behaviour of the dip. In particular, we would like to know whether it gets progressively wider with increasing gate energy (reflecting a damping width that is becoming large enough to produce the broad smearing) as was originally thought; or whether it remains essentially unchanged, and the kinds of cascades that generate it are simply replaced by other kinds that do not.

The latter possibility is rather strongly indicated in fig. 1, where the shape of the dip appears unchanged over a broad range of gate energies. In more detail, the dip seems to be entirely confined between the two first ridges in all cases; i.e., there are no "side valleys" (significant dips between the first and second ridges on each side). The dips in fig. 1 also have steep sides (~25 ± 5 keV, top to bottom) and seem to have reasonably flat bottoms. This indicates that the smearing effects on the dip itself are small--widths $\lesssim$50 keV. These same features can be seen in fig. 2 for the other two reactions, although the width of the dip is smaller, corresponding to a larger moment of inertia for these heavier nuclei. This narrower width makes it difficult to determine whether the valley bottom is flat, but the sides are as steep as those in fig. 1. Our conclusion is that the dips do not change shape appreciably with gate energy and show no evidence of large damping (smearing).

In order to avoid a significant smearing of the observed dip, the broad smearing must have a FWHM $\gtrsim$250 keV, in which case the dip it generates becomes so broad and shallow as to be very difficult to detect. It must also set in rather suddenly so that cascades either have very little smearing, or have the dip completely smeared out. In order to explore such a scheme, we have written a Monte Carlo computer code to simulate γ ray cascades through levels that can have these properties.

In this code, an initial spin is selected randomly from a triangular probability distribution that reflects the angular momentum input from the reaction. The initial excitation energy for γ ray emission is randomly selected from a gaussian distribution, chosen here to be centered 7 MeV above the yrast line, with a FWHM of 5 MeV. The cascade is a competition between rotational γ rays [of energy, $E_{rot} = 2(I - i)\hbar^2/\mathcal{J}$, and (relative) transition probability, $P_{rot} = E_{rot}^5$] and statistical γ rays [energy selected randomly from a distribution, $E_{stat}^n \exp(-E_{stat}/T)$, where T is the temperature and values of n of 3 and 5 were tested, and $P_{stat} = k\bar{E}_{stat}^n$ where $\bar{E}_{stat}$ is the average energy of the distribution]. The constant, k, determined the average competition between rotational and statistical transitions, and was adjusted so that the population at the yrast line was 1% at spin 40 (as is generally observed). At each step in the cascade a random choice (weighted by P_{rot}/P_{stat}) of transition type was made. We saw rather little difference between n values of 3 and 5 (with readjusted k values), and used 3 in the present calculations. The most important features of our simulated cascade were the damping effects. We chose to damp the moments of inertia and the alignments completely separately. At low temperatures there was a (gaussian) variation both in moments of inertia (with center, $\bar{\mathcal{J}}$, and FWHM, $\Delta\mathcal{J}/\bar{\mathcal{J}}$) and in alignment (with center at a fixed $\bar{i}/I$, and FWHM Δi), from which values of $\mathcal{J}$

and i were randomly selected, both initially and after each statistical transition. Around chosen temperatures, T_m for the moment of inertia, and T_a for the alignment, (over ranges ΔT_m and ΔT_a, taken here to be 0.1 MeV) these variations were reduced to zero and replaced by damping widths, Γ_m and Γ_a. These widths determined $\Gamma_{rot} = \sqrt{\Gamma_m^2 + \Gamma_a^2}$, the FWHM of a gaussian distribution from which the rotational transition energy was randomly chosen at <u>every</u> (rotational) step of the cascade. The separate alignment and moment-of-inertia damping are consistent with the calculations of Egido [5], where the alignments are damped earlier than the moments-of-inertia (shapes). However, these two separate steps could represent any two stages of the damping process.

Using this code we generated the spectra shown in fig. 3. Fig. 3a shows a portion of the spectrum obtained using a 300 keV Γ_{rot} replacing a $\Delta\mathcal{J}/\mathcal{J}$ variation of 40% and a Δi of $3\hbar$ for excitation energies more than 2 MeV above the yrast line. The remaining parameters of the calculation were appropriate for the $^{40}Ar + {}^{100}Mo$ reaction. The calculated data were treated exactly like the real data: the normalized full projection of the matrix was subtracted from each 4 keV-gated spectrum, a number of which were then shifted to align the gates and added. All the sections of fig. 3 correspond in energy to fig. 1b (1.2-1.4 MeV). Fig. 3a does not look very much like the data: the broad dip (~ 300 keV wide) is much too apparent and the ridge and side valleys are too prominent. To mask these features requires more variation in the undamped part of the cascade, and increasing $\Delta\mathcal{J}/\mathcal{J}$ and/or changing its shape (from gaussian), could solve this problem. Another way to solve it is illustrated in Fig. 3b. Here a Γ_m of 300 keV replaces a $\Delta\mathcal{J}/\mathcal{J}$ of 40% above

2 MeV much as before, but an additional Γ_a of 50 keV is introduced, replacing the Δi of $3\hbar$ at 0.5 MeV above yrast. This looks very much like the data in fig. 1b. The similarity is more striking when one notes that all the resolved lines in the calculation are (unrealistically) put into a single band with a fixed moment of inertia. This produces the overly sharp (resolved) lines in fig. 3, and especially in figs. 3b and 3c where the (unresolved) ridges are largely smeared out. The steep sides and relatively flat bottom of the dip are reasonably well reproduced in fig. 3b, as is the lack of side valleys. The area of this dip is also reasonable (~10% of one transition, very much like that in fig. 1b), and is determined largely by the 2 MeV boundary for the onset of the main damping effects. The effect of changing Γ_a from 50 keV to 100 keV is shown in fig. 3c. Here the dip clearly extends beyond the first ridges, apparently contrary to the data. Nevertheless, the (remaining) first ridges give the center part of the dip the appearance of steep sides with a rather flat bottom, so that one must be very careful not to judge the damping behavior strictly on these properties. We feel that fig. 3 shows one way to reproduce the observed effects, and other ways may also exist.

It is interesting to compare the experimental and simulated results with calculations of the damping effects that have been made by Lauritzen, Døssing and Broglia [3] and by Egido [5]. Both the calculations and the data suggest a rather sudden onset of the damping in the vicinity of 1 MeV above the yrast line, and a general magnitude of 100 keV for the FWHM. In these respects the calculations seem to be qualitatively correct. Egido actually calculated a damping of the alignment fluctuations ($\Gamma_a \lesssim 100$ keV) setting in earlier than the larger contribution ($\Gamma_m \approx 150$-200 keV) due to shape fluctuations.

This is in surprisingly good agreement with the simulation (fig. 3b), but one must remember that the simulation code was, to some extent, modeled after this calculation.An interesting effect predicted in ref. 3. was the motional narrowing at higher temperature, resulting in a decrease of Γ_{rot} to less than 100 keV. There is no evidence for this effect in the data, and, in fact, simulations suggest that any narrowing that would make $\Gamma_{rot} \lesssim 150$ keV in significantly populated regions ($\lesssim$10 MeV above yrast in our simulation) can be excluded. In this respect the data seem to be in qualitative disagreement with the calculation.

To summarize, the observed data in unresolved spectra can be remarkably well explained by introducing some damped rotational cascades, except for the absence of the predicted motional narrowing. The present results provide the strongest evidence yet available that the observed dip in coincidence spectra (or the "valley" in two-dimensional spectra) from this high-spin region is not a result of the main damping, but rather a residue of the (largely) undamped behavior. In fact, there is not yet overwhelming evidence that damping is involved anywhere--a sudden shift to very irregular cascades at ~2 MeV (e.g. a change to triaxial shapes) could explain the data. However, there are other arguments favoring the damping explanation: 1) the few lifetimes of unresolved states that have been measured are more consistent with fully rotational behavior; and 2) triaxial shapes are not expected to occur generally at the highest spins, whereas damping is. Understanding the behavior of these high-spin, high-temperature cascades appears to be one of the most interesting and fundamental problems in high-spin physics.

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Figure Captions

Fig. 1 Partial γ-ray spectra from the ^{136}Nd data, treated as discussed in the text. Fifty spectra, with a gate 4 keV wide, have been shifted and added, covering the energy ranges: a) 1.0-1.2 MeV; b) 1.2-1.4 MeV; c) 1.4-1.6 MeV. The γ-ray energies are given on the abscissa as distances from the gate energy, and, whereas the vertical height is arbitrary, the vertical expansions are indicated on the ordinate scale.

Fig. 2 Similar to fig. 1, except for the ^{160}Er data, a) and b), and the ^{168}Hf data, c). The energy ranges are: a) 0.96-1.08 MeV; b) 1.08-1.28 MeV; and c) 0.8-1.0 MeV.

Fig. 3 Calculated spectra corresponding to that shown in fig. 1b. Fig. 3a has only a broad damping width, while figs. 3b and 3c have additional smaller widths of 50 and 100 keV, respectively, as described in the text.

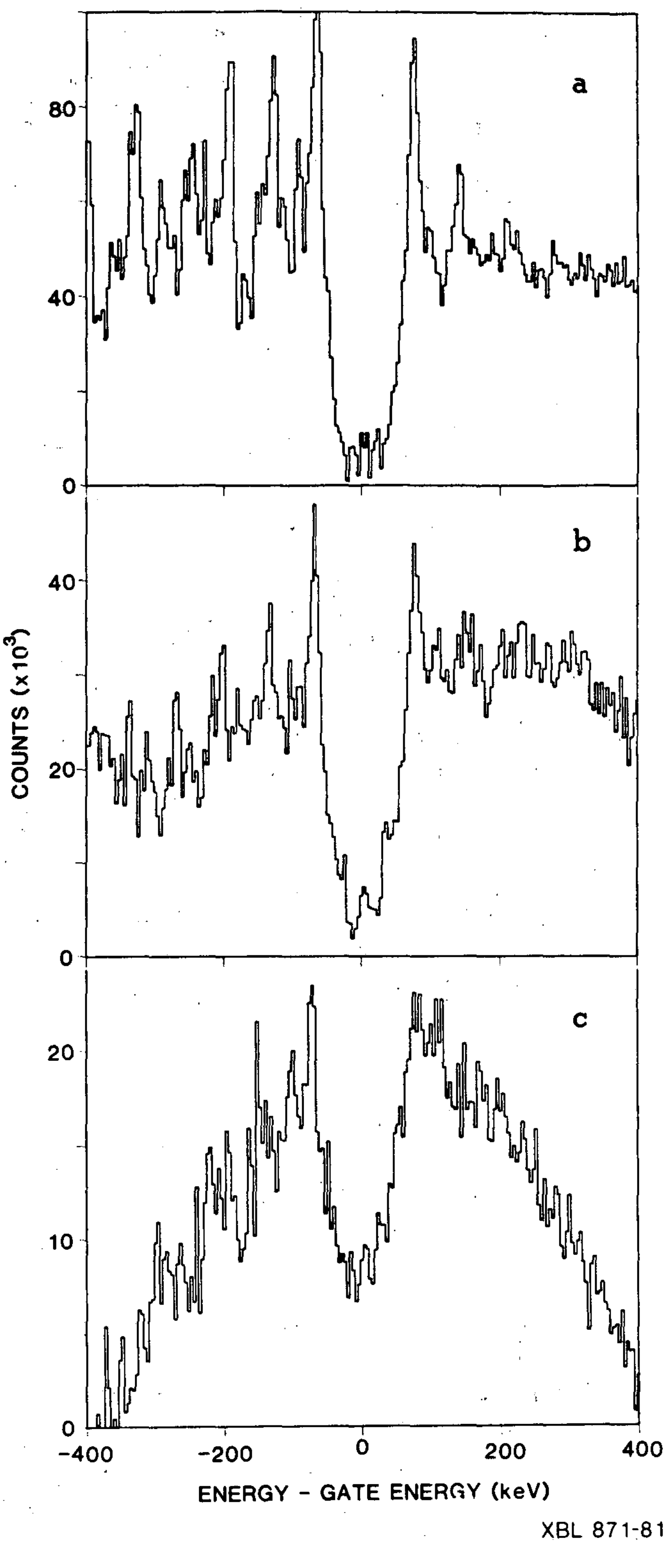
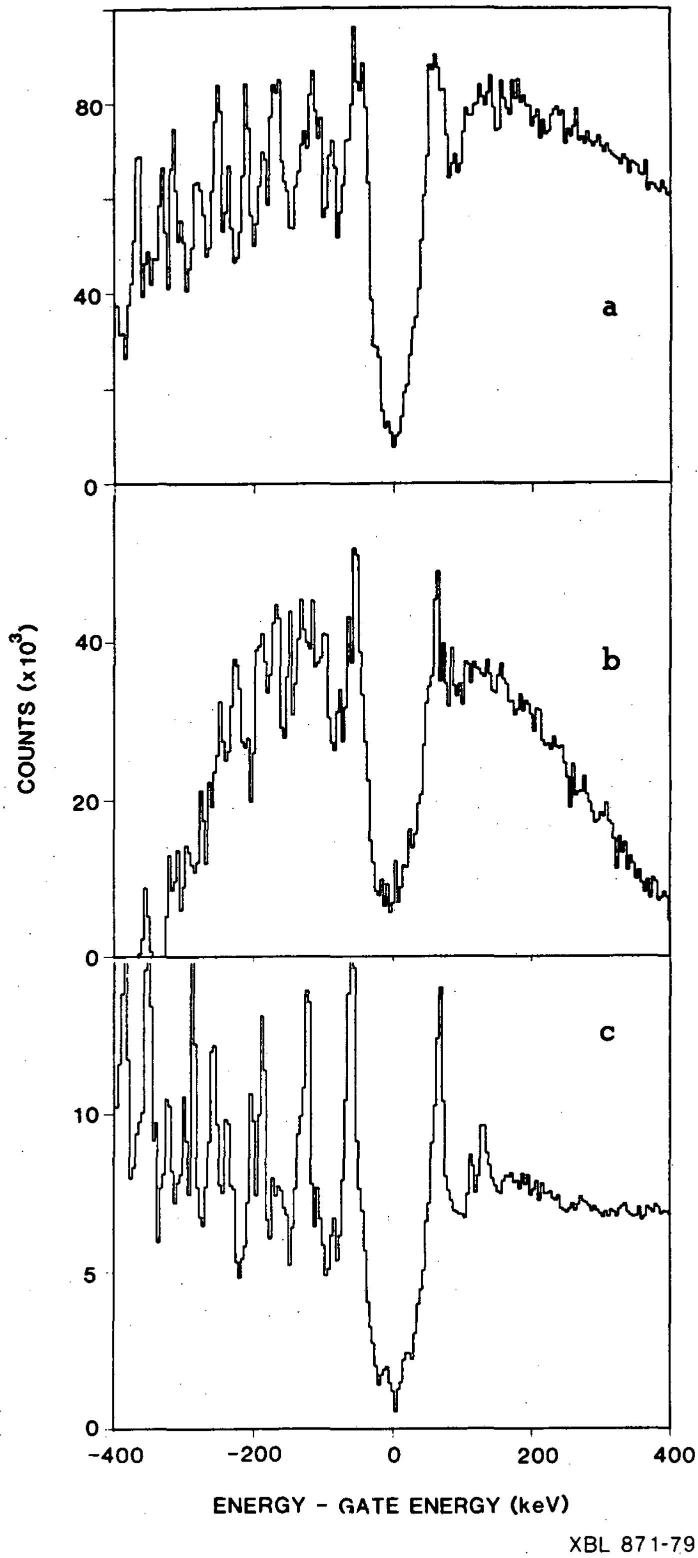

a
b
c
80
40
0
40
20
0
20
10
0
COUNTS (x10^3)
-400
-200
0
200
400
ENERGY - GATE ENERGY (keV)
XBL 871-81

Fig. 1



80
40
0
a
40
20
0
b
COUNTS (x10^3)
10
5
0
c
-400
-200
0
200
400
ENERGY - GATE ENERGY (keV)
XBL 871-79

Fig. 2

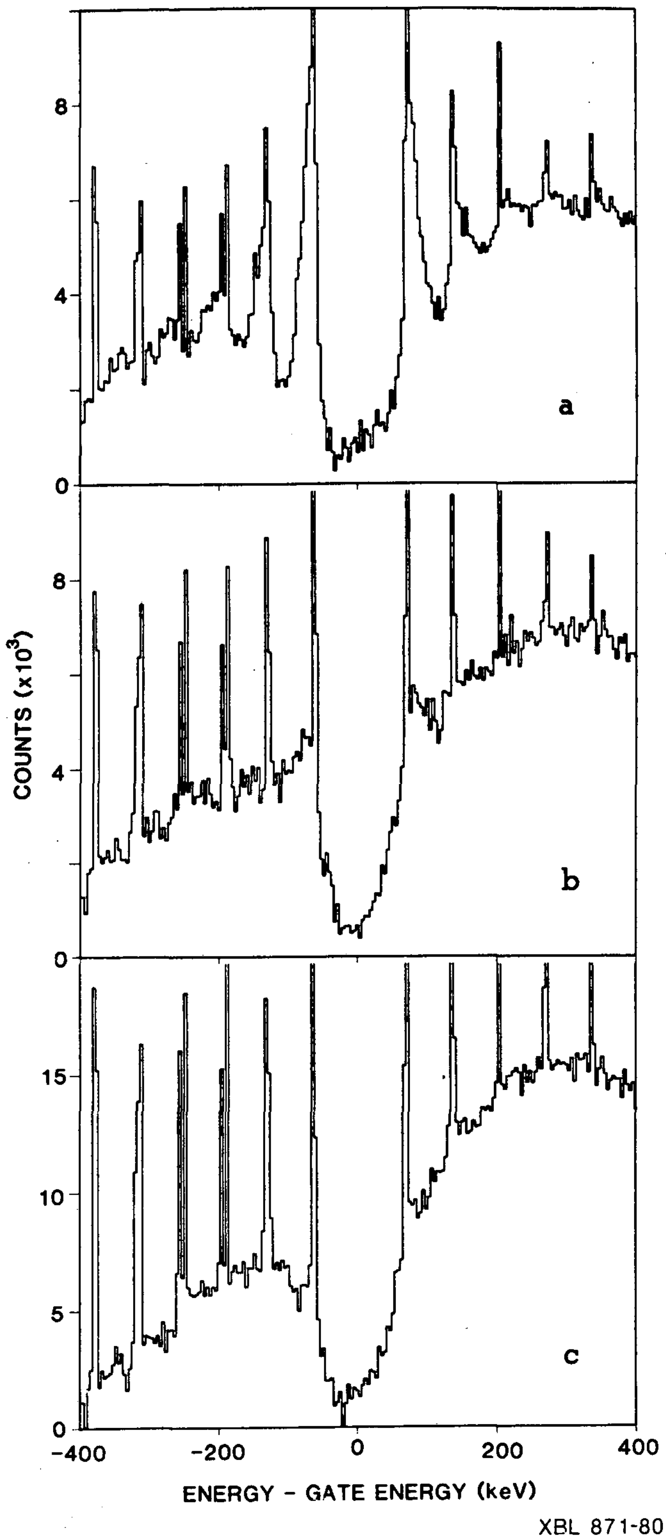

8
4
0
a
8
4
0
b
15
10
5
0
c
COUNTS (x10³)
-400
-200
0
200
400
ENERGY - GATE ENERGY (keV)
XBL 871-80

Fig. 3

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