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Report of the Study Group on Complete Spectroscopy

Workshop on the Nucleus at High Spin

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This report summarizes the topics considered in four discussions of about two hours each attended by most of the workshop participants. The contents of the lectures of David Radford, Fumihiko Sakata, Ben Mottelson, and Jerry Garrett pertaining to Complete Spectroscopy are contained elsewhere in this proceedings.

Most detailed nuclear structure information is derived from measurements of the spectroscopic properties (e.g. excitation energies, angular momenta, parities, lifetimes, magnetic moments, population cross sections, methods of decay, etc.) of discrete nuclear eigenstates. The present instrumentation allows in the best cases such measurements to approach the angular momentum limit imposed by fission [2] and to as many as fifteen different excited bands [3]. In anticipation of the new generation of detection equipment, such as the EUROBall and the GAMMASPHERE, the Complete Spectroscopy Study Group attempted to define

the limits to such studies imposed by physical considerations and to consider some of the new, interesting physics that can be addressed from more complete discrete spectroscopic studies.

1 The Limits of Discrete Line Spectroscopy

1.1 Limiting angular momentum

Stable medium-heavy compound nuclei are predicted for angular momentum as large as 90 units [2]. However, when the nucleus is formed at high temperatures in heavy-ion, fusion-evaporation reactions, fission is the dominate decay mode for the highest angular momentum. Only those angular momenta for which the fission barrier, B_f, is greater than the particle-emission barrier survive fission to emit gamma rays from the compound system [2,4]. (For neutron emission the particle-emission barrier is simply the neutron separation energy, S_n ; however, for charged-particle emission the

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Coulomb barrier of the emitted particle must be added to the separation energy.) Thus the maximum angular momentum for discrete spectroscopic studies drops to about 70-75 units in the best cases. If a mechanism could be devised to produce rapidly-rotating "cold" nuclei or to deexcite the nucleus on a time scale comparable to that of fission, a higher limit might be approached. However, such processes approach the difficulty of producing cold super-heavy nuclei, which is simply the same problem of surviving fission described above reduced to low angular momentum.

1.2 Limiting excitation energy

The spacing between the individual nuclear levels decrease with increasing intrinsic excitation energy. The point is rather quickly reached where the energies of the individual nuclear levels can no longer be resolved irregardless of the instrumentation. Even the use of bent-crystal spectrometers for low spin (n,γ) studies with resolutions of a few eV cannot resolve discrete states in rare-earth nuclei for $E_x >$ about 2 MeV, see e.g. ref. [5]. The increased resolving power associated with higher-fold coincidences will improve the detection of correlated gamma-ray transitions, e.g. those in rotational sequences [6]. Indeed, simple estimates [7] indicate that the "resolvability" of fifth-fold coincidence germanium data for heavy rapidly-rotating nuclei may approach that of single-fold bent-crystal spectrometer low-spin data. Though such experimental developements promise to extend discrete spectroscopy of high-spin states considerably, we should not expect with "equal experimental effort" to establish such states to an excitation of 2 MeV above the yrast line. The high-spin yrast states are not strongly correlated; therefore, the increased density of states starts nearer to the yrast line at high spins, see Fig. 1.

Apart from the technical problem of resolving increasingly more closely-spaced gamma rays, discrete-line spectroscopy will not continue to infinitely high excitation energy. At some point the average spacing of neighboring states with the same spin and parity, d, approaches the value of the average residual interaction of such states, V_{res}, and the states become strongly mixed. When $d \approx V_{res}$, the gamma-ray cascades no longer will follow specific rotational bands. The wave functions of a state of angular momentum I has a sizeable overlap with several $I-2$ states in neighboring decay sequences. Such a pattern of fragmented decay, signaling the "death" of discrete line spectroscopy, is depicted in Figure 2.

Such mixing is the basis of "rotational damping," a major topic of the Warm Nuclei Discussion Group [8]. Indeed, the excitation energy where such mixing sets in is closely related to the parameter controlling the minimum excitation energy for rotational damping in the simulation of experimental $E_\gamma - E_\gamma$ correlations [8]. The two experts in this field, Bent Herskind and Frank Stephens, qualitatively agree on the onset of rotational damping. Herskind gave a value of 1.0 - 1.3 MeV, and Stephens quoted 1 – 2 MeV.

The resulting "discrete spectroscopist playground" is shown in Figure 1.

1.3 How many discrete bands?

The organizers set the tone for this discussion by asking "How to use 100 times more bands?" in the announcement for the Workshop. Though no one really took such a number (> 1000) seriously, it is valid to consider "How many?" Since the limiting excitation-energy of discrete spectroscopy is uncertain (see the preceeding paragraph) and the number of intrinsic configurations increase exponentially with increasing excitation energy (relative to yrast), it is impossible give an accurate estimate. However, based on Sven Åberg's calculations of the density of intrinsic states 1 MeV above yrast [9]:

$$\rho(1MeV; I = 50, \pi = + or -, triaxial) \approx 90/MeV$$
$$\rho(1MeV; I = 50, \pi = + or -, oblate) \approx 45/MeV$$
$$\rho(1MeV; I = 50, \pi = + or -, superdeformed) \approx 22/MeV$$

as many as 30 - 150 intrinsic states for each I^π (i.e. from 120 to 600 decay sequences) may be available for study in the "discrete spectroscopist's playground."

Apparently there are an abundance of gamma-ray transitions between discrete nuclear states waiting for the new instrumentation. Therefore, it appears that discrete spectroscopy will be an important part of the "Era of New Spectroscopy" heralded by the organizers. Indeed, even the advanced instrumentation planned for Phase II of EUROBall probabaly is not sufficient to resolve all the discrete sequences. It also is obvious that the "Era of New Spectroscopy" must include automated techniques for constructing the level schemes (see the lecture of Radford [3]) and that statistical analyses of the properties of the nuclear states will become increasingly important (see the lectures of Mottelson [10] and Garrett [11]).

1.4 States that remain "pure" in a background of strongly-mixed states

Not all of the multitude of excited nuclear states mix equally well. The superdeformed states [12] remain pure even though at lower spins they are as high as 4 MeV above yrast, see Fig. 3. The potential energy barrier separating the nuclear shapes hinders the mixing between states corresponding to different shapes. Indeed the superdeformed states might be thought of as "ordered" nuclear states existing in a background of "chaotic" states.

Other special states that remain "pure" in the background of strongly-mixed states include:

1. Isobaric Analogue States
2. Molecular Resonances
3. Other Exotic Shapes
4. Very High-K States

Indeed an early effort to populate states as far from yrast as possible [13], using the $^{150}Nd(^{18}O,5n)^{163}Er$ reaction, produced only new decay sequences based on high-K configurations, probably missing low-K sequences at the same excitation energy (about 1 MeV above yrast – see Fig. 4). A comparison of the sequences populated in this light heavy-ion induced reaction with the similar diagram for a superdeformed case populated with sulfer to calcium beams emphasises the necessity to utilize a variety of reactions for complete spectroscopic studies. Both reactions populate interesting configurations near to yrast (superdeformed and high-K) which because of larger than average moments of inertia diverge from the yrast configuration at lower spin. The shape and the K selection rule inhibit decay to the "normal" nuclear states as the nucleus deexcites.

2 New Physics

2.1 Statistical Analyses

Average quantities. With "complete" data it is possible to separate average properties from the exceptions. For example, the near yrast states that have been studied for the past two decades in high-spin physics are based on the most alignable (i.e. high-j, low-Ω) configurations. Thus they are not representative of the average states of a rapidly-rotating nucleus. Mottelson emphasised in his lecture [10] how important it is to know the average spectroscopic quantities (e.g. level densities, transition rates, decay widths, etc.) as a function of the experimentally accesible quantities N, Z, I, π, and E_x. The question of whether an effective charge is needed at high spin (as it is at high temperature) was given as an example of the physics that such data would address.

Nearest neighbor analyses. It is becoming increasingly fashionable to consider the information content of the spectrum of eigenstates for quantal systems in terms of general statistical concepts. The rich spectum of nuclear states already has provided such information for the distribution of levels of the same spin and parity in excitation energy. For example:

1. The spacing of nuclear states at the neutron and proton thresholds are well described by random-matrix theory [14], or colloquially are "chaotic."

2. Recent extentions of such analyses to lower excitation energies, which are not specific to a particular range of spins and excitation energies in a single nuclear species, give a mixed result – not completely "ordered," not completely "chaotic" [15].

3. A preliminary analysis [16] of the 100 lowest positive-parity states in ^{26}Al gave a nearly "chaotic" distribution irregardless of the two isospins involved. These results produced such questions as, "What magnitude of isospin mixing is necessary to produce a "chaotic" distribution of nuclear level spacings?" A more complete recent analysis [17] of these same data indicates that this ensemble of states is less "chaotic"; however, no difference appears between ensembles of states with the same and different isospins.

For a more comprehensive, up-to-date review of such statistical concepts see the lecture of Sakata [18].

"Complete spectroscopy" will allow nearest-neighbor analyses as a function of angular momentum. A preview of coming attractions is shown in Fig. 5 and Table 1. These data are based on an analysis [11] of 101 I = 19 and 20 states (19.5 and 20.5 states in odd-A nuclei) from deformed nuclei with A = 155 - 184. This mass and spin range was chosen because the nuclear properties remain nearly constant [19]. Though the conclusions derived from the full distribution of level spacings is limited by sample size, rather definite conclusion can be derived from the tabulated values of the average level spacings. The significantly larger average spacing of the 20^+ states is a result of the special correlations of these states. Two-thirds of these spacings are between the S band and the extension of the ground-state band above the band crossing. Thus these states, which account for the excess probability for large spacings shown in Fig. 5, are not characteristic of the spacing of single-particle states. The lack of level spacing information for the positive-parity levels in odd-N nuclei is attributed to a lower density of positive-parity single-neutron states. Therefore, the spacings of the low-lying high-spin states of rare earth nuclei apparently are not described by either Wigner ("chaotic") or Poisson ("ordered") distributions. Instead they are characteristic of the correlations and the variations of the single-particle levels in this mass region. The spacings of the correlated states of rotating deformed nuclei are a new factor previously not considered in such analyses. It will be interesting to have sufficient data to make these statistical analyses, not only as a function of angular momentum, but also as a function of excitation energy (relative to the yrast configuration) where the relative correlations of the nuclear states may change.

2.2 Empirical Residual Interactions

With more complete spectroscopic information empirical residual interaction analyses, not only become more feasible, but also promise to be of more interest. The availability of such information for a larger variety of nuclear configurations reflecting different correlations should help to determine the relative sensitivity of these interactions to: (i) the polarization of the mean nuclear field (both shape and pair degrees of freedom); and (ii) the overlap of the specific quasiparticle orbitals involved. Qualitative information on the latter quantity as a function of configuration and angular momentum might be considered the goal of such analyses [20].

In the "standard" residual-interaction analysis [21] an empirical spectrum of multiple-quasiparticle states are constructed from the low-lying single-quasiproton and single-quasineutron states in odd-Z and odd-N nuclei. The residual interaction then is the energy difference between the constructed states and the corresponding experimental multiple-quasiparticle states. Even though not enough data often is available for such an analysis on an absolute scale, it still may be possible to obtain interesting relative values of the residual interactions [20].

Recently a new technique was devised by Zhang [22] for extracting average interaction energies between the pair of proton and the pair of neutrons nearest to the respective Fermi levels from gauge-space alignment plots or constant-N (or -Z) contour plots [11]. Values of the proton-neutron interaction, extracted for the yrast configuration of neighboring even-even isotopes and isotones with Z = 68-78 and N = 90-108, are shown in Fig. 6 as a function of N for various values of Z and $\hbar\omega$. The average value of this interaction, $< V_{pn} >= -240keV$, is reasonable. The N and Z dependence of V_{pn} usually are preserved independent of the rotational frequency; however, the variations are larger for increased $\hbar\omega$. The larger variations in $Vspn$ for larger rotational frequencies apparently is associated with the loss of pair correlations with increasing $\hbar\omega$. At small rotational frequencies the extracted values are quasiproton-quasineutron interactions; whereas, at the largest frequencies they are proton-neutron interactions between the last pair of protons and the last pair of neutrons coupled to spin zero and positive parity. At small values of $\hbar\omega$the pair correlations "smear" the effects of fluctuation in the spacings of single-proton and single-neutron levels, which apparently are associated with the larger variations of V_{pn} at large values of $\hbar\omega$. The observed pattern of proton-neutron interactions as a function of N and Z is not completely understood. However, it may be associated with the energy differences of the relative overlap for these proton and neutron orbits. This, of course, is the quantity which we hope to obtain from such analyses.

2.3 Nuclear Correlations at High Spins

Nearly a decade ago at the one of the earliest May Riso Workshops Ben Mottelson was pressed to speculate about what "really new" could come from future high-spin studies. His answer was, "new types of correlation."

Vibrational correlations at high spin. Often vibrational bands are discussed at very high spins, see e.g. [23]. Is this reasonable? The rotationally-induced Coriolis and centrifugal forces modify the intrinsic structure of the correlated state. Therefore, the wave function of the vibrational state at high spin must be quite different at, let's say $I = 30$, than at the band head. The appropriate theory for considering such vibrations is random phase approximation (RPA) calculations based on a single-particle spectrum of states in a rotating deformed system. Such calculations have been made for a few cases - see e.g. Shimizu, *et al.*[24] for pair vibrations and Matsuyanagi, *et al.*[25] for shape vibrations. Complete spectroscopy should provide the data necessary to sort out the various degrees of freedom at high spin.

Another possible high-spin excitation considered in the discussions was the collective excitation of high-spin shell model states (e.g. band terminations). The general opinion of the group was that such states probably will never be seen. Not only is the spectrum of states complicated at the expected energy of such excitations, but the components necessary to produce these collective degrees of freedom are absent at high spins. Only a limited number of high-spin states can be constructed without exciting particles or holes from another major shell.

"Coriolis correlations" In rapidly-rotating nuclei the Coriolis and centrifugal forces restrict nucleons corresponding to low-lying configurations to move in orbits with large aligned angular momenta, i.e. orbits with large positive values of j_1. (The Coriolis and centrifugal term in the nuclear hamiltonian is $-\omega j_1$.) In this case most of the valence nucleons move in equatorial orbits in the direction of the nuclear rotation as depicted in Fig. 7. These valence orbitals have large spatial overlaps, a necessary (though not sufficient) condition for correlations. Such "Coriolis correlations" might appear in residual-interaction analyses (described in the preceeding subsection) as configurations with anomalously attractive nucleon-nucleon interactions.

Wobbling Can we ever *really* believe stable triaxial deformations without seeing the pattern of bands characteristic of this degree of freedom?

2.4 Very High Spin

Spectroscopy at very high spin offers the unique opportunity to study independent-particle motion in a rotating unpaired quantum system. In this "unpaired" regime the features of the nuclear spectrum of states should be more sensitive to the other degrees of freedom, e.g. deformations, the existence of other correlations (such as described in the preceeding subsection), and the details of the single-particle potential.

Indeed many of the features already observed at very high spins (e.g. unpaired band crossings [26] and an established correspondence between experimental configurations and specific independent-particle states of a rotating deformed nucleus [26,27]) are also seen in studies of superdeformed nuclei. In both situations the effects of pair correlations probably are minimized.

2.5 Transition Rates at High Spin and Excitation Energy

It seems as if discussions such as this always end with a statement of the important role of transition rates in establishing details of the nuclear wave function not available from level scheme information. Indeed this comment is true. Specific information regarding the nuclear shape and the intranuclear electromagnetic currents and the orientation of these quantities relative to the axes defined by symmetries is obtainable from measured transition rates. One of the promising developements of the present generation of high-resolution detector arrays is the improved measurements of transition rates, see e.g. the contribution to these proceedings by Yu [28] and Hubel [29]. Indeed state of the art Total Routhian Surface (TRS) calculations have difficulty reproducing the Q_t values extracted from measured lifetimes for a chain of even-even ytterbium isotopes [11]. Surely even a larger fraction of the time of the planned large arrays will be devoted to extending such measurements a bit higher in spin and to nonyrast configurations.

3 References:

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Figure Captions

Figure 1 Pedagogical figure depicting the limits of discrete-line spectroscopy – "our playground."

Figure 2 Figure indicating how the decay pattern for strongly-mixed states imposes a high excitation energy limit to discrete-line spectroscopy.

Figure 3 Plot of the excitation energy as a function of angular momentum for single-particle, normally-deformed, and superdeformed states in ^{152}Dy.

Figure 4 Plot of the excitation energy as a function of angular momentum for a variety of experimental decay sequences in ^{163}Er. Note the similarity of the high-K relative to low-K sequences in this figure and the superdeformed relative to normally-deformed sequences in Fig. 3.

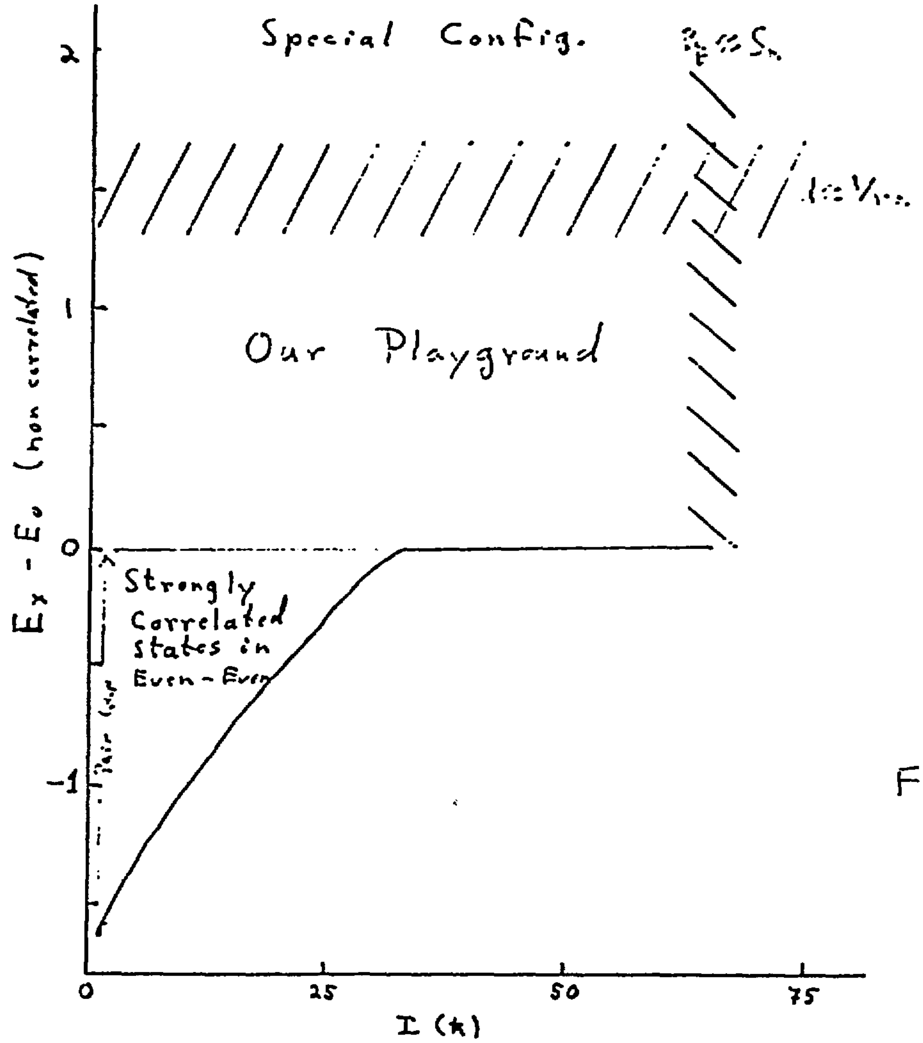
Figure 5 Comparison of the empirical level spacing distribution for 59 I = 19, 19.5, 20, and 20.5 spacings in deformed rare earth nuclei (A = 154 - 184) with Wigner and Poisson distributions.

Figure 6 Plot of V_{pn} as a function of N, Z, and $\hbar\omega$corresponding to the lowest even-spin, positive-parity configurations of even-even deformed rare-earth nuclei. A datum at N = 95 in the Z = 71-72 plot denotes the average proton-neutron interaction between the 95^{th} and 96^{th} neutrons and the 71^{st} and 72^{nd} protons.

Figure 7 Pedagogical figure depicting the valence nucleonic motion in a very rapidly-rotating deformed nucleus.

Table 1 Distribution of Data

	# Cases	Ave. Spacing (MeV)
Even-even		
19^+	0	-
20^+	20	.346
19^-	12	.194
20^-	7	.194
Odd-N		
19.5^+	0	-
20.5^+	0	-
19.5^-	6	.284
20.5^-	8	.201
Odd-Z		
19.5^+	0	-
20.5^+	0	-
19.5^-	3	.256
20.5^-	3	.286
Total	59	.263



Special Config.
Our Playground
Strongly Correlated states in Even-Even
$E_x - E_0$ (non correlated)
I (ħ)
0
25
50
75
2
1
0
-1

Fig. 1

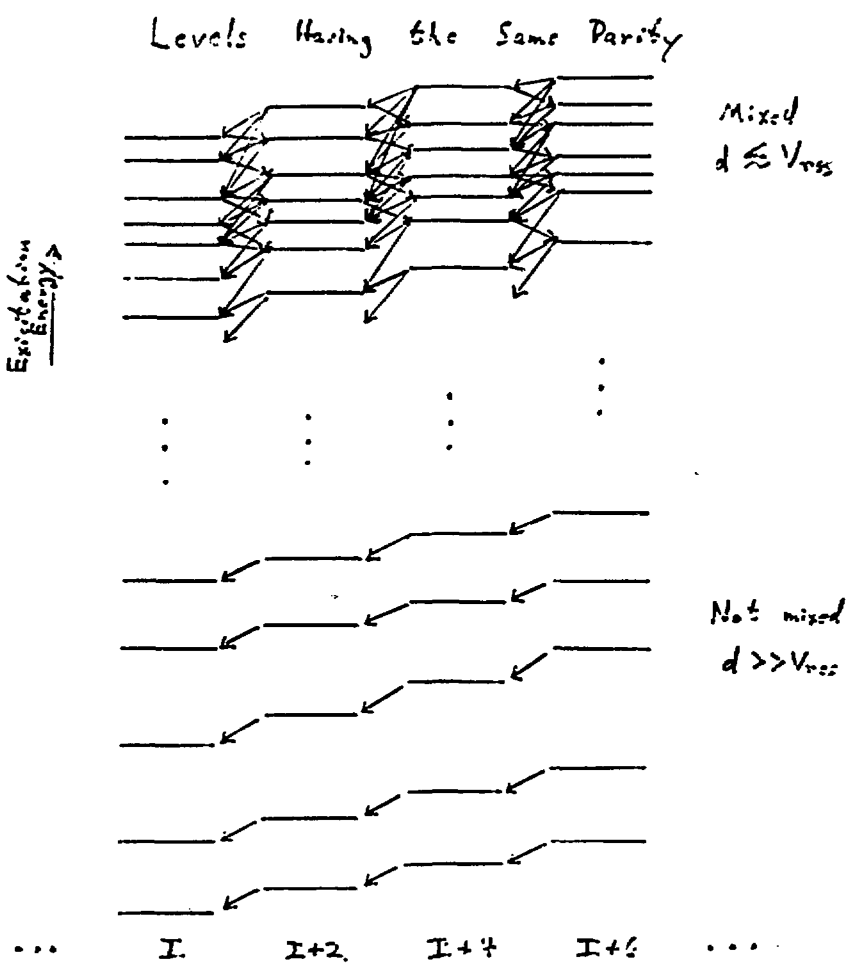

Levels Having the Same Parity
Mixed
d ≲ V_res
Not mixed
d >> V_res
Excitation Energy
I
I+2
I+4
I+6

Fig. 2

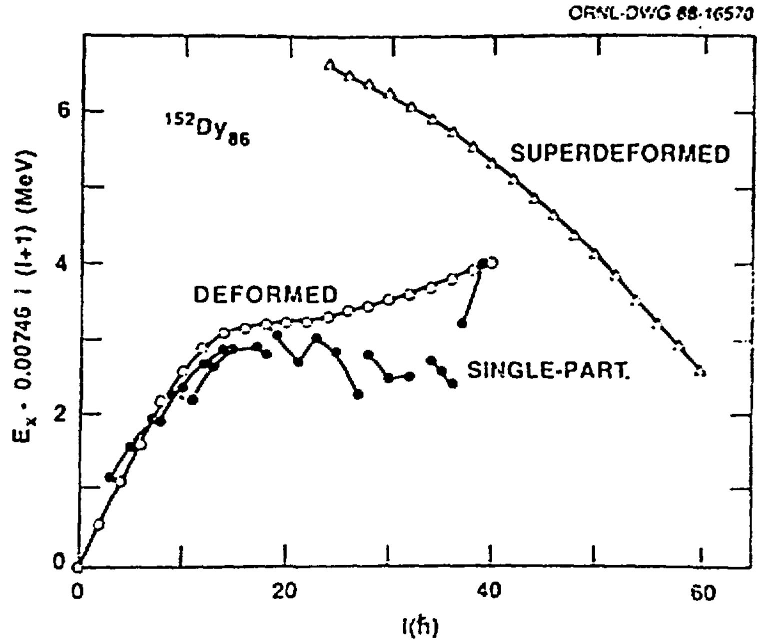

ORNL-DWG 88-16570
$^{152}Dy_{86}$
SUPERDEFORMED
DEFORMED
SINGLE-PART.
E_x - 0.00746 I (I+1) (MeV)
I(ħ)
0
2
4
6
20
40
60

Fig. 3

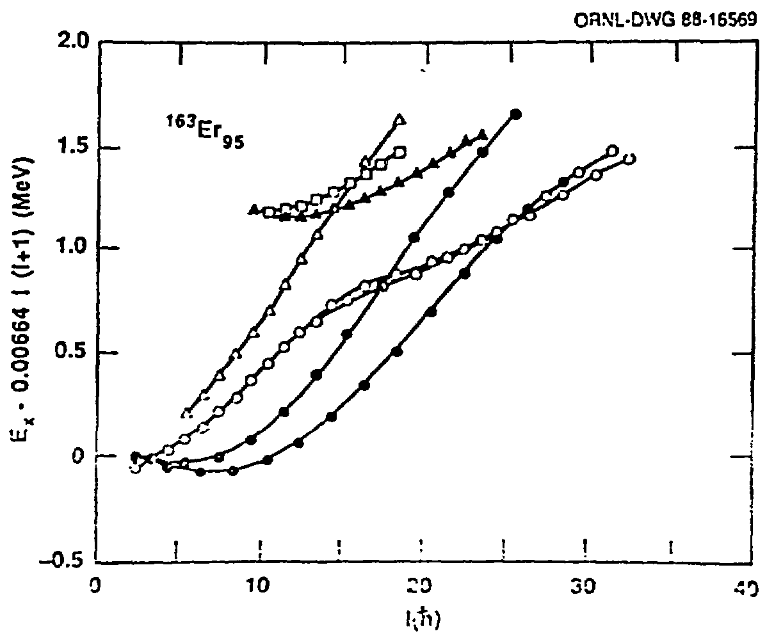

ORNL-DWG 88-16569
$^{163}Er_{95}$
E_x - 0.00664 I (I+1) (MeV)
I(ħ)
2.0
1.5
1.0
0.5
0
−0.5
10
30

Fig. 4

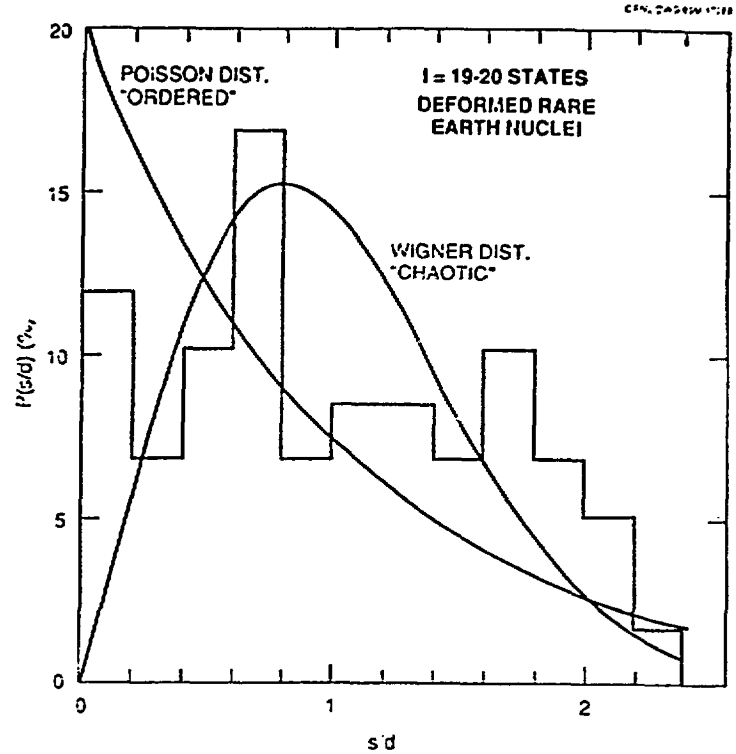

POISSON DIST.
"ORDERED"
I = 19-20 STATES
DEFORMED RARE
EARTH NUCLEI
WIGNER DIST.
"CHAOTIC"
P(s/d) (%)
s/d
0
5
10
15
20
1
2

Fig. 5

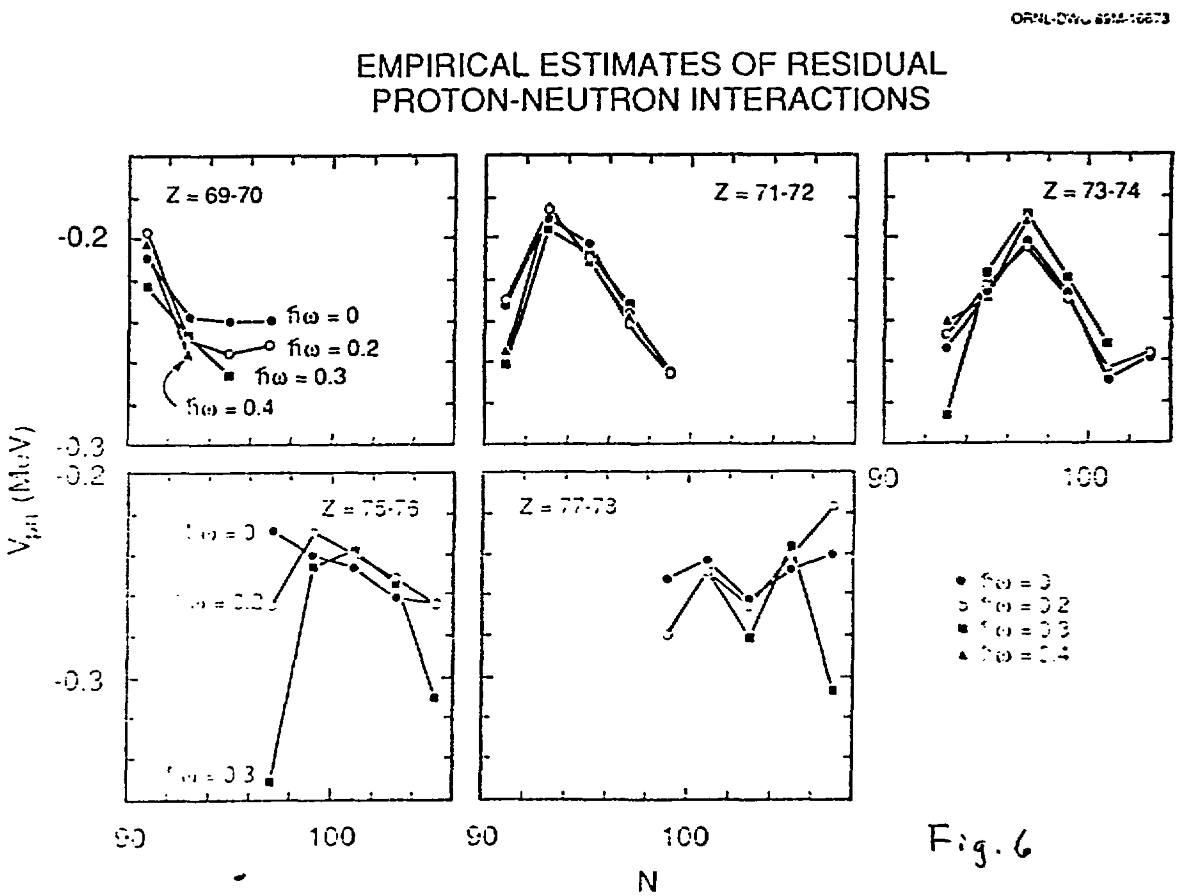
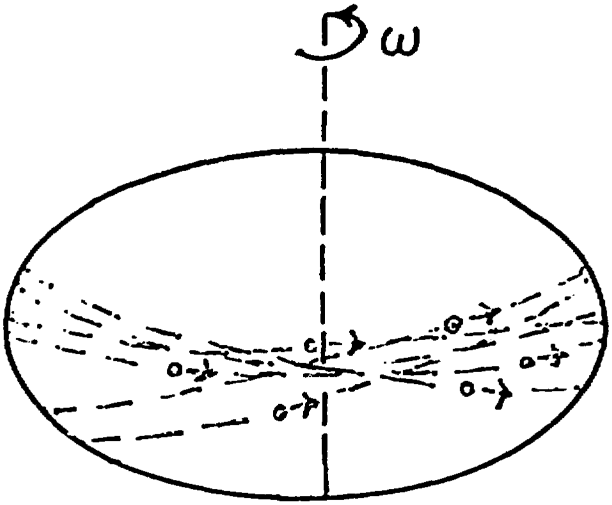

EMPIRICAL ESTIMATES OF RESIDUAL
PROTON-NEUTRON INTERACTIONS
Z = 69-70
Z = 71-72
Z = 73-74
ħω = 0
ħω = 0.2
ħω = 0.3
ħω = 0.4
-0.2
-0.3
N
90
100

Fig. 6



CORIOLIS FORCE CAUSES NUCLEONS FOR LOW-LYING CONFIGURATIONS TO MOVE IN SELECTIVE ORBITALS (THOSE WITH LARGE J_x) HAVING LARGE OVERLAPS.

THIS IS A NECESSARY (BUT NOT SUFFICIENT) CONDITION FOR <u>CORRELATIONS</u>.

EXPERIMENTAL <u>SIGNATURE</u>:

SYSTEMATIC, SELECTIVE LOWERING IN ENERGY OF SPECIAL CONFIGURATIONS.

⋮

Fig. 7