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THE DISTRIBUTION OF NUCLEAR QUANTUM STATES IN "COLD" ROTATING NUCLEI

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ABSTRACT

A statistical analysis of the distribution of level spacings for states with the same spin and parity is described in which the average spacing is calculated for the total ensemble. The resulting distribution of level spacings for states of deformed nuclei with $A = 155 - 185$ and $Z = 62 - 77$ is the closest to that of a Poisson distribution yet obtained for nuclear levels. However, when only the even-spin, positive-parity data for even-even nuclei are considered, the level-spacing distribution becomes double peaked. The anomalously-large separations are shown to be the result of the low energy of the strongly-correlated, completely-paired yrast configuration of even-even nuclei. Average values of the level spacings also are discussed as a function of spin, parity, and nuclear type (even-even, even-Z--odd-N, etc.). Likewise, deviations from a Poisson distribution for several spacings (s) less than about 60 keV are compared with similar values for ^{116}Sn on an absolute scale. Such discrepancies are attributed to interactions (level repulsions) which become increasingly significant for $s \leq 60$ keV.

BACKGROUND INFORMATION

It has become increasingly fashionable to consider the information content of the spectrum of eigenstates of a quantal system in terms of statistical concepts.¹ The rich spectrum of nuclear states provides an excellent opportunity for such analyses. Indeed, an analysis² of the extensive, "complete," spectroscopic information near the neutron and proton thresholds (typically at an excitation energy of about 8 MeV) from neutron- and proton-resonance measurements³ for a variety of nuclei, shown in Figure 1, indicates that the distribution of the spacing of these levels with the same angular momentum, I , and parity, π , can be reproduced by a parameter-free distribution derivable from the predictions of the Gaussian orthogonal ensemble (GOE) of random-matrix theory. Of course, even though the distribution of level spacings is "given" by statistics, the average level spacing, $d (= 1/\rho)$, where ρ is the average level density, remains sensitive to the details of nuclear structure. Such level-spacing distributions have been taken as evidence^{1,2} that the nuclear system at low spin and high excitation energy is "chaotic."

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Fig. 1. Distribution of level spacings (s) normalized to the average spacing (d) for neighboring nuclear levels with the same spin and parity just above the neutron- and proton-emission thresholds. For comparison the Wigner (or GOE) distribution, a parameter-free distribution derivable from random matrices, and a Poisson distribution, assuming no correlation between levels with the same spin and parity, also are shown. This figure is taken from ref. 2.

More recent analyses extend to lower excitation energies⁴⁻⁶ and attempt to extract information as a function of nuclear specie,⁴ for example, even-even versus odd- A , heavy versus light mass, or deformed versus spherical. Such analyses provide distributions intermediate to that expected for purely "ordered" (Poisson distribution) or purely "chaotic" (GOE or Wigner distribution) systems, see e.g. Figure 2, and a trend from GOE to Poisson proceeding from spherical regions to deformed regions, see refs.^{4,6}. To obtain sufficient data for such analyses it is necessary to extend the analysis over a large range of energies and angular momenta. Since the level density increases exponentially with increasing excitation energy, the sensitivity to the lowest states is rapidly lost in such an extended analysis.

ANALYSIS

The present contribution reports a statistical analysis of the distribution of level spacings for states of deformed nuclei with $A = 155 - 185$ and $Z = 62 - 77$ having the same spin and parity. In contrast to earlier analyses,^{2,4,6} the average spacing is calculated from the complete data ensemble, instead of for each individual spin-parity group in a specific nucleus. This modified prescription is partly justified by the fact that all levels considered are from deformed rare-earth nuclei, many of whose properties are known to be similar. For example, the moments of inertia calculated from the energy of the $22^+ \rightarrow 20^+$ yrast-sequence transition of even-even nuclei in the $A = 155 - 185$ mass region are equal within a five percent standard deviation,⁷ see Figure 3. Such a criterion circumvents the usual problem of obtaining sufficient data to establish an accurate average level spacing, d , for each spin-parity group in a specific nucleus. For example, in the previous attempts to

Fig. 2. Level-spacing distribution, taken from ref. 6, for eighty-three 0^+ , 1^+ , 2^+ , 3^+ , 4^+ , and 5^- states below $E_x = 4.3$ MeV in ^{116}Sn . See also the caption to Fig. 1.

Fig. 3. Kinetic moments of inertia, $\mathcal{J}^{(1)}$, calculated for the $22^+ \rightarrow 20^+$ transitions of the yrast decay sequence of even-even rare-earth nuclei, are shown as a function of the neutron number. The values of $\mathcal{J}^{(1)}$ (average value = 60.6 ± 3.0 MeV $^{-1}\hbar^2$) are surprisingly constant and do not show the $A^{5/3}$ dependence expected for a macroscopic rotor. These data are taken from and discussed in ref. 7.

Fig. 4. Distribution as a function of excitation energy and spin corresponding to the data sets for which level-spacing distributions are shown in this work. Distributions for Haq, et al.,² ^{116}Sn ,⁶ and the present analysis of $A = 155-185$ and $Z = 62-77$ data are shown in Figs. 1, 2, and 5-9, respectively. The average level spacings for these three analyses are of the order of 10 eV, 160 keV, and 300 keV, respectively.

obtain information for some of the best data sets at low excitation energy often there were as few as 3-4 levels per spin-parity group for each nucleus.⁴ The added statistics obtained by relaxing this requirement on the average spacing allows for the first time (see however ref. 8) an analysis of level spacings for near yrast configurations -- see e.g. Figure 4. This procedure also will provide sufficient statistics to obtain similar information specific to angular momentum, parity, and nuclear type (i.e. even-even, odd-even, etc.) for this mass region.

Of course, the relaxation of a criterion that requires several level spacings for each spin-parity group leads to other problems (it always is necessary to pay a price for advantages gained). For example, the missing level problem (replacing two smaller spacings with a larger spacing) may become more severe producing a bias toward larger spacings. Conversely, larger spacings, being more difficult to establish from experiment, will occur less frequently in the data sets producing a bias toward smaller spacings.

The experimental data for the even-even and odd-mass nuclei used in the analysis were obtained from the Evaluated Nuclear Structure Data Files (ENSDF)⁹ available in November 1990 and from the Oak Ridge -- University of Tennessee High Spin Data Base.¹⁰ Level spacings for odd-odd nuclei were not included in the analysis, because such data sets are less complete and have fewer firmly established spin and parity assignments. Complete references to the 132 nuclei for which data have been included in the analysis is omitted from this preliminary report of our work. They can be obtained from the data bases.^{9,10} Data for $^{155-156}\text{Sm}$, $^{155,157,159}\text{Eu}$, $^{155-161}\text{Gd}$, $^{155,157,159,161,163}\text{Tb}$, $^{155-165}\text{Dy}$,

Fig. 5. Level-spacing distributions (histograms) for nuclear states with the same spin and parity for "cold" deformed rare-earth nuclei having $A = 155 - 185$ and $Z = 62 - 77$. For comparison, curves, corresponding to Poisson and Wigner distributions (often associated with "ordered" and "chaotic" behavior, respectively), are shown.

$^{157,159,161,163,165,167}\text{Ho}$, $^{156,158-171}\text{Er}$, $^{159,161,163,165,167,169,171}\text{Tm}$, $^{158,160-175,177-178}\text{Yb}$, $^{165,169,171,173,175,177}\text{Lu}$, $^{162,165-171,173-179}\text{Hf}$, $^{171,173,175,177,179}\text{Ta}$, $^{170-172,175,178-185}\text{W}$, $^{171,173,175,177,181,183,185}\text{Re}$, $^{177,179-185}\text{Os}$, and $^{179,181,183,185}\text{Re}$ were used in the analyses.

LEVEL-SPACING DISTRIBUTIONS

The distribution of the 2522 level spacings included in the present analysis are compared in Figure 5 with calculated Poisson and Wigner distributions. (The Poisson and Wigner distributions usually are associated with "ordered" and "chaotic" systems, respectively.¹⁾ Except for the very smallest separations (histogram bins corresponding to the two smallest values of s/d shown in Figure 5), the agreement of the experimental spacings with the Poisson distribution is exceptional. Indeed these data are the closest to a Poisson distribution yet obtained for nuclear levels. Such an excellent Poisson distribution for the experimental level spacings is a surprise, since the missing level problem (replacing two small spacings with a single large spacing) might be thought to be serious in this data set, which often contains only a single spacing for a particular spin-parity-nucleus group. (Indeed the deviations noted for the lowest spacings may be the result of missed levels;

Fig. 6. Comparison of the level-spacing distributions for rare-earth states as a function of parity. See also the caption to Figure 5.

Fig. 7. Comparison of the level-spacing distributions for rare-earth states as a function of angular momentum. See also the caption to Figure 5.

Fig. 8. Comparison of the level-spacing distributions for rare-earth states of even-even, even-Z--odd-N, and odd-Z--even-N nuclei. See also the caption to Figure 5.

however, they also may indicate level repulsions for very closely-spaced levels, see the summary section.) The close agreement between these data and the Poisson distribution may be taken *a posteriori* as a partial justification of the assumptions of the analysis (see the preceding section).

The present analysis includes enough level spacings to allow some exclusive information to be obtained as a function of parity, angular momentum, and nuclear type (i.e. even-even, even-Z--odd-N, or odd-Z--even-N). Such analyses are shown in Figures 6-8. The experimental level spacings corresponding to positive- and negative-parity states (Figure 6), low- and intermediate-spin states (Figure 7), and even-even and even-Z--odd-N nuclei (Figure 8) also have distributions close to the Poisson distribution. Of course, the statistical fluctuations in the distributions increase with the decreasing number of spacings in the sample, as expected. The distribution of the 680 spacings from odd-Z--even-N nuclei (Figure 8) deviates significantly from Poisson; neither is it Wigner. Even larger deviations from a Poisson shape is observed for the distribution corresponding to $16 \leq I < 24$. This distribution is intermediate between Poisson and Wigner. Likewise, the lack of very small spacings, observed in the analysis of all levels, persists for all the distributions shown in Figures 6-8.

Fig. 9. Comparison of the level-spacing distributions of rare-earth states for a sequence proceeding from the complete data set to increasingly more exclusive conditions and ending with the $I^\pi = 2^+$ states of even-even nuclei. The progression from a Poisson distribution for the complete data set to a double-peaked distribution for the 2^+ states is discussed in the text. See also the caption to Figure 5.

A sequence of five level-spacing distributions based on various criteria, proceeding from the complete data set to increasingly more exclusive conditions and ending with 103 spacings for $I^\pi = 2^+$ states in even-even nuclei, is shown in Figure 9. The strikingly Poisson-shaped distribution for the total ensemble becomes increasingly more complex as the conditions become more exclusive. Indeed, a peak appears in the data at s/d just less than 2 for the positive-parity states of even-even nuclei. The magnitude of this peak is enhanced when the data is restricted to low-spin, positive-parity levels in even-even nuclei. It becomes particularly pronounced when the level-spacing distribution for a single low-spin value of positive-parity states (e.g., the 2^+ states -- see Figure 9) in even-even nuclei is considered. Inspection of the data indicates that the spacings in the $s/d \approx 2$ peak mostly correspond to that of the lowest pair of states (i.e., the spacing between the completely-paired, even-spin, positive-parity yrast states in even-even nuclei and the first-excited states of the same spin in these nuclei). Of course, this spacing is not characteristic of the spacing of single-particle states. Instead it includes contributions from the correlation energy associated with pair correlations.^{11,12} Similar conclusions have been made from a preliminary analysis of $I = 19$ -20.5 near-yrast data.¹³ The average level spacing, d , also increases as the large spacing between the completely-paired and the first-excited states of the same spin in even-even nuclei becomes a larger fraction of the data (see Figure 9).

AVERAGE VALUES OF THE LEVEL SPACINGS

Except for a few cases, such as the 2^+ states of even-even nuclei shown in Figure 9, the statistics of the data set is insufficient for extracting complete level-spacing distributions for each spin, parity, and nuclear type. However, meaningful average values of the level spacings can be obtained as a function of these quantities for a much wider range of values. Average level spacings are shown in Figure 10, as a function of angular momentum, for positive- and negative-parity, near-yrast states of even-even, even-Z--odd-N, and odd-Z--even-N nuclei with $A = 155 - 185$.

For even-Z--odd-N and odd-Z--even-N nuclei, the average level spacings mostly represent average differences of quasiparticle energies, E_v , for configurations based on different Nilsson configurations of a specific parity. (Multiple-quasiparticle excitations, which will be important at higher excitation energies, and quasiparticle-vibrational coupled states do not dominate these data, which concentrate, especially at high spin values, on near-yrast configurations.) The quasiparticle energy is given by¹¹

$$E_v = \sqrt{\Delta^2 + (\epsilon_v - \lambda)^2},$$

where ϵ_v , Δ , and λ are the energy of the single-particle Nilsson state, the pair-gap parameter, and the Fermi level respectively. Therefore, the average spacings should reflect, but not equal, the average spacing of the near-yrast, single-particle states of a specific parity. Indeed, they provide a lower limit for this value in the limit of a vanishing pair gap. The precipitous drop in the average level spacing, as a function of angular momentum, for small values of angular momentum is a result of the absence of states with $I < \Omega = K$ in rotational bands. That is, $d(I = 1/2)$ reflects the average spacings between $\Omega = 1/2$ configurations, $d(I = 3/2)$ reflects the average spacing between $\Omega = 1/2$ and $3/2$ configurations, etc. For even-Z--odd-N nuclei the average spacing of positive-parity levels is consistently larger than that of negative-parity levels of the same angular momentum -- see Figure 10. In contrast, the opposite is observed for odd-Z--even-N, $d(\pi = -) > d(\pi = +)$.

Fig. 10. Comparison of the distribution of average level spacings, d , as a function of angular momentum for the positive- and negative-parity levels (solid and open data points, respectively) of even-even, even-Z-odd-N, and odd-Z-even-N rare-earth nuclei.

These systematics agree with expectations. For the $A = 155 - 185$ rare-earth nuclei the density of negative-parity, single-neutron states near the Fermi level is greater than that of positive-parity states. In the $N = 82 - 126$ neutron shell there are 30 doubly-degenerate negative-parity neutron states (corresponding to the Nilsson components of the $h_{9/2}$, $f_{7/2}$, $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ shell-model states) and 14 positive-parity states (corresponding to $i_{13/2}$) that span nearly the same range of excitation energies. For protons, which fill the next lower shell (with 20 $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, and $s_{1/2}$ positive-parity states and 12 $h_{11/2}$ negative-parity states), the opposite is true. However, the reason that the overall average level spacings are less for the odd-Z-even-N than for the even-Z-odd-N nuclei (see Figure 10) remains unexplained. There are more single-neutron states than single-proton states in the valence shell; hence the spacing of single-neutron states would be expected to be less. Likewise, the slightly larger proton pair gap than neutron pair gap¹⁴ on average is not enough to explain this difference in rare earth nuclei where the proton and neutron odd-even mass differences are nearly equal.

For even-even nuclei the average level-spacing distributions are more complicated than for odd-A nuclei, due to the mixture of quasiparticle and strongly-correlated states (e.g., the completely-paired, even-spin yrast configuration and a variety of vibrational configurations) in the data set. In addition to the spacings of the various quasiparticle and correlated states, the relative number of each type of state in the data set also must be considered. For example, the spacing of 0^+ states is dominated by the large excitation energy difference between the ground-state and the bandhead of the beta band, whereas the

spacing of 2^+ states also contains data for the smaller spacings between beta, gamma and two-quasiparticle bands. Hence, the average spacing decreases sharply between 0^+ and 2^+ . Likewise, the increase in average spacings for $I^\pi = 4^+ - 8^+$ is associated with the decrease of data for vibrational and two-quasiparticle states from (n,γ) and transfer studies. Therefore, with increasing spin the data become increasingly dominated by (heavy-ion,xn) data, which for intermediate angular momentum are sensitive to the large spacing between the strongly-correlated, paired yrast configuration and that of the lowest-excited two-quasiparticle configuration (S band), based on the excitation of the most-alignable (i.e., those most strongly affected by the Coriolis force) quasiparticles.^{15,16} Thus for $I^\pi = 10^+ - 14^+$ the spacing between the ground-state and S bands decreases until these bands cross at $I^\pi = 14^+ - 16^+$, producing a minimum in the average level spacing distribution. Above the band crossing, of course, the spacings will increase.

Though octupole correlations may be important for negative-parity states,¹⁷ such correlations are expected to be less important in the average level spacing for the negative-parity states of even-even nuclei than the stronger, more-prevalent correlations of positive-parity states described in the preceding paragraph. Thus the level spacings for negative-parity states of even-even nuclei should reflect the spacing of the quasiparticle states to a greater degree than the positive-parity states. Indeed the level-spacing distribution for the negative-parity states of even-even nuclei follows a pattern similar to that observed for odd-A nuclei.

DISCUSSION AND SUMMARY

A statistical analysis of level spacings is described in which the average spacing is calculated for the total data set, which is restricted to nuclei with similar properties. The resulting distribution of level spacings for nuclear states of deformed nuclei with $A = 155 - 185$ and $Z = 62 - 77$ is the closest to a Poisson distribution yet obtained for nuclear levels. In contrast to previous analyses,^{2,4-6} these data are concentrated on near-yrast states with small intrinsic excitation energies, see Figure 4. Thus, the average level spacing is large; $d = 296$ keV for the total sample. Indeed this value is larger than the interaction matrix elements expected to mix these states. Therefore, neighboring states with the same quantum numbers are expected to retain individual character, i.e. to have distinctively different wave functions. This is the meaning of "order" in the present context. It, however, is tempting to ascribe the deviations from the Poisson distribution observed for the two lowest spacing bins shown in Figure 5 to the onset of level repulsion based on interactions that produce strong mixing between closely-spaced states. The lowest (0-30 keV) and the next-lowest (30-60 keV) bins contain only about 65 and 90% respectively of the probability of the Poisson distribution. Such deviations could be produced by interaction matrix elements (≤ 30 keV) that perturb a significant fraction of the states for $s \leq 60$ keV. A reduced probability for small spacings is observed in all the exclusive level-spacing distributions (see Figs. 6-8), indicating that reduced probability (relative to the Poisson distribution) for small spacings is spread systematically throughout the data. Missing levels also may contribute to such deviations, see the preceding discussion in the level spacing distribution section.

In contrast, previous analyses of the low excitation energy region⁴⁻⁶ with level spacing distributions intermediate between a Poisson and a Wigner distribution are based on data sets that extend to higher intrinsic excitation energies (i.e., the excitation energy relative to the yrast configuration) than that of the present analysis, see Figure 4. Thus many of the states in these data sets are more closely spaced than those of the present analysis. This is especially true, since the level density increases exponentially with increasing intrinsic

excitation energy. For example, the average spacing of the twenty-eight 2^+ states in the ^{116}Cd analysis,⁶ which extends to an excitation energy of 4.3 MeV, is 111 keV, and a significant fraction of these spacings are less than 50 keV. Indeed, a comparison of the level spacing distribution of the present work and that of ^{116}Sn on an absolute energy scale indicates that the maximum for the present analysis occurs at a larger spacing than that corresponding to ^{116}Sn . However, this feature is masked in the normalized distributions (compare Figures 2 and 5) by the vastly different average level spacing of these two data sets. At the neutron threshold, where the level-spacing distribution is that of a Wigner distribution, the average level spacing for $1/2^+$ states established from s-wave capture on even-even targets are typically¹⁸ 10 eV, a value much less than the interaction expected between these states.

Therefore, a coherent picture begins to emerge. When the nuclear states are well separated, such as the majority of the states in the analysis described in the present work with $d \approx 300$ keV, each state contains detailed nuclear structure information, the level-spacing distribution is Poisson, and the situation is described as "ordered." In the other extreme, illustrated by the closely-spaced nuclear levels at the particle thresholds with $d \approx 10$ eV, neighboring states have nearly-identical, strongly-mixed wave functions, the level-spacing distribution is Wigner, and the situation is described as "chaotic." That is, the wave functions of the individual states contain only average information on the ensemble of nuclear states in a specific excitation region. When $d \approx 100$ keV, an intermediate situation emerges in which the level-spacing distribution is between that of a Poisson and a Wigner distribution. Indeed even the data from the present analysis show significant deviations from a Poisson distribution for $s < 60$ keV. In order to be quantitative with respect to the interaction strength at which the levels begin to mix producing the "transition from order to chaos," detailed analyses are needed for a wide range of excitation energies in the same mass region. At present the data is not adequate to completely characterize this "phase transition"; however, it is indicated that level repulsion becomes increasingly important for spacings less than about 60 keV.

The present analysis also illustrates how known correlations, such as the completely-paired state, can distort level-spacing distributions and average values of the level-spacing for exclusive data sets in which the spacing between such correlated and uncorrelated states is enhanced.

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