Decisive role of fragmentation of quasiparticle–phonon configurations in the transition from order to chaos in nuclei

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The particular excitation energies at which the transition from order to chaos occurs in heavy and intermediate-weight nuclei are determined. It is suggested that a study be made of the fragmentation of many-quasiparticle and quasiparticle–phonon configurations. The fragmentation of three-quasiparticle configurations at the long-lived isomer ^{178m2}Hf—a fragmentation of five-quasiparticle configurations—should be studied in one-nucleon exchange reactions at odd–odd targets, e.g., ^{176}Lu and ^{180}Ta. Analysis of the γ decays of high-spin isomers can yield information on the fragmentation of quasiparticle–phonon configurations.

Each excited state of a nucleus is characterized by an angular momentum I, a parity π, other quantum numbers, an energy, and a wave function. If the distribution of distances between neighboring levels with given I^{π} obeys the statistics of an orthogonal Gaussian ensemble, then chaos is assumed to exist in the excited nuclear states.[1] The wave functions of states with energies above 3 MeV have many terms, with various numbers of quasiparticles and phonons, with several values of the projection (K) of the angular momentum onto the symmetry axis in deformed nuclei, with isospins T_0 and T_0+1, etc. The wave functions of heavy and intermediate-weight nuclei are superpositions of several orthogonal Gaussian ensembles. It was accordingly asserted in Ref. 2 that one cannot reach a definite conclusion about the existence of a chaos from the distribution of nuclear levels, and that the transition from order to chaos should be studied on the basis of the wave functions.

To describe the energies and wave functions, it is necessary to introduce a mean field and residual interactions. The mean field and the residual interactions which lead to pairing and collective vibrational states are responsible for order in nuclei. The interactions of collective and noncollective degrees of freedom, including interactions of quasiparticles with phonons, lead to a fragmentation (a distribution of the strength) of quasiparticle–phonon configurations. The wave functions of the excited states are written as series in the number of operators of quasiparticles and phonons, multiplied by the wave function of the ground state of the even–even nucleus.

It was asserted in Ref. 2 that large components of the wave functions are evidence of an order, while small components are distributed at random. The experimental information available on the large components of the wave functions of low-lying states, of high-spin isomers, and of isobar-analog states points to an order. Essentially no experimental information is available on the small components of the wave functions of low-lying states. The partial radiative widths of γ-ray transitions from neutron resonances to low-lying states are determined by very small components of the wave functions of neutron resonances. The distribution of radiative widths obeys the statistics of an orthogonal Gaussian ensemble.

The transition from order to chaos was interpreted in Ref. 2 as a transition from large to small components of the wave functions. Chaos sets in at those excitation energies at which the wave functions do not have large components. At such energies it is pointless to study the properties of individual nuclear states. A study of the fragmentation of quasiparticle–phonon configurations thus plays a decisive role in determining the particular excitation energies at which the transition from order to chaos occurs in heavy and intermediate-weight nuclei.

The fragmentation of one-quasiparticle states in spherical nuclei has been studied experimentally and has been described correctly.[3,4] The fragmentation increases as the distance from the one-particle level to the Fermi level increases. Up to excitation energies of 6–8 MeV, the cross sections for one-nucleon exchange reactions have local maxima, which stem from one-quasiparticle states which have not undergone complete fragmentation. The transition from order to chaos is usually linked with a total fragmentation of one-quasiparticle states.[5] However, that interpretation overlooks the circumstance that the wave functions can have large quasiparticle–phonon components at these excitation energies.

The next step is to study the fragmentation of three- and five-quasiparticle states, quasiparticle–phonon states, and two-phonon states. If as targets we use the naturally occurring long-lived isotopes ^{180}Ta and ^{176}Lu along with the man-made isomer[6] ^{178m2}Hf, with a half-life of 31 yr, then we can study the fragmentation of three-quasiparticle states in ^{175}Yb, ^{175,177}Lu, ^{179,181}Hf, and ^{177,179}Ta and the fragmentation of five-quasiparticle states in ^{177}Lu and ^{177,179}Hf in one-nucleon exchange reactions.

Let us consider three- and five-quasiparticle states in ^{179}Hf. Figure 1 shows experimental data[7] on three-quasiparticle and quasiparticle–phonon states with energies below 1.5 MeV, along with calculated energy centroids of three- and five-quasiparticle states. A nonrotational state is characterized by the value of K^{π} and by the asymptotic proton (p) and neutron (n) quantum numbers, $Nn_z\Lambda\uparrow$ for $K=\Lambda+1/2$ or $Nn_z\Lambda\downarrow$ for $K=\Lambda-1/2$, of those one-particle levels[8] which have quasiparticles. Here 2_{γ}^{+}, 0_{β}^{+}, and $1_{\rm oct}^{-}$ mean gamma, beta, and octupole phonons. In the reaction ^{180}Ta(t,α) one can study fragmentation in the energy interval 2–5 MeV of three-quasiparticle configurations consisting of a proton quasiparticle and a neutron quasiparticle, $p514\uparrow$ $+n624\uparrow$, with $K^{\pi}=9^{-}$, which characterize ^{180}Ta and which are added to each state of a proton quasiparticle, as shown in Fig. 1. If one uses as target the isomer ^{178m2}Hf, with $K^{\pi}=16^{+}$, $p514\uparrow$ $+$p$404\downarrow$ $+$n$514\downarrow$ $+$n$624\uparrow$, then one can use (d,p) and $(\alpha,{}^{3}\mathrm{He})$ reactions to study, in the energy interval 3–6 MeV, the fragmentation of five-quasiparticle configurations in which one neutron quasiparticle is added to each of the four-quasiparticle configurations introduced above.

In the $(d,\,p)$ reaction at ^{176}Lu, with $K^{\pi}=7^{-}$ and $p404\downarrow$ $+$n$514\downarrow$, there is an excitation in ^{177}Lu in the energy interval 1–4 MeV of the following three-quasiparticle configurations with $K=7\pm K'$, in which neutron quasiparticles are added to $p404\downarrow$

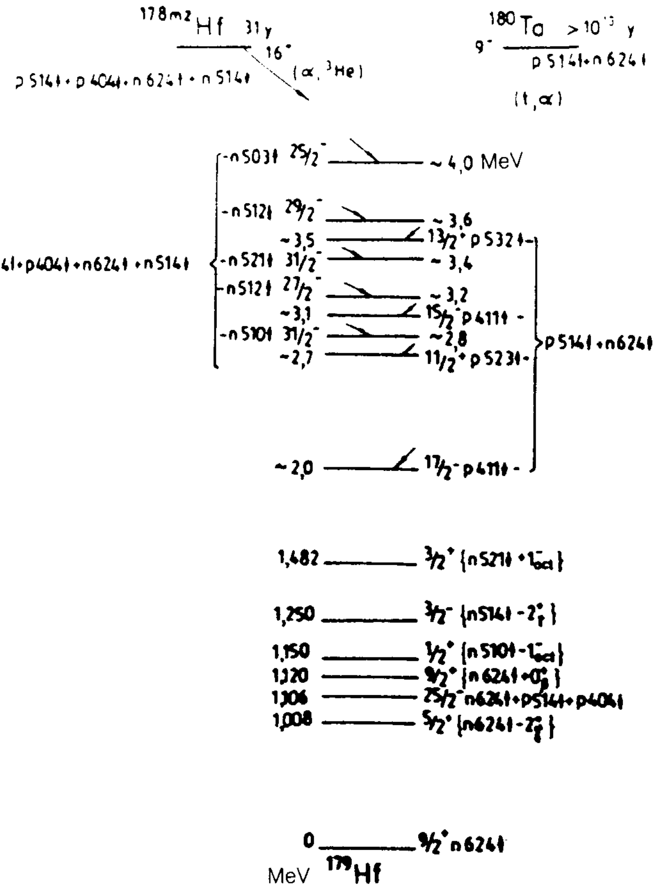

FIG. 1. Known quasiparticle–phonon states and calculated centroids of the energies of the three- and five-quasiparticle states in ^{179}Hf which are filled in (t,α) and $(\alpha,{}^3\mathrm{He})$ reactions.

+n514↓ : $K^\pi = 5/2^-$, $23/2^-$, $n624\uparrow$; $K^\pi = 9/2^+$, $19/2^+$, $n512\uparrow$; $K^\pi = 11/2^+$, $17/2^+$, $n512\downarrow$; and $K^\pi = 13/2^+$, $15/2^+$, $n510\uparrow$. In the (t, α) reaction at ^{176}Lu, there is an excitation in ^{175}Yb in the interval 1.5–4.0 MeV of the following three-quasiparticle states with $K = 7 \pm K'$, in which proton quasiparticles are added to $p404\downarrow$ $+n514\downarrow$: $K^\pi = 13/2^-$, $15/2^-$, $p411\downarrow$; $K^\pi = 7/2^+$, $21/2^+$, $p523\uparrow$; $K^\pi = 5/2^+$, $23/2^+$, $p514\uparrow$; $K^\pi = 11/2^-$, $17/2^-$, $p411\uparrow$; and $K^\pi = 9/2^+$, $19/2^+$, $p532\uparrow$. The first step should be to study the fragmentation of three-quasiparticle configurations with the smallest values of K.

Information on the fragmentation of quasiparticle–phonon configurations in spherical nuclei can be extracted from an analysis of γ transitions in the decays of high-spin isomers. For example, one could analyze the γ transitions from the long-lived isomer[9] with $I^\pi = 65/2^-$ in ^{213}Fr or the isomer[10] with $I^\pi = 34^-$ in ^{212}Fr. The fragmentation of three- and five-quasiparticle states may be manifested in the decays of high-spin states excited in heavy-ion reactions. For example, indications of a fragmentation of three- and five-quasiparticle states have been observed[11] in ^{143}Nd in the ^{130}Te(^{16}O, $5n$) reaction. Further research on the γ decays of high-spin states is required in order to learn about the fragmentation of quasiparticle–phonon configurations.

Not enough experimental information on the fragmentation of one- and two-quasiparticle states and one-phonon states is available to determine the particular excitation energies at which the transition from order to chaos occurs. There is accordingly a need for experiments on the fragmentation of multiquasiparticle and quasiparticle-phonon configurations; the technical capabilities for such experiments exist today.

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