Pairing in excited nuclei: a review†

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The present review summarizes the recent progress in the study of pairing properties in excited nuclei and their analogy to those appeared in other finite systems including superconductors, metallic nano sized clusters/grains, and solid-state materials such as ferromagnets. The review consists of four parts.

The first part discusses the treatment of pairing within a uniform model based on the BCS Hamiltonian within the grand canonical ensemble.

The second part focuses on the grandcanonical treatment of pairing within the Hartree-Fock-Bogoliubov theory and finite-temperature pairing reentrance phenomenon in superconducting ultrasmall metallic grains as well as in even-even and odd nuclei.

The third part presents the results obtained from the treatment of nuclear pairing within the canonical and microcanonical ensembles, from which the effect caused by the finite size of the systems is highlighted. Different approaches to canonical and microcanonical ensembles including particle-number projection, particle-number projection plus static path approximation, solutions of BCS with Lipkin-Nogami particle-number projection incorporating the self-consistent quasiparticle random-phase approximation embedded into the canonical and microcanonical ensembles, shell model Monte Carlo method at finite temperature, and exact solutions of the pairing problems, which are embedded into the canonical and microcanonial ensembles, are introduced.

In the fourth part, the first experimental evidence of the pairing reentrance phenomenon in a warm rotating ^{104}Pd nucleus, which was observed via the local enhancement of nuclear level density at low temperature and high angular momentum extracted from the reaction ^{12}C + ^{93}Nb at the incident energy of 40–50 MeV, is analyzed and discussed within the framework of the finite-temperature BCS (FTBCS), which includes the quasiparticle-number fluctuations (FTBCS1) at angular momentum J (Fig. 1). The similar behavior of pairing reentrance observed in the condensed-matter counterpart such as metallic compound of $Eu_{0.75}Sn_{0.25}Mo_6S_{7.2}Se_{0.8}$ and heavy-fermion cubic system of $CePb_3$, quasi-2D organic conductor κ-$(BETS)_2FeCl_4$, and ferromagnetic superconductor of URhGe under the strong magnetic field is also summarized.

It has been found that, by applying the BCS theory

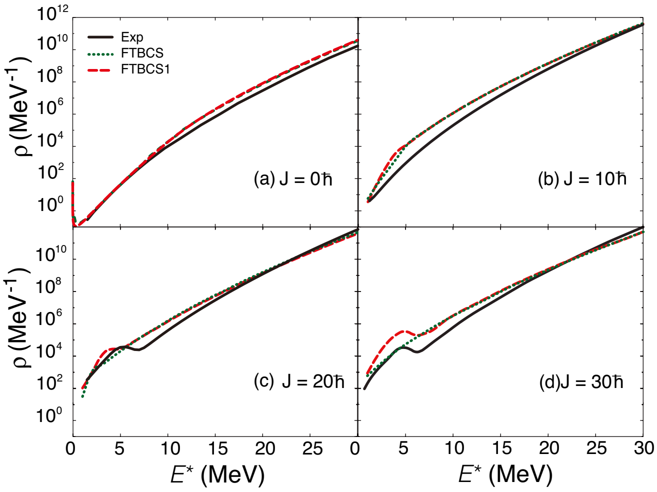

Fig. 1. Level densities for ^{104}Pd as function of excitation energy E^* at the quadrupole deformation parameter $\beta_2 = 0.276$ and different values of total angular momentum J. The dotted and dashed lines stand for the FTBCS and FTBCS1 results, respectively. The solid lines are the experimentally extracted level densities.

at finite temperature and angular momentum to the uniform nuclear model, for which the analytic solutions of the BCS equation can be obtained, one is able to study the appearance of the first-order and second-order phase transitions in finite nuclear systems when either the total angular momentum or the number of quasiparticles or the total energy of the system is fixed. However, it has also been pointed out that these shape phase transitions are simply an artifact caused by the application of the BCS theory to finite nuclei, neglecting all the thermal fluctuations. In fact, strong thermal fluctuations in finite systems smooth out all the phase transitions, leading to different behaviors of nuclear thermodynamic quantities. For example, the fluctuations of the quasiparticle number are one of the microscopic origins caused the nonvanishing nuclear pairing gaps at finite temperature, resulting in the smoothing of the superfluid-normal (second-order) phase transition. This finding is important in the sense that thermal fluctuations should always be considered whenever the statistical methods are applied to finite systems.

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