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Finite-temperature pairing re-entrance in the drip-line nucleus ^{48}Ni

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Finite-temperature Hartree-Fock-Bogoliubov theory using Skyrme interactions and relativistic Hartree-Fock effective Lagrangians predicts ^{48}Ni as being a possible candidate for the finite-temperature pairing re-entrance phenomenon. For this proton-drip-line nucleus, proton resonant states are expected to contribute substantially to pairing correlations and the two predicted critical temperatures are $T_{c1} \sim 0.08$–0.2 MeV and $T_{c2} \sim 0.7$–0.9 MeV. It is also shown that pairing re-entrance modifies the proton single-particle energies around the Fermi level, as well as occupation numbers and quasiparticle levels. The understanding of pairing re-entrance in ^{48}Ni presently challenges our understanding of exotic matter under extreme conditions.

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I. INTRODUCTION

Proton-rich nuclei provide interesting information on the strong interaction which is complementary to neutron-rich nuclei [1–3]. Among them, ^{48}Ni, with 28 protons and 20 neutrons, is one of the most proton-rich nuclei ever identified. It was experimentally discovered in 1999 at the SISSI/LISE3 facility of GANIL, where a lower limit for its half-life was found to be about 0.5 ms [4]. This doubly magic nucleus located at the proton drip line exhibits remarkable stability with respect to external perturbation compared to neighboring nuclei. Owing to its doubly magic properties, ^{48}Ni is also of particular interest because it is at the extreme limit of nuclear stability, where the nuclear forces are no longer able to bind all protons and neutrons together. Therefore, a possible decay mode of ^{48}Ni was found to be the emission of two protons ($2p$ radioactivity). First indications of this new type of radioactivity have been found in an experiment at the SISSI/LISE3 facility of GANIL [5] in 2004 and confirmed at the National Superconducting Cyclotron Laboratory at MSU in 2011 [6].

From the theoretical side, the ground-state properties of ^{48}Ni and surrounding proton-rich nuclei have been widely studied within the nuclear shell model [7], the Hartree-Fock-Bogoliubov (HFB) theory [8], and the relativistic Hartree-Bogoliubov (RHB) theory [9]. The realistic description of proton emitters requires further developments, treating on an equal footing bound, resonant, and scattering states as well as the coupling to decay channels [1]. Let us mention some of the recent calculations in this direction: R matrix [10,11], three-body models [12], and shell model embedded in the continuum [13]. Schematic pairing approximations including resonance width have shown the interplay between pairing and resonant states for drip-line nuclei [14,15]. The effect on resonant states on pairing correlations was studied in the framework of the BCS approximation, both for zero [16–18] and finite temperatures [19] and in the framework of HFB theory [20–31], but essentially applied to neutron-rich nuclei. In these papers, the important role of resonant states has been underlined as nuclei get closer to the drip lines. More recently, a *pairing persistent* effect against temperature has been found [32,33]. Pairing persistence occurs if a finite amount of temperature could populate single particle (s.p.) states above the Fermi level. The temperature should be less than the critical temperature, which is ≈ 1 MeV in finite nuclei, implying that the excited states shall be less than ≈ 4 MeV above the Fermi level. When the *pairing persistent* effect occurs, the critical temperature is found to be increased with regard to the usual BCS estimation, $T_c \approx 0.57\Delta\ (T = 0)$, where $\Delta(T = 0)$ is the pairing gap at zero temperature. If the ground state is unpaired and a finite amount of temperature modifies the occupation of the s.p. orbitals enough to switch on pairing, then a very surprising behavior called *pairing re-entrance* in the thermal equilibrium state could be observed. In this case, the hole states around the Fermi level become unblocked at finite temperature and participate together with the excited states to the pairing correlations. This behavior is going against the general rule that temperature destroys pairing, and as a consequence, this phenomenon may occur only at low temperature (below the critical temperature).

Pairing re-entrance phenomenon was first predicted for hot rotating nuclei by Kammuri [34] and Morreto [35], and called *thermally assisted pairing* or *anomalous pairing*. Later it was also predicted in odd nuclei by Balian *et al.* [36], who introduced the name *pairing re-entrance*. More recent studies of pairing re-entrance at finite temperature have been carried out for the rotational motion of nuclei [37–39] and the deuteron pairing channel in asymmetric matter [40]. At finite temperature, pairing re-entrance in the equilibrium state was predicted for the first time in the neutron channel of extremely neutron-rich nuclei, $^{176-180}$Sn [32].

In this paper, we investigate the finite-temperature Hartree-Fock-Bogoliubov (FT-HFB) theory with Skyrme forces [19,41–43] and relativistic Lagrangians (FT-RHFB)

[33], which will be very briefly described in Sec. II. In Sec. III, we discuss pairing re-entrance in ^{48}Ni. Since this nucleus is located at the edge of the present experimental possibilities, it has been produced only in a few numbers and it may hopefully be produced in larger amounts at the future experimental facilities, such as FAIR or FRIB. Finally, conclusions are presented in Sec. IV.

II. FINITE-TEMPERATURE HFB

For the sake of simplicity, we detail here some important FT-HFB equations with Skyme forces only. The more complex FT-RHFB equations can be found in our recent work [33]. Denoting by $h_T(r)$ the thermal averaged mean field Hamiltonian and by $\Delta_T(r)$ the thermal averaged pairing field, the radial FT-HFB equations read [19,41–43]

$$\begin{pmatrix} h_T(r)-\lambda & \Delta_T(r) \\ \Delta_T(r) & -h_T(r)+\lambda \end{pmatrix}\begin{pmatrix} U_i(r) \\ V_i(r)\end{pmatrix} = E_i \begin{pmatrix} U_i(r) \\ V_i(r)\end{pmatrix}, \quad (1)$$

where E_i stands for the positive quasiparticle energy eigenvalue, U_i and V_i are the components of the radial FT-HFB wave function, and λ is the Fermi energy associated to the particle conservation equation. For the zero-range Skyrme forces, the FT-HFB Hamiltonian and pairing field can be written in terms of the particle density,

$$\rho(r) = \frac{1}{4\pi}\sum_i (2J_i+1)[V_i^*(r)V_i(r)(1-f_i) + U_i^*(r)U_i(r)f_i], \quad (2)$$

where $f_i = [1+\exp(E_i/k_B T)]^{-1}$ is the thermal occupation probability of quasiparticle states with angular momentum J_i, k_B is the Boltzmann constant, and T is the temperature. The FT-HFB Hamiltonian depends also on the thermal spin and kinetic densities which are defined, for instance, in Ref. [43]. In Eq. (2), the summation is going over the whole quasiparticle spectrum. The thermal average pairing field is calculated with a density-dependent contact force of the following form [29]:

$$V(r-r') = V_0\left[1-\eta\left(\frac{\rho(r)}{\rho_{\rm sat}}\right)^{\alpha}\right]\delta(r-r'), \quad (3)$$

where $\rho(r)$ is the density ($\rho_{\rm sat} = 0.16$ fm^{-3}) and V_0 is the strength of the force. We have considered a mixed surface-volume pairing interaction [44,45] by fixing the two other parameters η and α to the values $\eta = 0.7$ and $\alpha = 0.45$. With this force, the thermal averaged pairing field is local and is given by

$$\Delta_T(r) = V_{\rm eff}[\rho(r)]\kappa_T(r), \quad (4)$$

where $\kappa_T(r)$ is the thermal averaged pairing tensor given by

$$\kappa_T(r) = \frac{1}{4\pi}\sum_i (2J_i+1)U_{i,q}^*(r)V_i(r)(1-2f_i). \quad (5)$$

The thermal average pairing gap is obtained from the thermal average pairing field $\Delta_T(r)$ and the thermal pairing tensor $\kappa_T(r)$ solutions of the finite-temperature HFB model as [43,46]

$$\Delta \equiv \frac{\int d^3r\,\Delta_T(r)\kappa_T(r)}{\int d^3r\,\kappa_T(r)}. \quad (6)$$

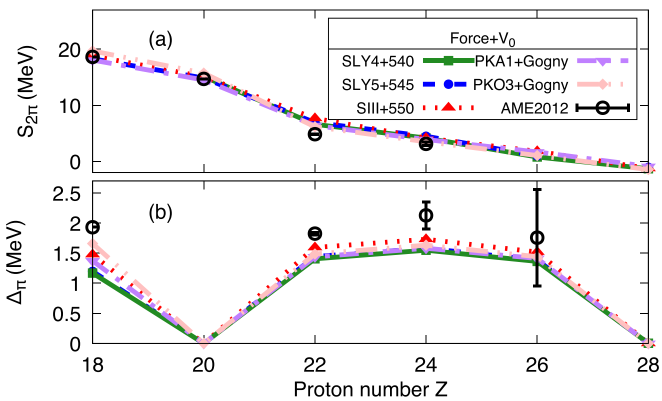

FIG. 1. Two-proton separation energies (upper panel) and proton pairing gaps (lower panel) vs the number of protons for $N = 20$ isotones obtained within the FT-HFB model at zero temperature, for SLY4-5 [47] and SIII [51] Skyrme forces and PKA1 [58] and PKO3 [59] effective Lagrangians. The experimental data are deduced from the AME2012 mass table and the experimental three-point formula is used for the comparison to the proton pairing gap.

In practice, the self-consistent FT-HFB equations (1) are solved by iterations, fixing at each iteration the chemical potential λ and the pairing field $\Delta_T(r)$, until the convergence of the total energy. The wave functions U_i and V_i are solved in coordinate space using the Numerov method with Dirichlet asymptotic boundary conditions [28]. The size of the box is fixed to be 30 fm and the step in coordinate space is 0.2 fm. The cutoff is fixed to be 60 MeV and the maximal value of the angular momentum considered here is $J_{\rm max} = 30$. We have checked the stability of our results against these parameters and found convergence; see, for instance, Fig. 4 of Ref. [32] for more details. In the present work, continuum states are represented by the positive-energy states of the box. In doing so, we neglect the effect of the resonance state widths, which is expected to reduce the pairing correlations [16,19–24]. In the present calculation, we carefully adjust the pairing interaction to the two-neutron separation energy of nearby nuclei and check the proton pairing gap against the three-point formula, see Fig. 1, in order to minimize the error induced by our approximation for the continuum states.

We have searched for the occurrence of pairing re-entrance using various nuclear interactions and running over magic nuclei and their neighbors. In more detail, we have performed systematical calculations with various effective Skyrme interactions such SLY4-5 [47], SKMS [48], SKI1-5 [49], SGII [50], SIII [51], and RATP [52], for many nuclei, namely, ^{14}C, ^{12,16,22,24}O, ^{30}Ne, ^{34,40,48,58}Ca, ^{34}Si, ^{38}Ar, ^{48,56,60,66,76}Ni, ^{82}Ge, ^{90}Zr, ^{100,120,132}Sn, ^{140}Ce, ^{146,190}Gd, and ^{176,208}Pb. These nuclei are semimagic or doubly magic and they are located at or close to the drip lines, which is a condition for pairing re-entrance [32]. We have focused on nuclei which have already been produced at nuclear facilities. From these extensive studies, we have found that only the doubly magic

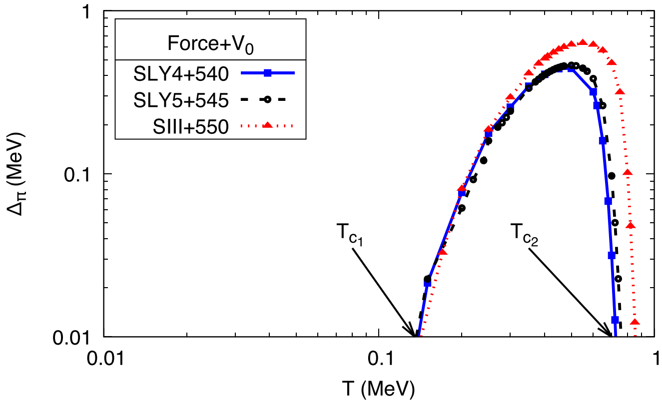

FIG. 2. Temperature-averaged proton pairing gap vs temperature for ^{48}Ni nuclei based on SLY4-5 and SIII Skyrme interactions. See text for more details.

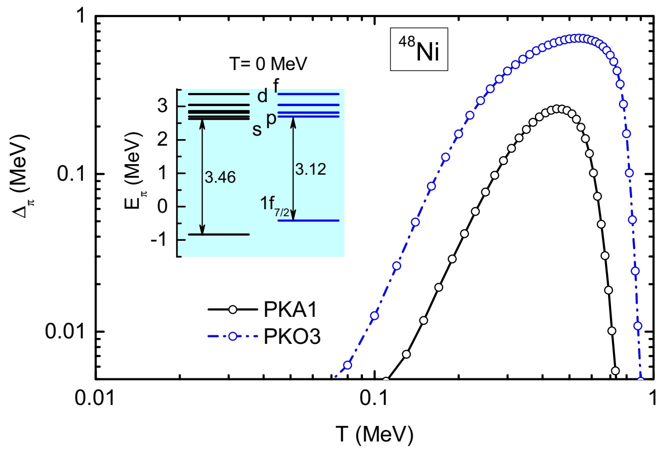

FIG. 3. Prediction for the proton pairing gap in Ni^{48} as function of the temperature based on FT-RHFB PKA1 [58] and PKO3 [59] effective Lagrangians. See text for more details.

neutron-deficient nucleus ^{48}Ni may manifest the re-entrance phenomenon in its thermally equilibrated state.

In the case of ^{48}Ni and surrounding nuclei, the values of the pairing strength V_0 have been determined for each Skyrme interaction such as the experimental two-proton separation energies S_{2p} and the proton pairing gaps Δ_p for $N = 20$ determined from the three-point formula [53–55], where the experimental nuclear masses provided by the AME2012 mass table [56] are in overall agreement within the known differences between these quantities [57]. The comparison between the model predictions for S_{2p} and Δ_p and the experimental data is shown in Fig. 1. The values of V_0 (in MeV fm^3) are given in the legend of Fig. 1 for the Skyrme interactions SLY4 [47], SLY5 [47], and SIII [51]. The two other parameters η and α are not modified. For the effective Lagrangian PKA1 [58] and PKO3 [59], the pairing interaction is derived from the Gogny D1S [60] finite-range interaction; see Refs. [33,61,62] for more details. There is a good agreement between the model predictions and the experimental data, given the experimental and systematical uncertainties. Notice that only the experimental uncertainties for mass measurements are represented in Fig. 1. The evaluation of the systematical uncertainties, especially for Δ_p, is difficult to estimate, but it is expected to be of the order of a few 100 keV [53–55].

III. RESULTS AND DISCUSSION

The predictions for the temperature-averaged proton pairing gaps Δ_p are shown in Fig. 2 for the same interactions as in Fig. 1. The pairing re-entrance phenomenon is predicted for SLY5, SLY4, and SIII Skyrme forces with critical temperatures $T_{c1} \sim 0.1$–0.2 MeV and $T_{c2} \sim 0.7$–0.8 MeV. These critical temperatures correspond to the low- and high-temperature boundaries of the pairing re-entrance domain. Out of this domain, matter is predicted to be in its normal phase where pairing is quenched. Notice that the high-temperature boundary T_{c2} is below or about the same as the single critical temperature in ordinary nuclei ∼1 MeV [19,32,33,41,42]. Other Skyrme forces considered here do not predict the re-entrance phenomena for reasons that we detail hereafter.

Finite-temperature pairing re-entrance is also predicted by other interaction models. For instance, the prediction from effective Lagrangians PKA1 [58] and PKO3 [59] are shown in Fig. 3. These Lagrangians are considered to be among the best ones presently existing since they are based on the exchange of σ, ω, ρ, and π mesons and consistently include the Fock exchange term. The predictions of PKA1 and PKO3 for the critical temperatures T_{c1} and T_{c2} are quite similar to the one based on SLy4, SLY5, and SIII; see Fig. 2: They predict a domain of temperature for the re-entrance phenomenon going from 0.08–0.1 MeV up to 0.7–0.9 MeV. The strength of the pairing gap at maximum varies from one interaction to another. The single-particle energies are given in the inset of Fig. 3 for PKA1 (left) and PKO3 (right), predicting proton gaps of the order of 3.12 MeV for PKO3 and 3.46 MeV for PKA1. It is quite logical, since the s.p. gap is slightly smaller for PKO3 compared to PKA1, that the pairing re-entrance domain as well as the value of the proton pairing gap are bigger for PKO3 compared to PKA1. Notice that the relative low-energy s.p. gap of the $Z = 28$ shell favors the appearance of the re-entrance pairing correlation.

The structure of the single-particle states around the Fermi energy provides a good understanding of the theoretical results for pairing re-entrance. As nuclei get closer to the drip lines, the coupling to the continuum becomes more important, and continuum resonant states may play an important role if they are located at low energy [28,31–33]. For pairing re-entrance, it is important that these resonant states are sufficiently high (above about 2 MeV) such that the ground state is unpaired, but at the same time, it shall be sufficiently low (below about 4 MeV) to be populated by low-temperature thermal excitation [32,33]. Notice that the energy boundaries given here are only illustrative and could not be used to predict if pairing re-entrance occurs or not. These boundaries change with the pairing strength, which is known to change through the nuclear chart. The critical temperature T_{c1} depends on the position of the resonant state, and the closer it is to the Fermi energy, the lower T_{c1} is. The other critical temperature T_{c2} is limited to a value which is about 1 MeV, as for the usual critical

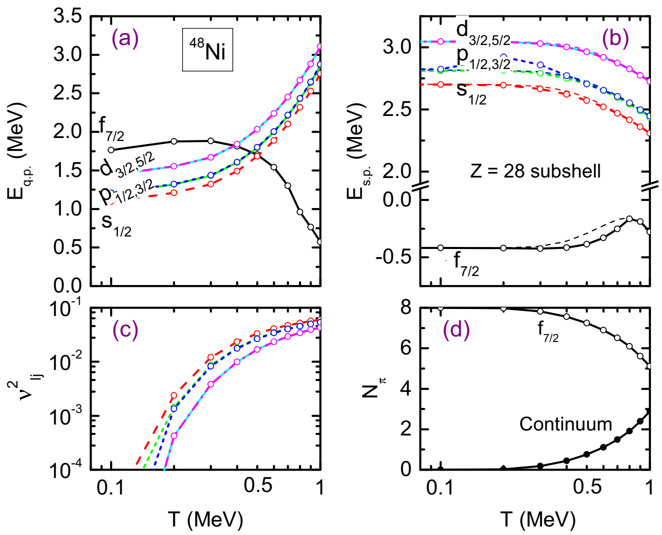

FIG. 4. (a) Temperature evolution of the proton quasiparticle energies corresponding to the states around the Fermi energy: $1f7/2$ (hole), and $s1/2$, $p1/2$-$3/2$, and $d3/2$-$5/2$ (particles). (b) Temperature evolution of the same proton states in the canonical basis. (c) Occupation numbers of the particle states function of the temperature. (d) Occupation numbers of the $1f7/2$ hole state as function of the temperature. In panel (d), we also represent the sum of the occupation probabilities (called continuum) for the particle states shown in panel (c). These are results of FT-RHFB with PKO3 effective Lagrangian and the Gogny pairing force D1S.

temperature in ordinary paired nuclei [19,32,33,41,42]. The quenching mechanism is indeed the same in the re-entrance case and in ordinary paired nuclei: The single-particle thermal excitation breaks the Cooper pairs, since the cost in kinetic energy of having particles well above the Fermi energy is no longer compensated by the gain in forming Cooper pairs. Since the quenching mechanism is the same for ordinary paired nuclei and for pairing re-entrance, the critical temperature T_{c2} is also limited to values around about 1 MeV.

In order to understand the behavior of the nuclear structure of ^{48}Ni in the region of re-entrance, we now analyze results obtained from FT-RHFB with PKO3 effective Lagrangian and the Gogny pairing force D1S; see Ref. [33] for more details on the theory side. The evolution of the proton properties around the Fermi energy with respect to the temperature is shown in Fig. 4 (top panel) for temperatures between 0.08 and 1 MeV. The quasiparticle states [Fig. 4(a)] are increasing functions of the temperature for particles and decreasing for holes. Assuming that the quasiparticle energy is related to the s.p. energies [Fig. 4(b)] by the relation $E_{qp} = \sqrt{(e_{\text{s.p.}} - \mu)^2 + \Delta^2}$, and knowing that the chemical potential $\mu(T)$ is a decreasing function of the temperature, it can be understood that for constant $e_{\text{s.p.}}$ and Δ, the quasiparticle energy decreases for hole states and increases for particle states. The s.p. energies $e_{\text{s.p.}}$ shown in Fig. 4(b) are almost constant up to $T \sim 0.5$ MeV and change by about 200 keV at $T \sim 1$ MeV. The thin dashed lines in Fig. 4(b) show the T dependence of s.p. states in the absence of pairing correlation (pairing interaction has been numerically quenched). The impact of pairing correlations can therefore be estimated by comparing the thin dashed and the solid lines. Pairing correlations tend to stabilize the T dependence of $f7/2$ state up to $T \sim 0.5$ MeV, while the other states are almost unmodified. The effect of temperature is to populate particle states, which are $s1/2$, $p1/2$-$3/2$, and $d3/2$-$5/2$ states, while depopulating hole states, such as the $f7/2$ state. The effect of the temperature on changing the occupation numbers is shown in Figs. 4(c) and 4(d). Figure 4(c) shows the increasing occupation numbers of the particle states as function of temperature, and Fig. 4(d) shows the sum of particle states, labeled Continuum, against the occupation number of the $f7/2$ state. There is an almost perfect symmetry between the occupation numbers of $f7/2$ states and the continuum states, showing that the main states playing an important role in the re-entrance phenomenon are the $f7/2$, $s1/2$, $p1/2$-$3/2$, and $d3/2$-$5/2$ states. The other nuclear interactions shown in Figs. 2–4 predict similar qualitative behavior of the quasiparticle properties. Notice that changing the size of the box has a very marginal impact, as has already been shown in Ref. [32].

On the experimental side, the observation of the pairing re-entrance phenomenon is very challenging and requires the production of a large amount of ^{48}Ni, which is yet impossible. One might think in a first step to better investigate the position of the resonant states in the continuum through one-proton transfer reactions. While not being a direct probe of the pairing re-entrance phenomenon, such a preliminary experimental investigation would test the necessary condition to make finite-temperature pairing re-entrance possible. Two-proton transfer could also be considered, where thermal excitation may be induced by highly charged incident particles. Ultimately, in the future when a very large amount of ^{48}Ni will be available, the study of hot giant resonances in ^{48}Ni may provide a clear signal to probe the thermal pairing re-entrance phenomenon.

IV. CONCLUSIONS

In summary, based on the FT-HFB and FT-RHFB approach, we found that ^{48}Ni may be the only nucleus presently synthesized where the finite-temperature re-entrance phenomenon in the thermal equilibrium state may occur. This prediction has to be tested against improved nuclear modeling. The domain of temperature where this phenomenon could occur, as well as the size of the proton pairing gap, still depends on the detailed s.p. level structure, which varies from one interaction to another. The treatment of the continuum states in the present FT-HFB and FT-RHFB approach shall be improved in the future, and important questions related to the effect of particle number resaturation or additional correlations shall also be investigated. The present work is, however, the first one suggesting that ^{48}Ni may be re-entrant at finite temperature. The present nuclear theories, as well as the experimental facilities, are still far from being able to provide a clear understanding of exotic matter under extreme conditions, and our prediction challenges them both further.

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