Renormalized particle-particle and particle-hole random-phase approximation correlations at finite temperature: Effects upon the nuclear level density parameter

O. Civitarese, A. G. Dumrauf, and M. Reboiro
Department of Physics, University of La Plata, 1900 La Plata, Argentina
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Finite temperature bosonic contributions to the nuclear level density parameter are calculated. The adopted formalism is based on the random-phase approximation treatment of particle-particle, hole-hole, and particle-hole channels of an isospin-independent δ force. The particle-particle (hole-hole) channels are renormalized and they are treated together with the particle-hole channels. Random-phase approximation contributions to the level density parameter are found to display low-temperature features which are similar to the ones that are due to the collapse of pairing correlations.

I. INTRODUCTION

The treatment of two-body correlations via the random phase approximation (RPA) has been studied long ago[1] and has been discussed in detail in textbooks.[2] The RPA treatment of particle-hole (ph) and particle-particle (pp) or hole-hole (hh) two-body correlations, induced by residual nuclear interactions, has been considered in dealing with the properties of both the nuclear ground state and collective excited states as well as in connection with transition densities and transition matrix elements of relevant operators for electromagnetic and transfer processes.[1,2] These studies have been performed in the context of zero-temperature theories, namely from the point of view of microscopic descriptions of the ground state, which do not include the effect of thermal excitations upon single-particle distribution functions.

Recently, with the systematic exploration of highly excited nuclear properties, i.e., in heavy-ion collisions, the study of nuclear effects at finite temperature has been extensively developed.[3-14] Obviously, the theoretical aspects that are relevant for the microscopic description of a thermally excited nucleus are the same, which one faces in dealing with the zero-temperature case, except for the need of a simultaneous treatment of two-body correlations that are not necessarily present at zero temperature in a given nucleus, i.e., ph and pp or hh correlations in a system with a fixed number of particles. It is well known[2] that these are channels that should be taken into account when excited states of A, $A+2$, and $A-2$ systems are described as resulting from collective excitations of a nucleus with A particles. However, as a consequence of the thermal occupation of single-particle states at temperature $T\neq 0$, all of them could be activated. In other words, the nontrivial ($T\neq 0$) distribution of single-particle orbits consistently treated in the macrocanonical ensemble implies that all type of correlations have to be included in the RPA description of the excited states of a given system.[8,10-12,14]

The above-mentioned subject, i.e., the extension of the RPA method in order to include ph, pp, and hh channels in dealing with the diagonalization of residual two-body interactions at finite temperature, has been raised in a number of recent publications[5-7] and we think that it still deserves some attention, particularly, concerning renormalization effects at $T\neq 0$.

The aim of this paper is to calculate relative contributions to the nuclear level density parameter given by ph, pp, and hh channels of the residual two-body interaction. A similar study, for the case of double magic nuclei and for a zero range interaction, has been reported by Vinh Mau and Vautherin.[8] A strong mass dependence of RPA contributions to the level density parameter has been found.[8] The order of magnitude of these contributions, for the case of ^{56}Ni, has been found to be larger than in other calculations.[15] Less significant results have been obtained by the same authors[8] for the case of ^{40}Ca. In both cases pairing correlations have been neglected because of the double magic structure of these nuclei. In this context, and with the aim to evaluate the effect of pairing correlations upon RPA contributions to the level density parameter, we have performed a BCS+RPA calculation of a superfluid nucleus by using the same interaction for monopole pairing and multipole correlations. In this case the residual two-body interaction has been represented by a δ force treated at finite temperature. We have calculated RPA contributions to the level density parameter[8] using this interaction, and we have compared their values with the single-particle contribution given by the uncorrelated fermionic motion.[9,16] Concerning the competition between different channels of the interaction, we have considered the case of quadrupole vibrations in ^{62}Zn, which could strongly reflect the effects of ph and pp (or hh) channels because of the double open shell structure of this nucleus. In order to quantitatively describe the effects of these channels, we have renormalized the pp (hh) strength of the force and we have calculated RPA energies and their contributions to the level density parameter for various values of the nuclear temperature.

The formalism, which is based on the well-known RPA treatment given long ago by Baranger,[1] is presented in Sec. II. Some results are discussed in Sec. III for the case of the nucleus ^{62}Zn and also for a very schematic situation. Finally some conclusions are drawn in Sec. IV.

II. FORMALISM

The treatment of a two-body residual interaction, in the framework of the RPA method, has been discussed long ago[1] and we shall briefly introduce, hereby, the formulas that are relevant for our calculation.

We can write, in standard notation, for the model Hamiltonian H

$$H = H_{\rm sp} + H_{\rm tb} \ , \tag{1}$$

where $H_{\rm sp}$ is the single-particle term and $H_{\rm tb}$ is a two-body interaction defined by

$$H_{\rm tb} = \sum_{\alpha\beta\gamma\delta} V_{\alpha\beta\gamma\delta} a^\dagger_\alpha a^\dagger_\beta a_\delta a_\gamma \ . \tag{2}$$

The matrix elements $V_{\alpha\beta\gamma\delta}$ can be defined in terms of the quantum numbers associated with the single-particle states that participate in the configurations, (α,β) and (γ,δ), and for an isospin independent δ force we can write them as

$$V^{(J)}_{\alpha\beta\gamma\delta} = \frac{\hat{j}}{4\pi} R_{\alpha\beta\gamma\delta} (-)^{j_\alpha - j_\delta - 1} \begin{pmatrix} j_\alpha & j_\beta & J \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix} \times \begin{pmatrix} j_\gamma & j_\delta & J \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix} \tfrac{1}{2}[1 + (-)^{l_\alpha + l_\beta - J}] \ , \tag{3}$$

for particle-particle (hole-hole) configurations and

$$\tilde{V}^{(J)}_{\alpha\beta\gamma\delta} = (-) \frac{\hat{j}}{8\pi} R_{\alpha\beta\gamma\delta} \left[(-)^{l_\alpha + l_\gamma} \begin{pmatrix} j_\alpha & j_\beta & J \\ \frac{1}{2} & \frac{1}{2} & -1 \end{pmatrix} \begin{pmatrix} j_\gamma & j_\delta & J \\ \frac{1}{2} & \frac{1}{2} & -1 \end{pmatrix} + (-)^{j_\beta + j_\delta} \begin{pmatrix} j_\alpha & j_\beta & J \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix} \begin{pmatrix} j_\gamma & j_\delta & J_0 \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \end{pmatrix} (-)^{l_\alpha + l_\beta - J} \right] \ , \tag{4}$$

for particle-hole configurations.

In Eqs. (3)–(4) we have defined the radial integrals

$$R_{\alpha\beta\gamma\delta} = \int_0^\infty r^2 R^{(r)}_\alpha R_\beta(r) R_\gamma(r) R_\delta(r) dr \ , \tag{5}$$

where $R_\alpha(r)$ are single-particle radial wave functions, and

$$\hat{j} = [(2j_\alpha+1)(2j_\beta+1)(2j_\gamma+1)(2j_\delta+1)]^{1/2} \ .$$

A well-known relationship[17] between both matrix elements, reads

$$\tilde{V}^{(J)}_{\alpha\beta\gamma\delta} = (-) \sum_{J'} (2J'+1) \begin{Bmatrix} j_\alpha & j_\beta & J \\ j_\gamma & j_\delta & J' \end{Bmatrix} V^{(J')}_{\alpha\beta\gamma\delta} \ , \tag{6}$$

and its derivation, in the context of the treatment of residual two-body interactions, implies that particle-particle and particle-hole configurations are weighted by the same strength, or in other words that both of them should be multiplied by the same coupling constant.

In this case, because we are interested in the study of effects associated with a renormalization of the particle-particle channel, we shall define two coupling constants, namely $g_{\rm pp}$ and $g_{\rm ph}$, for particle-particle and particle-hole configurations, respectively, and we shall write, for the RPA matrices A and B, the expressions

$$A^{(J)}_{\alpha\beta\gamma\delta} = (E_\alpha + E_\beta)\delta_{\alpha\beta,\gamma\delta} - g_{\rm pp} N_{\alpha\beta\gamma\delta} V^{(J)}_{\alpha\beta\gamma\delta} (u_\alpha u_\beta u_\gamma u_\delta + v_\alpha v_\beta v_\gamma v_\delta) - g_{\rm ph} N_{\alpha\beta\gamma\delta} \tilde{V}^{(J)}_{\alpha\beta\gamma\delta} (u_\alpha v_\beta u_\gamma v_\delta + v_\alpha u_\beta v_\gamma u_\delta) + g_{\rm ph} N_{\alpha\beta\gamma\delta} \tilde{V}^{(J)}_{\alpha\beta\delta\gamma} (u_\alpha v_\beta v_\gamma u_\delta + v_\alpha u_\beta u_\gamma v_\delta) \theta(\gamma\delta,J) \ , \tag{7}$$

$$B^{(J)}_{\alpha\beta\gamma\delta} = g_{\rm pp} N_{\alpha\beta\gamma\delta} V^{(J)}_{\alpha\beta\gamma\delta} (u_\alpha u_\beta v_\gamma v_\delta + v_\alpha v_\beta u_\delta u_\gamma) - g_{\rm ph} N_{\alpha\beta\gamma\delta} \tilde{V}^{(J)}_{\alpha\beta\gamma\delta} (u_\alpha v_\beta v_\gamma u_\delta + v_\alpha u_\beta u_\gamma v_\delta) + g_{\rm ph} N_{\alpha\beta\gamma\delta} \tilde{V}^{(J)}_{\alpha\beta\delta\gamma} (u_\alpha v_\beta u_\gamma v_\delta + v_\alpha u_\beta v_\gamma u_\delta) \theta(\gamma\delta,J) \ , \tag{8}$$

where

$$N_{\alpha\beta\gamma\delta} = \frac{2}{(1+\delta_{\alpha\beta})^{1/2}(1+\delta_{\gamma\delta})^{1/2}} \ ,$$

and

$$\theta(\gamma\delta,J) = (-)^{j_\gamma + j_\delta + J} \ .$$

In Eqs. (7) and (8) we have defined the occupation numbers u_α and v_α, which for open shell systems are obtained from the BCS treatment of the monopole ($J=0$) part of the two-body force, while that for closed shell systems are 1 (0) or 0 (1) for particle (hole) states. The RPA matrix equation reads

$$\begin{bmatrix} A & B \\ -B & -A \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} = \omega \begin{bmatrix} X \\ Y \end{bmatrix} \ , \tag{9}$$

and we have to solve it in order to obtain the spectrum of J^{π} excited states.

The finite temperature treatment of the RPA theory has been discussed previously[18–20] and we shall not discuss it here. Let us remind the reader that it mainly reflects the fact that thermally occupied single-particle orbits should be considered in dealing with the construction of the unperturbed configurations. This is done by a proper inclusion of temperature-dependent weighting factors in Eqs. (7) and (8). The most important effect of the inclusion of temperature-dependent single-particle occupation numbers could be described in terms of a blocking mechanism responsible for the so-called thermally collapse of pairing correlations.[3,4,9] For long-range correlations it has been found that minor changes in the nuclear response could be attributed to thermal excitations.[10,20,21]

In the following section we are going to discuss the role of single-particle and vibrational (bosonic) degrees of freedom upon the nuclear level density parameter,[16] i.e., the scale factor that relates excitation energy and nuclear temperature when a renormalized particle-particle channel is included in the RPA equation of motion. The procedure that we have followed in order to obtain the desired information has been described previously[18–20] for the case of multipole excitations induced by separable forces. In the present case we have to solve Eq. (9) and once the RPA energies are determined we can introduce boson occupation factors:[8,11,18]

$$n_{\nu}=\frac{1}{\exp(\omega_{\nu}/T)-1} , \tag{10}$$

where ω_{ν} are the positive eigenvalues of Eq. (9), which, of course, are temperature dependent. The resulting statistical factors can readily be used for the evaluation of mean values and with them we can finally obtain the contributions to the level density parameter due to vibrational excitations,[8] namely

$$a_{\mathrm{RPA}}(T)=\frac{E^{*}_{\mathrm{RPA}}}{T^{2}} , \tag{11}$$

where[19]

$$E^{*}_{\mathrm{RPA}}=\mathrm{Tr}\ (\rho_{\mathrm{RPA}}H_{\mathrm{RPA}})/\mathrm{Tr}(\rho_{\mathrm{RPA}}) ,$$

and

$$\rho_{\mathrm{RPA}}=\exp(-H_{\mathrm{RPA}}/T)$$

is the density operator[5] constructed from the RPA equation of motion, Eq. (9).

Since this procedure does not imply new theoretical developments, we would like to pass by the details, which can be found in Refs. 5, 8, and 18–20 and proceed to the next section.

III. RESULTS AND DISCUSSION

Before starting with the discussion of a realistic case, let us consider the results of the preceding presented formalism for a truncated single-particle basis. Our model space includes two j shells (with $j=\frac{3}{2}$) separated by an energy spacing $2\epsilon=2$ MeV. We have assumed that each shell possesses a $2j+1$ degeneracy and that the matrix elements of the interaction between particle-particle, hole-hole, and particle-hole configurations are the same except for the occupation factors corresponding to particles or holes. Furthermore, we have assumed that the system can be thermally excited and we have solved the associated statistical factors neglecting the effects of pairing correlations. Therefore, the factors u_{α} and v_{α} of Eqs. (7) and (8) will be absorbed in the definition of the thermal occupation factors $F_{\mathrm{pp}}(T)$ and $F_{\mathrm{ph}}(T)$, which for this case are

$$F_{\mathrm{pp}}(T)=F_{\mathrm{ph}}(T)=\tanh(\epsilon/2T) ,$$

T being the nuclear temperature in units of energy.

The RPA equation of motion, Eq. (9) takes, in this model space, a simple form and for $J^{\pi}=2^{+}$ excitations we have obtained the eigenvalues:

$$\omega_1=\pm 2\epsilon(1-C/\epsilon)^{1/2}$$

and

$$\omega_2=2\epsilon(1-D/\epsilon)^{1/2} ,$$

where

$$C=5.10^{-4}g_{\mathrm{pp}}F_{\mathrm{pp}}(T)\ (\mathrm{MeV})$$

and

$$D=1.10^{-3}g_{\mathrm{ph}}F_{\mathrm{ph}}(T)\ (\mathrm{MeV})$$

are the matrix elements of the pp and ph channels, respectively, for a $j=\frac{3}{2}$ single-particle shell. In this case we can associate to ω_1 the value of the energy for the vibrations in the $A+2$ ($\omega_1>0$) and $A-2$ ($\omega_1<0$) systems measured from the ground state of the system with A particles, A being the number of particles of the initial nucleus; in this case we have adopted the value $A=4$ in order to simulate a fully occupied lower shell situation. The energy ω_2 can be associated to ph vibrations in the initial nucleus, instead. The results which are shown in Fig. 1 represent the behavior of $|\omega_1|$ and ω_2, for various values of T, as a function of the ratio between the pp and ph coupling constants. For a given value of the temperature pp (or hh) RPA energies are larger than ph ones provided $g_{\mathrm{pp}}/2g_{\mathrm{ph}}<1$. It should be noted that for this simple case the value $g_{\mathrm{pp}}/2g_{\mathrm{ph}}=1$ corresponds to the standard relationship between pp and ph matrix elements, without any renormalization, and for it both roots, ω_1 and ω_2, have the same value. By the other hand, for $g_{\mathrm{pp}}/2g_{\mathrm{ph}}>1$, pp (or hh) RPA energies are lower than the ph ones. Both roots, ω_1, and ω_2, display a critical behavior, as a function of the temperature, for a fixed value of the ratio $g_{\mathrm{pp}}/2g_{\mathrm{ph}}$ thus reflecting a thermal blocking of the configurations. Finally, for some cases ($T=0$ and $T=0.5$ MeV) RPA solutions for pp (hh) channels become imaginary for $g_{\mathrm{pp}}/2g_{\mathrm{ph}}>1$. This fact indicates that strongly renormalized pp (hh) channels can induced permanent deformations of the system. It should be mentioned that the values of the temperature T, for this schematic case, are conditioned by the energy scale, ϵ,

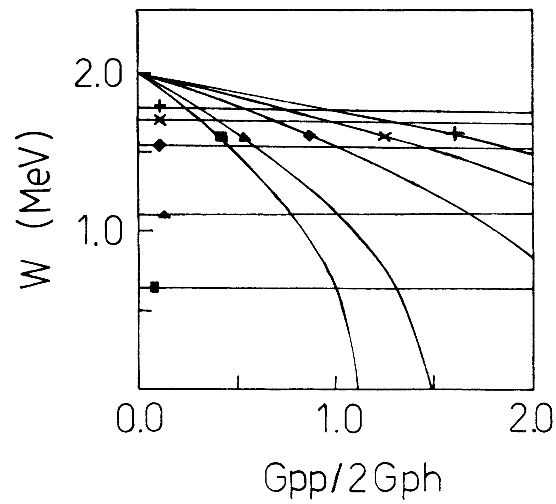

FIG. 1. Temperature dependence of the RPA energies, W, for a two level model space as a function of the ratio between particle-particle and particle-hole strengths of the residual interaction, $g_{pp}/2g_{ph}$. Curves and horizontal lines correspond to RPA energies ω_1 and ω_2, respectively (see the text). Values of the temperature T, in units of MeV, are indicated by square ($T=0$), triangle ($T=0.5$ MeV), diamond ($T=1$ MeV), cross ($T=1.5$ MeV) and plus ($T=2$ MeV) signs, respectively. Details about the structure of the model space and of the RPA equation of motion are given in Sec. III.

which we have previously defined.

The behavior of the RPA energies, as a function of T, is of particular importance for our discussion of a realistic case since, as shown in Refs. 5 and 8, bosonic contributions to the nuclear level density parameter are sensitive to it. We have calculated the RPA vibrational spectrum of ^{62}Zn, at finite temperature, including pp (hh) and ph channels of an isospin-independent δ force. We have renormalized pp (hh) channels of the interaction in order to determine the effect of this renormalization upon the RPA energies and, consequently, upon the level density parameter, i.e., via the relationship between the total excitation energy of the nucleus and its temperature T.

Our model single-particle basis includes all single-particle states up to the oscillator shell with $N=6$ for neutrons and protons. The single-particle energies have been taken from Nilsson's model[22] with the following parameters: $\chi_Z=0.07135$, $\chi_Z\mu_Z=0.0251$, $\chi_N=0.07366$, and $\chi_N\mu_N=0.019$, which reproduce the observed sequence of single-particle states in the region of interest. First, we have solved the monopole part, $J^\pi=0^+$, of the interaction in the BCS approximation. We have adjusted the corresponding coupling constants in order to reproduce the observed gap parameters, Δ_N and Δ_Z, for neutrons and protons, respectively. We have obtained, for the active single-particle shells with $28\le N\le 50$ and $28\le Z\le 50$, the values $\Delta_N=1.457$ MeV and $\Delta_Z=1.346$ MeV, for neutrons and protons, respectively. The experimental values, extracted from Ref. 23, are $\Delta_N=1.434$ MeV and $\Delta_Z=1.336$ MeV.

In our model space we have obtained the results which are shown in Fig. 2, where the fermionic contribution to the nuclear level density parameter is displayed as a function of the nuclear temperature T. Figure 2 shows a bump due to the thermal collapse of pairing correlations,[9,24,25] at the temperature $T=0.65$ MeV, which is of the order of $T\cong\Delta/2$ or half the zero-temperature gap, hereon the pairing critical temperature.[3,4,9,24,25] Since proton and neutron pairing gap parameters are nearly of the same value, we have obtained a single bump and the asymptotic value of the level density parameter, $a(T)$, approaches $a(T)\cong a_F\cong 7$ MeV^{-1} for temperatures of the order of $T\cong 1.2$ MeV. One should note that the value of $a(T)$ at $T\cong 0.6$ MeV is of the order of 12 MeV^{-1}, nearly twice the asymptotic value, a_F, for an uncorrelated Fermi gas.[16] The discussion of this effect has been presented previously.[9,24,25] In these works the increase of the level density parameter for a superfluid system nearby the pairing critical temperature has been discussed in the context of a phase transition between the superfluid and normal phases.

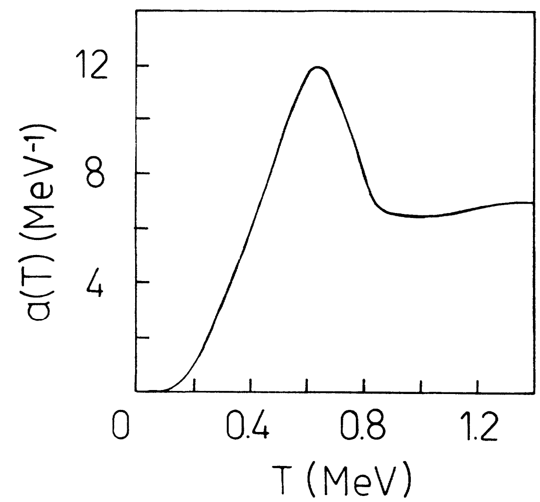

FIG. 2. Fermionic contribution to the level density parameter, $a(T)$ (MeV^{-1}), for the nucleus ^{62}Zn, as a function of the nuclear temperature, T (MeV).

RPA contributions to the level density parameter, Eq. (11), are shown in Fig. 3. These results, for different

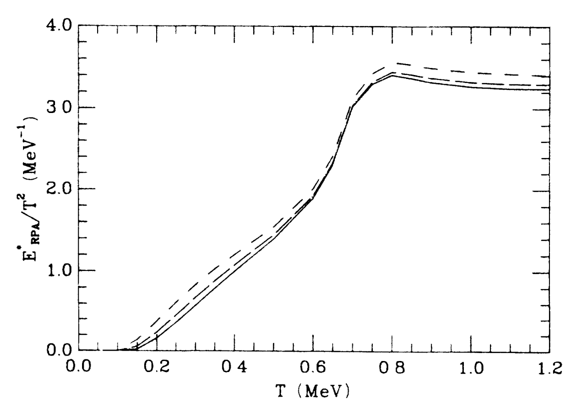

FIG. 3. RPA contributions, to the level density parameter, $a_{RPA}(T)=E^*_{RPA}/T^2$ (MeV^{-1}), Eq. (11), for quadrupole excitations in ^{62}Zn, as a function of T (MeV). Solid, dashed-dotted and dashed lines correspond to $g_{pp}/g_{ph}=0.0$, 1.0, and 2.0, respectively; $g_{pp}/g_{ph}=1.0$ corresponds to the unrenormalized strength of the force for each channel.

values of the ratio g_{pp}/g_{ph}, show a temperature dependence which is similar to the one shown in Fig. 2, namely a nearly quadratic increase with T, for temperatures below the pairing critical temperature $T_c \cong 0.65$ MeV, followed by a saturation for $T > T_c$. The saturation value of the RPA contributions to the level density parameter is, in this case, of the order of 50% the saturation value corresponding to fermionic contributions. It should be noted that the results which are shown in Fig. 3 are weakly dependent upon the renormalization of the particle-particle (hole-hole) channels of the interaction. The quadratic dependence of $a_{\mathrm{RPA}}(T)$, Eq. (11), at low T, could be interpreted in terms of the statistics, namely the underlying bosonic nature of the excitations. In fact, one would expect that weakly temperature-dependent phonon energies could reflect statistical features similar to the ones that are found in a noninteracting gas of bosons. If this is the case then the RPA contributions to the excitation energy of the nucleus would not necessarily change quadratically with T and a higher power of T would be more adequate to describe their temperature dependence. Naturally it would be desirable to determine the order of this temperature dependence, although it could not be identified with the above-mentioned RPA contributions to the level density parameter. In order to illustrate this point we have defined the quantity:

$$\sigma(T)=E^*_{\mathrm{RPA}}/T^4 \ . \tag{12}$$

Its temperature dependence is shown in Figs. 4 and 5, for different values of the ratio g_{pp}/g_{ph}. These results show that, when renormalized values of the ratio g_{pp}/g_{ph} are used, the relative magnitude of pp (hh) contributions to $\sigma(T)$ could be of the same order of magnitude as for the ph ones. We can compare these results, Figs. 4 and 5, with previously reported ones[18,19] of finite temperature RPA calculations where pp (or hh) channels of the residual interaction have not been considered. In Refs. 18 and 19 configuration spaces are enlarged, at finite temperature, as the consequence of the thermal activation of high-lying single-particle states. For these cases only one bump in the scale factor $\sigma(T)$ has been obtained which mainly reflects the effect of the temperature dependence of the structure of the first excited states. In this case the same effect can be observed and it should be associated with the bump located at $T \cong 0.7$ MeV, as shown in Figs. 4 and 5. By the other hand, the main result of the inclusion of pp (or hh) channels and their renormalization could be associated with the appearance of a second bump at a lower temperature, of the order of $T \cong 0.20$ MeV, which should be interpreted in terms of the thermal blocking of these channels. Since these excitations normally involve low-energy transitions between partially occupied single-particle orbits nearby the Fermi level their collapse require a lower temperature than the one associated to the thermal collapse of the transitions across the Fermi level, i.e., of the ph type. In this respect, the bulk of the results for ^{62}Zn could also be analyzed in terms of the results, which we have already discussed, for the case of a crude two-shell model space. In fact, both cases have the common feature of a pronounced thermal dependence for pp (hh) channels as well as a dependence upon the renormalization of the pp (hh) strength of the force. It means that in dealing with the macroscopic picture of the noninteracting gas of RPA bosons all channels of the interaction have to be included at finite T. A similar conclusion has been reported by Vinh Mau.[5]

To complete our discussion, let us mention that we have adjusted the strengths of the force, for the $T=0$

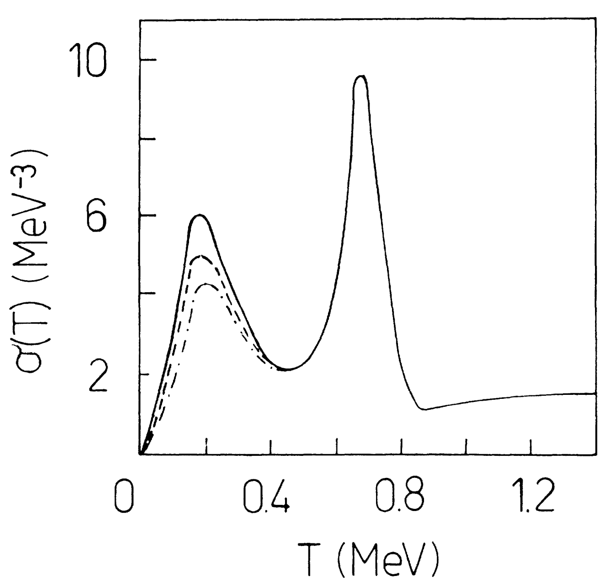

FIG. 4. RPA contributions to the energy versus temperature scale factor $\sigma(T)$, Eq. (12), for quadrupole vibrations in the nucleus ^{62}Zn, as a function of the nuclear temperature, T. Results corresponding to different values of the ratio g_{pp}/g_{ph} are indicated by solid ($g_{pp}/g_{ph}=1$), dashed ($g_{pp}/g_{ph}=1.5$), and dashed-dotted ($g_{pp}/g_{ph}=2$) lines, respectively.

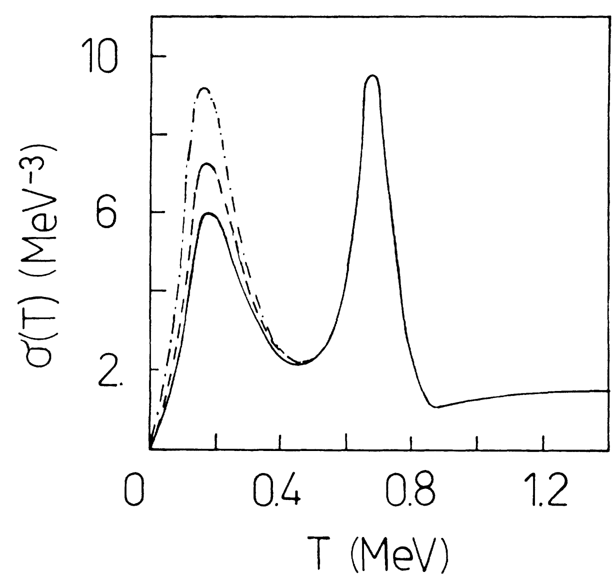

FIG. 5. The same quantity, $\sigma(T)$, for the values of g_{pp}/g_{ph} denoted by solid ($g_{pp}/g_{ph}=1$), dashed ($g_{pp}/g_{ph}=0.5$), and dashed-dotted ($g_{pp}/g_{ph}=0$) lines, respectively.

TABLE I. Theoretical values of the energy, $\omega(2_1^+)$, and quadrupole electric transition probability, $B[E2,2_1^+\rightarrow$ ground state (g.s.)] as a function of the ratio between particle-particle and particle-hole strengths of the residual interaction, g_{pp}/g_{ph}, for the first excited state $J^\pi=2^+$ state in ^{62}Zn. The values correspond to zero temperature ($T=0$).

g_{pp}/g_{ph}	$\omega(2_1^+)$ (MeV)	$B(E2;2^+\rightarrow$g.s.) (spu)
0.0	1.066	5.54
0.5	1.012	5.52
1.0	0.953	5.49
1.5	0.890	5.45
2.0	0.822	5.39

case, in order to reproduce the observed properties of the low-lying $J^\pi=2^+$ state of ^{62}Zn. We have obtained, for the energy and quadrupole electric transition probability, the values $\omega(2_1^+)=0.953$ MeV and $B(E2)=5.49$ single-particle units (spu) which should be confronted with the experimental values of 0.954 MeV and 5.6 spu, respectively.[23]

The behavior of the first excited $J^\pi=2^+$ state, in ^{62}Zn, as a function of the ratio g_{pp}/g_{ph} is shown in Table I. These results, which have been obtained at $T=0$, show a dependence of the microscopic structure of the state on the renormalization of the pp channels of the two-body interaction. This tendency is also present in the $T\neq0$ results, as we have seen from our calculations. Finally, let us mention that the results which we have reported are not affected by the addition, to our model single-particle space, of single-particle orbits with $N>6$. In fact, as we have seen from numerical test, the associated energy weighted sum rules remain almost constant for $0\leq T\leq 1.2$ MeV and excitation energies, for fermionic and bosonic degrees of freedom do not show the decreasing trend which is due to the saturation of the occupation numbers of high-lying single-particle orbits at high temperatures.

IV. CONCLUSIONS

We have calculated RPA energies for quadrupole excitations in ^{62}Zn at finite temperature by including particle-particle, hole-hole, and particle-hole channels of a residual, isospin-independent δ force. We have treated monopole components of the force in the BCS approximation and we have obtained temperature-dependent pairing occupation numbers and quasiparticle energies for temperature values in the range $0\leq T\leq 1.2$ MeV.

With these values we have calculated RPA contributions to the level density parameter, $a_{RPA}(T)$; the results show a weak dependence of $a_{RPA}(T)$ upon the renormalization of the force but a clear temperature dependence. The corrections to the level density parameter due to RPA quadrupole phonon excitations amount, in this case, to nearly 50% of the quasiparticle contribution.

At the same time we have analyzed the effects due to a renormalization of the particle-particle strength, in the range $0\leq g_{pp}/g_{ph}\leq 2$, upon the scale factor $\sigma(T)$, which relates the RPA excitation energy with the fourth power of T. The results of this RPA calculations show that, in addition to the already reported bump due to particle-hole configurations,[18,19] a second, low temperature bump could be observed in the temperature dependence of the scale factor. The appearance of this second bump could be taken as an indication about the need to include, in a realistic description of nuclear level densities, all allowed configurations in addition to the particle-hole ones, at the RPA level of approximation.

In conclusion, the results of the preceding section seemingly reinforce the findings of another authors[5] concerning the influence of finite temperature particle-particle interactions upon the level density parameter. The amount of renormalization, for these channels, could be eventually determined from the comparison between theoretical and experimental results for other observables, like γ rays multiplicities and particle evaporation data, from hot nuclei. Finally, and in order to give some support to the above-mentioned renormalization effect upon particle-particle channels of residual two-body interactions, calculations of nuclear matter properties with renormalized effective interactions would be desirable.

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[1]M. Baranger, Phys. Rev. **120**, 957 (1960).

[2]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. II, Chap. 6 and references therein; A. De Shalit and H. Fesbach, *Theoretical Nuclear Physics* (Wiley, New York, 1972), Vol. I, Chap. V, pp. 541–547; G. E. Brown, *Many Body Problems* (North-Holland, New York, 1972), Chap. 4, pp. 99–112.

[3]A. Goodman, Nucl. Phys. **A352**, 30 (1981); **A352**, 45 (1981).

[4]O. Civitarese, G. G. Dussel, and R. P. J. Perazzo, Nucl. Phys. **A404**, 15 (1983).

[5]N. Vinh Mau, Nucl. Phys. **A491**, 246 (1989).

[6]K. Tanabe, Phys. Rev. C **37**, 2802 (1988).

[7]T. Hatsuda, Nucl. Phys. **A492**, 187 (1989).

[8]N. Vinh Mau and D. Vautherin, Nucl. Phys. **A445**, 245 (1985).

[9]O. Civitarese and A. L. De Paoli, Nucl. Phys. **A440**, 480 (1985).

[10]P. F. Bortignon, R. A. Broglia, G. F. Bertsch, and J. Pacheco, Nucl. Phys. **A460**, 149 (1986).

[11]S. Jang and C. Yannouleas, Nucl. Phys. **A460**, 201 (1986).

[12]R. W. Hasse and P. Schuck, Phys. Lett. B **179**, 313 (1986).

[13]P. F. Bortignon and C. H. Dasso, Phys. Lett. B **189**, 381 (1987).

[14]T. Troudet, Nucl. Phys. **A441**, 676 (1985).

[15]A. V. Ignatyuk; Yad. Fiz. 29, 875 (1975) [Sov. J. Nucl. Phys. **29**, 450 (1979)].

[16]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vol. I, Chap. 2, pp. 183–188.

[17]G. Berstch, *Practitioners Shell Model* (Elsevier, New York, 1972).
[18]F. Alasia, O. Civitarese, and M. Reboiro, Phys. Rev. C **35**, 812 (1987).
[19]F. Alasia, O. Civitarese, and M. Reboiro, Phys. Rev. C **36**, 2555 (1987).
[20]F. Alasia, O. Civitarese, and M. Reboiro, Phys. Rev. C **39**, 1012 (1989).
[21]O. Civitarese, R. A. Broglia, and C. H. Dasso, Ann. Phys. (N.Y.) **156**, 142 (1984).
[22]S. G. Nilsson *et al.*, Nucl. Phys. **A131**, 1 (1969).
[23]*Nuclear Data Sheets* (Academic, New York, 1979), Vol. 28, No. 2.
[24]A. L. Goodman, Phys. Rev. C **29**, 1887 (1984).
[25]O. Civitarese, G. G. Dussel, and A. Zuker, Phys. Rev. C **40**, 2900 (1989).