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EFFECTS OF THERMAL AND PARTICLE NUMBER FLUCTUATIONS ON THE GIANT ISOVECTOR DIPOLE MODES FOR ^{58}Ni-NUCLEUS IN THE FINITE TEMPERATURE RANDOM PHASE APPROXIMATION

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1. Introduction

The validity of the mean-field theory at finite temperature and the fluctuations in the thermal mean-field approach have been the subject of various studies over the past few years. In the finite temperature Bardeen-Cooper-Schrieffer theory (FT-BCS) it has been predicted that an overall collapse of the BCS-pairing gap should take place at a critical temperature corresponding to the phase transition from the superfluid phase to the normal fluid phase [1]. Recently, it has been shown by many authors that such effect does not exist in realistic medium and heavy nuclei. Indeed, in the calculations taking the thermal and quantum fluctuations at finite temperature into account [2,3], the sharp phase transition is completely washed out. However, in these studies of the phase transition region at finite temperature only simplified schematic models with two levels [1], a single-j shell [2] or with a degenerate energy spectrum [3] were employed. Although there is some hope that the inclusion of more j-shells should not appreciably alter the conclusion [2], it is certainly interesting to study what indeed happens to the pairing gap at finite temperature in calculations based on a realistic single-particle energy spectrum in realistic nuclei in order to give a more adequate and concrete answer to this problem. On the other hand, so far all the calculations of the collective state characteristics in the framework of the finite temperature random-phase approximation (FT-RPA) ignore as a rule the effect of washing out the phase transition from superfluid to normal. The pairing gap $\Delta(T)$ at finite temperature T in these studies is either equal to its zero temperature value $\Delta(0)$ [1,4] or undergoes a collapse at critical temperature T_{crit} ($\Delta(T)=0$ for $T \geqslant T_{crit}$) as in the phase transition case [1,5,6]. By this reason up to now it is not clear how the fluctuations influence the FT-RPA results in realistic nuclei with a realistic single-particle spectrum.

In this work we therefore investigate the behaviour of the giant resonance characteristics at finite temperature in the even-even spherical ^{58}Ni nucleus in the FT-RPA using a realistic single-particle spectrum and taking into account the effects of thermal and quantum particle number fluctuations on the BCS pairing gap. The paper is organized as follows. In § 2 we draw the outline of the model and the method we employ to perform our investigation. We also discuss the choice of parameters we use in calculations. The results are displayed and discussed in § 3. In the last section we summarize the paper.

2. Outline of the Model and the Method. Choice of Parameters

We use the set of FT-RPA equations in the formalism of the quasiparticle-Phonon Nuclear Model (QPNM) /7/ that has recently been extended by one of us to finite temperature /5,8/. These equations have already been derived in our approach in /5/, so we do not repeat them here. They have also been obtained by other authors by somewhat different methods /9/. We use the QPNM Hamiltonian consisting of the terms describing the motion of nucleons in the nuclear mean field, the superfluid pairing interaction and the residual interaction in the form of the separable multipole isoscalar and isovector forces /7/. The form of the mean-field is described in the calculations by the Woods-Saxon potential U(r). We also use the derivative $\partial U(r)/\partial r$ for the radial dependence of the reduced matrix elements of the single--particle operators generating excitation of multipolarity λ . For details of the QPNM we direct readers to Refs. /7/. Due to the high interest in the giant dipole resonances (GDR) in hot nuclei observed recently in experiments /10/, we concentrate our consideration in this paper only on the electric isovector dipole collective modes ($\lambda^{\pi}=1^-$). The thermal fluctuations in the mean-field induced by temperature T are taken here into account by the method employed in /2/, where the Δ -dependence of mass is neglected. As has been shown in /2/, this Δ -dependence of mass leads only to some slight shift in the temperature dependence of the BCS-pairing gap Δ . Thus, we have for the thermal average gap $\langle\Delta\rangle$ the expression /2,11/

$$\langle\Delta\rangle = \int_0^\infty \Delta(T)\exp[-F(\Delta(T))/T]\,d\Delta(T) \Big/ \int_0^\infty \exp[-F(\Delta(T))/T]\,d\Delta(T), \quad (1)$$

where $F(\Delta(T))$ is the free energy /3,5/.

In the quasiparticle representation the quantum fluctuations of the particle number are caused by the nucleon-number nonconservation due to the Bogolubov transformation from particles to quasiparticles. It has been shown in /12/ that the particle number fluctuations in

the ground-state, whose wave function is defined as the quasiparticle vacuum, renormalize the pairing gap Δ as

$$\tilde{\Delta} = [1 + 1/\Delta N^2]\Delta . \quad (2)$$

where the particle number fluctuations ΔN^2 are

$$\Delta N^2 = \sum_j (j+1/2)\Delta^2/[(E_j-\lambda)^2+\Delta^2] . \quad (3)$$

In Eq.(3) E_j are the single-proton (or neutron) energies defined by using the set of parameters for the Woods-Saxon potential U(r) chosen at zero temperature in /13/; λ is the chemical potential (λ_n for neutrons, and λ_p for protons, respectively). We shall use Eqs.(1)-(3) at finite temperature to define the gap $\langle\Delta\rangle$, where the thermal fluctuations are taken into account, and the gap $\langle\tilde{\Delta}\rangle$, where both thermal and particle number fluctuations are included. The zero temperature single-particle energy spectrum is used by us also at finite temperature since its temperature dependence is very smooth and weak up to T=6 MeV, as has been shown in /14/. The pairing constants are chosen to be G_n=0.28MeV for neutrons and G_p=0.30MeV for protons in ^{58}Ni. The pairing gap at zero T is therefore found to be $\Delta_n \approx$ 1.4 MeV and Δ_p=0. The critical temperature T_{crit}, where the collapse of the mean-field pairing gap takes place, is evaluated to be $T_{crit}=0.567\Delta(T=0)$ /11/. For ^{58}Ni nucleus $T_{crit}\approx$ 0.79 MeV. It is also evident from Eq.(3), that in difference with /2/, the quantum particle number fluctuations considered by this method exist even at T=0 .

The parameters of the effective dipole modes, namely the isoscalar $\varkappa_0^{(1)}$ and isovector $\varkappa_1^{(1)}$ constants are chosen following the procedure discussed in /5/. Thus, at zero temperature the energy $\omega_0^{(1)}$ for isoscalar dipole modes in the FT-RPA calculations is put equal to zero for excluding "spurious" states. The isovector dipole constant $\varkappa_1^{(1)}$ is defined to reproduce the empirical location of the isovector dipole resonance ($\omega_{E1}^{exp}\approx$ 17 MeV for ^{58}Ni /15/). These values of the constants also have a rather weak temperature dependence /16/ and therefore are used for all temperatures lower than 6 MeV throughout our calculations. The electric dipole strength distributions are calculated based on the expression for the residual electric transition probabilities $B_T(E1,\omega_i)$ at finite temperature T obtained by us in /5/.

3. Results and Discussion

Figure 1 depicts the temperature dependence of the BCS-pairing gap Δ , the thermal average pairing gap $\langle\Delta\rangle$ and the gap $\langle\tilde{\Delta}\rangle$ calcu-

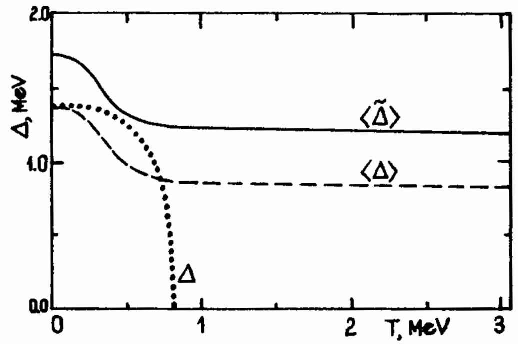

Fig. 1. Pairing gaps versus temperature in ^{58}Ni. The dotted curve represents the FT-BCS gap Δ. The broken curve denotes the thermal average pairing gap $\langle\Delta\rangle$, computed from Eq.(1). The full curve describes the temperature dependence of the pairing gap $\langle\tilde{\Delta}\rangle$ when both thermal and particle number fluctuations are taken into account.

lated from (2) with taking into account the particle number fluctuations. The effect of washing out the phase transition obtained in the schematic calculations/2/ due to the thermal fluctuations is also clear in our realistic case. The particle number fluctuations somewhat intensify this effect and increase the pairing gap $\langle\Delta\rangle$ to $\langle\tilde{\Delta}\rangle$. However, as compared to the schematic models, where the pairing gap $\langle\Delta\rangle$ decreases noticeably with increasing T /1-3/, for ^{58}Ni we see some very smooth decrease in the gaps $\langle\Delta\rangle$ and $\langle\tilde{\Delta}\rangle$ at T higher than about 1 MeV. At higher temperatures up to 3 MeV these values of the pairing gaps remain nearly constant and sufficiently large as compared to their values at zero temperature. Of course, for temperature higher than about 5-6 MeV the temperature dependence of the single-particle energies should be taken into account and a more appreciable decrease in $\langle\Delta\rangle$ and $\langle\tilde{\Delta}\rangle$ with increasing T should be expected.

The temperature dependence of the particle number fluctuations calculated from Eq.(3) is displayed in Fig. 2 as the values $1/\Delta N^2$. While this temperature dependence is very close to the schematic single j-shell/2/ at T lower than T_{crit}, it increases slowly with increasing T higher than T_{crit} and remains nearly constant at $T > 3$ MeV. We note that for sufficiently high temperature (e.g., $T \geqslant 5 \div 6$ MeV) the expansion (2) turns out to be poor and the higher expansion orders should be included/12/.

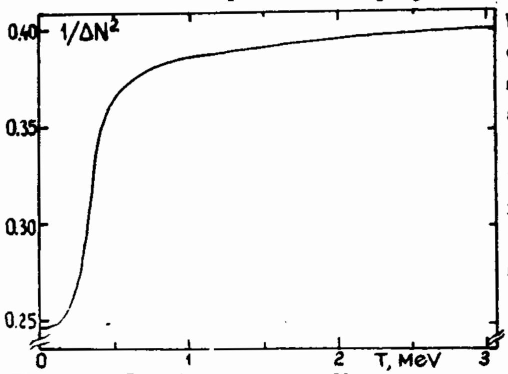

Fig. 2. Particle number fluctuations in ^{58}Ni versus temperature.

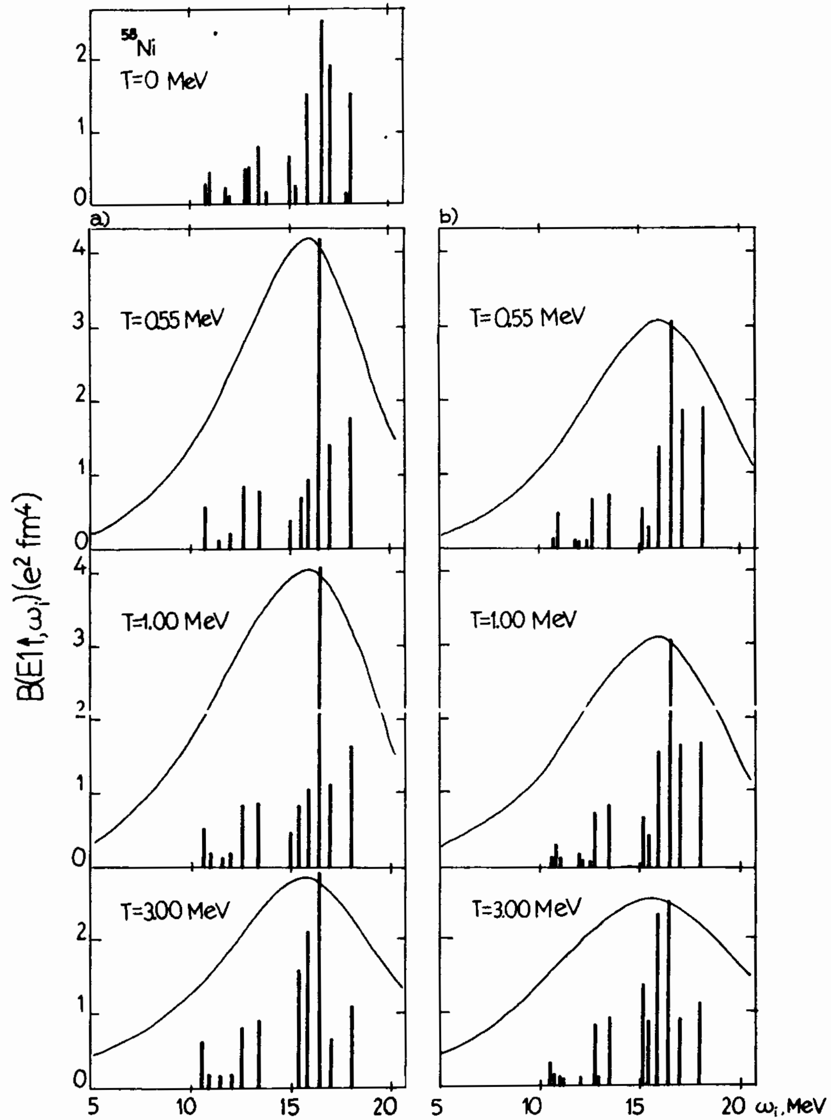

Fig. 3. Reduced electric transition probabilities for the isovector giant dipole modes in ^{58}Ni at several temperatures. The full curves are computed by using the phenomenological Lorentzian distribution given in/17/. a) Results computed with the values of the thermal average gap $\langle\Delta\rangle$. b) Results computed with the values of $\langle\tilde{\Delta}\rangle$, i.e. when both thermal and particle number fluctuations are taken into account.

The distributions of the electric dipole strengths computed in the FT-RPA with the value $\langle\Delta\rangle$ and $\langle\tilde{\Delta}\rangle$, respectively, are represented in Fig. 3 for several temperatures. In this figure the curves of the phenomenological Lorentz distribution normalized at the maximum value of $B(E1\uparrow, \omega_i)$ are also depicted. (For the formula of the distribution, see /17/). With increasing temperature there is some weak intensification of the transition probabilities in the states at the tail of the GDR. The intensities of the strengths at the main GDR peaks are reduced slightly to distribute more evenly over neighbouring states.

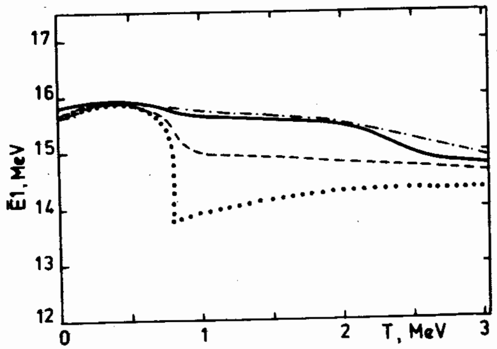

Fig. 4. Isovector giant dipole resonance centroids in ^{58}Ni versus temperature. The dotted, broken and full curves correspond to the results obtained by using the pairing gaps Δ, $\langle\Delta\rangle$ and $\langle\tilde{\Delta}\rangle$ from Fig. 1 respectively. The chain curve represents the result computed with the zero temperature pairing gap $\Delta(0)$.

The most interesting result of the thermal and quantum particle number fluctuation effects on the GDR characteristics is observed in the temperature dependence of the GDR energy centroid as depicted in Fig. 4. While the collapse of the BCS pairing gap Δ at T_{crit} leads to a break in the curve describing the GDR energy centroid $\bar{E}1$ as a function of temperature (the dotted curve), the thermal fluctuations smear out this discontinuity in the curve of $\bar{E}1$ computed with the values $\langle\Delta\rangle$ (the broken curve). The quantum particle number fluctuations intensify this effect as shown by the full curve. In consequence, the temperature dependence of $\bar{E}1$ computed with the values $\langle\tilde{\Delta}\rangle$ lies very close to the one that is obtained by càlculation with the temperature independent pairing gap $\Delta(T) = \Delta(0)$ (the chain curve). Therefore, we see that for calculations in the FT-RPA one can readily use at $T \neq 0$ the same value of the pairing gap Δ defined at zero temperature. We also note that the values of the GDR energy centroids $\bar{E}1$ in Fig. 4 are obtained by summation in the energy interval 10 MeV$\leqslant \omega_i \leqslant$ 30 MeV. The change of the energy interval

of summation may influence the values of $\bar{E}1$ (Cf. /5/). In any case the constants $\varkappa_1^{(1)}$ can always be chosen so that the centroid $\bar{E}1$ (but not the main peak of the GDR as in our calculations presented here) be equal to ω_{E1}^{exp}. However, this does not influence the behaviour of $\bar{E}1$ as a function of temperature studied above.

4. Conclusions

Summarizing our results we find: The calculations in ^{58}Ni nucleus by using a realistic single-particle spectrum show qualitatively the same effects of thermal and particle number fluctuations on the characteristics of the IV-GDR in the FT-RPA in comparison with schematic models. However, in the temperature region higher than T_{crit} up to 3 MeV the pairing gap is rather stable and sufficiently large with increasing temperature. The IV-GDR energy centroid computed by using the thermal average pairing gap and taking the particle number fluctuations into account is close to the one of the calculations with the use of the zero temperature pairing gap $\Delta(T) = \Delta(0)$. This energy centroid decreases slowly with increasing temperature. Our results also show that the change of the pairing gap at finite temperature can influence noticeably the IV-GDR energy location. This situation is different from the zero temperature case where the effect of the alteration of the pairing gap on the giant resonance location is negligible. In any case, in calculations for realistic hot nuclei the thermal and quantum particle number fluctuations play an important role. They must be undoubtedly taken into account in order to obtain correct results in the mean-field theory formalism at finite temperature. Under the influence of these fluctuations, as in the case of schematical models, it is hardly to observe the phase transition driven by temperature in realistic superfluid nuclei with a realistic single particle spectrum, at least in such nuclear characteristics as the pairing gap and the giant resonance energy location.

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Эффекты квантовых и термодинамических флуктуаций на гигантские изовекторные дипольные моды для ^{58}Ni в приближении случайных фаз при конечной температуре /КТ-ПСФ/

На основе реалистического одночастичного спектра в потенциале Вудса-Саксона среднего поля рассчитана парная щель БКШ для ^{58}Ni в зависимости от температуры с учетом термодинамических флуктуаций и квантовых флуктуаций числа частиц. В рамках КТ—ПСФ с гамильтонианом квазичастично-фононной модели ядра рассчитаны распределение сил электрических дипольных переходов и центроиды изовекторного гигантского дипольного резонанса /ИВ ГДР/. Показано, что изменение парной щели при конечной температуре может существенно влиять на положение ИВ ГДР. С учетом обоих типов флуктуаций в парной щели эффект фазового перехода из сверхтекучего состояния в нормальное состояние в температурной зависимости центроида ИВ ГДР полностью стирается.

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Effects of Thermal and Particle Number Fluctuations on the Giant Isovector Dipole Modes for ^{58}Ni-Nucleus in the Finite Temperature Random Phase Approximation

Using the realistic single-particle energy spectrum obtained in the Woods-Saxon nucleon mean-field potential, we calculate the BCS-pairing gap for ^{58}Ni as a function of temperature taking into account the thermal and particle number fluctuations. The strength distributions of the electric dipole transitions and the centroids of the isovector giant dipole resonance (IV-GDR) are computed in the framework of the finite temperature RPA based on the Hamiltonian of the Quasiparticle-Phonon Nuclear Model with separable forces. It is shown that the change of the pairing gap at finite temperature can noticeably influence the IV-GDR localization in realistic nuclei. By taking both thermal and particle number fluctuations in the pairing gap into account the effect of phase transition from superfluid to normal in the temperature dependence of the IV-GDR centroid is completely smeared out.

The investigation has been performed at the Laboratory of Theoretical Physics JINR.

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