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EFFECTS OF THE QUASIPARTICLE–PHONON INTERACTION IN MAGIC AND NON-MAGIC NUCLEI*

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The results of the recent ^{40}Ca and ^{58}Ni(α,α') experiments at $E_\alpha =$ 240 MeV are analyzed within a consistent microscopic model which takes into account both the effective particle–hole interaction and the quasiparticle–phonon one. A good agreement with the experiment for the isoscalar E0 EWSR was obtained for ^{40}Ca. But due to using microscopic transition densities instead of phenomenological ones for ^{58}Ni we obtained 71% of the EWSR instead of the noticeably less experimental value. Therefore, a part of the E0 strength may be hidden in the experimental background in the ^{58}Ni experiments. An equation for the nuclear gap in non-magic nuclei which takes into account both a particle-particle interaction and the quasiparticle-phonon one has been obtained. The first results of its solution have been represented.

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1. Introduction

Progress of the modern microscopic theory of nuclear stucture is connected with taking into account the quasiparticle-phonon interaction (QPI), in addition to the usual effective nucleon-nucleon interaction, both in magic and in non-magic nuclei. In magic [1] and semi-magic [2] nuclei it is possible to restrict ourselves to the approximation of the squared phonon creation amplitude g^2 in the propagators of integral equations under consideration [2]. In the simplest g^2 approximation this corresponds to infinite summation of 1p1h and 1p1h$\otimes$phonon configurations for magic even-even nuclei or 1qp1qh and 1qp1qh$\otimes$phonon configurations in non-magic ones (the "qp" means here the Bogolubov quasiparticle). In this talk we represent our new results based

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on the consistent use of the Green function method to take the QPI into account for excited states (Section 1, where we discuss the old problem of the isoscalar E0 giant resonance in some nuclei with A<90) and for the ground state (Section 2, which is devoted to a nuclear gap equation accounting for the QPI).

2. Isoscalar E0 resonace in ^{40}Ca and ^{58}Ni

There are still many open questions connected with properties of isoscalar (IS) E0 giant resonance in nuclei with $A<90$, an important one being the problem of distribution of E0 strength and small amount of it observed in several nuclei [3–5]. The newest $^{40}\mathrm{Ca}(\alpha,\alpha')$ experiments at $E_\alpha = 240$ MeV at small angles including 0°, which were performed for the (8–29) MeV excitation energy, gave (92 ± 15)% of the IS E0 EWSR in this interval [6]. However the same experiments and the same analysis for ^{58}Ni gave unexpected results. Only 32% (at best <50%) of the IS E0 EWSR was observed in the (12.0–25.0) MeV region mainly in two peaks at 17.4 and 20.8 MeV [7]. As was noticed in Ref. [7], if there is similar unobserved E0 strength in other nuclei, this may have serious consequences for the problem of nuclear incompressibility. The authors used the standard data-analysis procedures with phenomenological transition densities ρ_{tr} which were the same for different energy regions. For the IS E0 resonance it was given by Satchler [8].

2.1. Theory

The nuclear structure part, *i.e.* the quantities ρ_{tr}, were calculated within our approach [9, 10] taking into account the single-particle continuum, RPA and more complex 1p1h⊗configurations, and ground state correlations induced by these complex configurations. The Woods–Saxon single-particle basis and residual Landau–Migdal interaction with the known parameters have been used.

In our earlier calculations for ^{40}Ca [11] , which were cited in Ref. [6], we obtained the IS E0 resonance which was reasonably structured but the summed strength in the observed interval was noticeably smaller than that observed in [6]. In the present and late calculations [12, 13], we have used a slightly modified interpolation formula of the Landau–Migdal forces (for details see Refs. [10, 12–14]). There we used the calculated nuclear density instead of the usual Fermi distribution. Such a choice was confirmed also by a reasonable agreement between our calculations and the available experimental data for the IS E0 and E2 resonances in ^{40}Ca, including recent $(e,e'x)$ data [15].

The cross section calculations for the ^{58}Ni(α,α') were performed using the modified code DWUCK4. The multipole transition potentials were constructed by folding the density-dependent Gaussian effective interaction [5] over our microscopic $\rho^L_{\rm tr}$ for ^{58}Ni. The parameters of the optical potential were taken from Ref. [17].

2.2. ^{40}Ca results

It is important that a large energy interval (8–29) MeV was studied in Ref. [6] and in fact the full IS E0 strength was found in it. Due to the above-mentioned change of the interpolation form of the interaction, we obtained a more compact E0 resonance in ^{40}Ca compared to that in our earlier calculations [11]. But it remains highly structured and spread out over a large energy interval: 65% of the EWSR is in the (11–23) MeV interval and 106.7% is in the (5.0–45.0) MeV interval (see Ref. [13]).

The percentage of the IS E0 EWSR in the observed intervals (8.0–29.0) MeV and (15.0–20.0) MeV is 82.1% and 32.2% whereas the experiment [6] gives (92 $\pm$ 15)% and (33 $\pm$ 4)% respectively. We have obtained also a reasonable agreement between the experimental cross section and the one obtained by Youngblood which converted our strength function into the cross section [14].

A good description of the experimental splitting of the IS $(E0 + E2)$ strength into three peaks, which was observed in the $(e, e'x)$ data [15], was also obtained in such calculations, see Ref. [12]. There is a good agreement between the $(E2 + E0)$ theoretical EWSR, which is equal to $[6581{+}(25/16\pi)3729] = 8436$ e^{2}MeV fm^4 [12], and the experimental value (7899 $\pm$ 1580) e^{2}MeV fm^4 [15] observed in the $(10.0 - 20.5)$ MeV interval.

2.3. ^{58}Ni results

In our calculations [14] of the IS E0 resonance in ^{56}Ni we find that 69.2% of the IS E0 EWSR is in the (12.0–25.0) MeV interval which disagrees with the above-mentioned experimental results for ^{58}Ni [7] because inclusion of two additional neutrons in ^{58}Ni would not change the EWSR so strongly. To better understand this apparent disagreement, we calculated the cross section observed in Ref. [7] using our microscopically calculated $\rho_{\rm tr}$. In order to account for the difference between ^{58}Ni and ^{56}Ni we have added the low-lying 2^+ and 4^+ phonons to our set of phonons in ^{56}Ni with the characteristics taken from experiment [16].

Like in the analysis of Ref. [7] contributions of the IS and IV E1 and IS E2, E3, E4 resonances, which were calculated within our approach, have been taken into account. The calculations have been performed for each of five ΔE = 5 MeV energy bins in the (5.0–30.0) MeV region. It turned out that this procedure was important because, as was shown in Ref. [13], the calculated $\rho_{\rm tr}$'s show noticeable differences in form for various energy intervals under consideration.

The calculated $\rho_{\rm tr}$'s are also different from the phenomenological $\rho_{\rm tr}$ used in Refs. [5, 6]. As an example, we represent in Fig. 1 the macroscopic [8] and microscopic IS E0 $\rho_{\rm tr}$ for the observed (12.0 - 25.0) MeV interval, both normalized to the same (microscopic) B(E0) value.

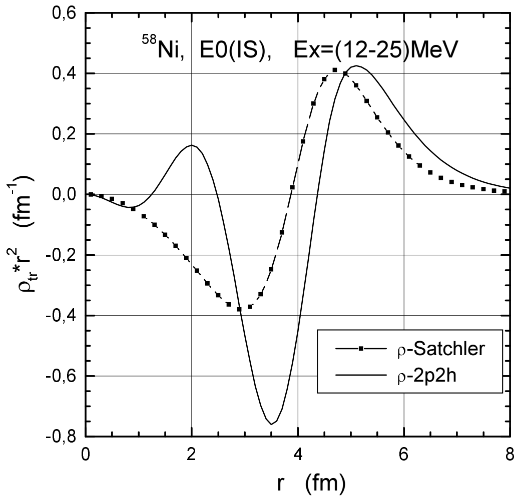

Fig. 1. The microscopic (solid line) and phenomenological (dashed line) IS E0 transition densities in ^{58}Ni calculated for the (12–25) MeV interval.

We see a noticeable difference between them which is rather clearly seen in the cross section for the same energy interval [14], and gives an underestimation of the E0 strength found in Ref. [7]. A similar but not so strong effect is observed also for other resonances. It should be noted that we were not able to obtain an agreement between the cross sections calculated using the phenomenological and microscopic $\rho_{\rm tr}$ by changing geometric parameters of the phenomenological $\rho_{\rm tr}$: it was possible to do so only by means of an unrealistic change in the Gaussian effective interaction.

In Fig. 2 the calculated cross sections of the $^{58}Ni(\alpha,\alpha')$ at the observed angle $\theta \simeq 1^\circ$ are shown. We obtained a good agreement with the form of the experimental curve [7]. For the IS E0 and E2 resonances we found 74.1% and 65.1% of the corresponding EWSR. But, like in the experimental analysis [7], to obtain the agreement with the experiment it was necessary for us to add a background, see Ref. [14].

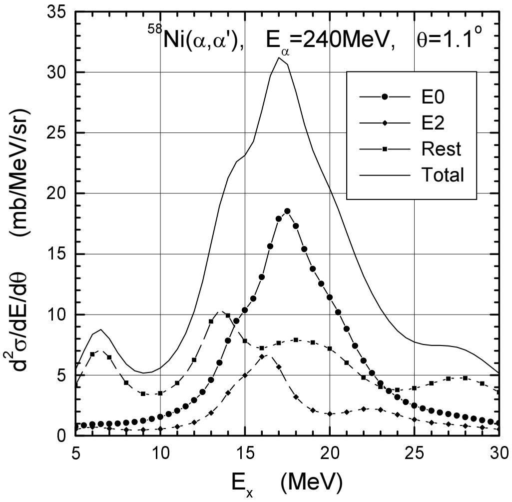

Fig. 2. Cross sections of ^{58}Ni(α,α') at $E_\alpha = 240$ MeV and $\theta \simeq 1°$.

Thus, using a microscopic nuclear structure model that takes into account the continuum RPA and 1p1h$\otimes$phonon configurations gives a reasonable agreement with experiment [6] for the IS E0 strength in ^{40}Ca measured in the large energy interval where in fact all the strength was observed. We were able to reproduce the cross section results for ^{58}Ni in the observed energy interval [7] with the microscopic $\rho_{\rm tr}$. However the percentage of the IS E0 EWSR turned out to be equal to 71.4% instead of the experimental value of 32% (improved analysis in Ref. [5] gave 50%). It would appear now that a part of the IS E0 strength in ^{58}Ni may be hidden in the experimental background [1]. Theoretically, it is difficult to imagine any mechanism which would reduce so strongly the IS E0 strength in nuclei heavier than ^{40}Ca.

3. The nuclear gap equation accounting for the quasiparticle–phonon interaction

For the ground states of non-magic nuclei, first of all for the pairing problem the QPI has not been considered explicitly and quantitatively. To be exact, the QPI mechanism of pairing was treated only in such a way that it was reduced to the well known Bardeen–Cooper–Schriffer (BCS) mechanism, *i.e.* to the case of an energy-independent particle–particle interaction which is usually determined phenomenologically.

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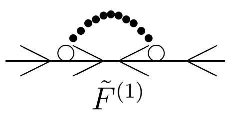
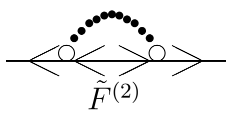
[1] At the Topical Conference on Giant Resonances (Varenna, Italy, May 11-16, 1998) it was announced by the authors of Ref. [7] that their improved analysis should give 75% or more for the IS E0 EWSR in ^{58}Ni.

Therefore, if we take the QPI into account explicitly in a definite approximation for the particle-hole channel, as is usually done [10, 18], we must account for it in the same approximation, generally speaking, also for the particle–particle channel for both excited states and ground states of non-magic nuclei including the (static) pairing problem. For the excited states this was partly done in [18] (see [2]), for the pairing problem attempts were doing in [19].

In order to treat the QPI explicitly for the pairing problem and in the g^2 approximation it is necessary to add, to the energy-independent BCS part of the "anomalous" mass operator, the following simplest energy-dependent contributions to these operators:

$M^{(1)} =$ 

$M^{(2)} =$ 

and take care to avoid double counting of the QPI. The latter is necessary at least if the initial quantities of the problem are phenomenological single-particle energies ε_λ and gaps Δ_λ (being determined from the BCS equation with the phenomenological particle-particle interaction). Here $\tilde{F}^{(1)}$ and $\tilde{F}^{(2)}$ are "refined", *i.e.* without the $M^{(1)}$ and $M^{(2)}$ contributions, anomalous Green functions and the circles denote the phonon creation amplitude g of the usual 1qp1qh phonon (pairing phonons are neglected).

Further, we should solve a correspondingly generalized system of the Dyson equations for one-particle Green functions G and F in the g^2 approximation for all the mass operators [2] . It turned out that these even more general solutions can be formally reduced to the known form [2, 19]

$$E_\lambda = \sqrt{\varepsilon_\lambda^2 + \Delta_\lambda^2}\,, \tag{1}$$

where in our g^2 approximation

$$\Delta_\lambda = \Delta_\lambda^{(1)} = \Delta_\lambda^{(2)} = [\tilde{\Delta}_\lambda^{(2)} + M_\lambda^{(2)}(E_\lambda)][1 - M'_\lambda(E_\lambda)/E_\lambda]^{-1} \tag{2}$$

with M' being the odd part of the normal mass operator M which is similar to $M^{(1)}$ but contains the "refined" usual Green function $\tilde{G}$.

In Eq. (2) the quantity $\tilde{\Delta}_\lambda^{(2)}$ is a "refined" gap, *i.e.*, to avoid the double counting, it does not contain the $M^{(2)}$ contribution which is energy-dependent. It is an unobservable quantity which satisfies the following symbolic equation

$$\tilde{\Delta}^{(2)} = W[\tilde{F}^{(2)} + \tilde{F}^{(2)} M \tilde{G} + \tilde{G}^{(h)} M^{(h)} \tilde{F}^{(2)} - \tilde{F}^{(2)} M^{(1)} \tilde{F}^{(2)} + \tilde{G}^{(h)} M^{(2)} \tilde{G}]\,, \tag{3}$$

where W is a new ("refined") particle-particle interaction which differs from the usual phenomenological one due to explicit treatment of the QPI. The quantities $\tilde{F}^{(1)}, \tilde{F}^{(2)}, \tilde{G}, \tilde{G}^{h}$ and mass operators M, M^{h}, $M^{(1)}$, $M^{(2)}$ are known (see Ref. [2]) and contain the "refined" single-particle energies $\tilde{\varepsilon}_{\lambda}$ and gaps $\tilde{\Delta}_{\lambda}$. The first r.h.s. term in Eq. (3) has the usual BCS form but with a "refined" interaction W.

The approach under consideration makes it possible to consider and analyse simultaneously both the BCS mechanism of nuclear pairing and the quasiparticle-phonon one, and also to take consistently into account ground state correlations.

Preliminary results of the solution of Eqs. (2),(3) show that the contribution of the terms containing the QPI is very noticeable [2].

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