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MICROSCOPIC DESCRIPTION OF PHOTON SCATTERING BY THE GIANT DIPOLE RESONANCES IN SPHERICAL NUCLEI

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1. INTRODUCTION

The nuclear giant multipole resonances have been studied experimentally in detail in many nuclear reaction processes. The most thorough compilation of the characteristics of giant multipole resonances is given in reviews [1-3]. In recent years the experimental investigations of the partial γ-decay of the giant resonances to the low-lying nuclear states have been performed in [4]. These experiments provide us with the information about the complex configurations in the wave function of giant resonances. Such information may also be obtained in the photon scattering reaction. In [5,6] the elastic and inelastic photon scattering cross sections in the giant dipole resonance (GDR) region of some spherical nuclei have been measured. The data analysis using the dynamic collective model (DCM) [7] has shown that calculation cannot fit the data in some cases. The DCM gives a good description of the energy dependence of the cross sections but the calculated cross sections overestimate the experimental ones in most cases. It should be noted that the DCM Hamiltonian has been diagonalized in a truncated basis consisting of quadrupole and dipole phonons only and the widths of the dipole states in the GDR region have been introduced phenomenologically as adjustable parameters [6].

In recent years the microscopic nuclear models [3] are widely used for the description of various characteristics of nuclear giant resonances. The quasiparticle-phonon nuclear model (QPM) is such a microscopic model [8]. The detailed study of giant multipole resonances in spherical nuclei within the frame of QPM has been performed in [9-14]. In this work the differential cross sections of elastic photon scattering in the GDR region of ^{56}Fe ^{60}Ni and ^{92}Mo have been calculated within the QPM. The widths of dipole states in the GDR region, due to the interaction between one- and two-phonon states, are calculated microscopically.

2. DETAILS OF CALCULATION

The QPM Hamiltonian includes the average field for protons and neutrons in the Woods-Saxon form, the pairing forces, the effective isoscalar and isovector multipole and spin-multipole interactions including charge-exchange term. The detailed description of the QPM Hamiltonian is given in [8]. The Hamiltonian parameters are chosen [8] so as to describe correctly in the random phase approximation (RPA) the experimental data for the electromagnetic transition probabilities of the lowest collective states. With taking into account the two-phonon components in the wave function for excited states in the even-even nuclei, either the energy and transition probabilities can be described correctly. The average field parameters and pairing constants used in our calculation are the same as defined in [11]. The dipole interaction constants are fixed so that the calculated in the RPA centroids of the GDR energy reproduce the experimental data [1]. For nuclei under consideration, the results of calculation give about 90% contribution to the model independent dipole energy weighted sum rule. The wave function of an excited state with spin J and its projection M is taken as follows:

$$\Psi_\nu(JM) = \{\sum_i R_i(J\nu)\, Q^+_{JMi} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)[Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{JM}\}\Psi_0 . \quad (1)$$

Here $Q^+_{\lambda\mu i}$ is the phonon creation operator and Ψ_0 is the wave function of the ground state of the even-even nucleus. The structure of one-phonon states is calculated in the RPA, the energies $\eta_{J\nu}$ of states described by the wave function (1) are found by solving appropriate secular equations [8]. There may be terms violating Pauli principle in the two-phonon components of (1). In the calculation of this work the Pauli principle is taken into account approximately, because the earlier calculations for the giant multipole resonances have shown that the strict [16] and rough [14] inclusion of Pauli principle gives nearly the same results in this energy region. The numerical calculations with the wave function (1) have been performed using the code GIRES [15].

The differential cross sections of dipole photon scattering can be written in the form [17]

$$\frac{d\sigma}{d\Omega}\Big|_\theta = \frac{E'_\gamma}{E_\gamma(2I_i+1)} \sum_{J=0,1,2} |\langle I_f \| P^{11}_J \| I_i\rangle|^2 g_J(\theta), \quad (2)$$

where I_i and I_f are the initial and final spins of the nucleus, E_γ and E'_γ are the energies of the incident and scattered photons, respectively. The angular distributions are

$$g_0(\theta) = \frac{1+\cos^2\theta}{2}, \quad g_1(\theta) = \frac{2+\sin^2\theta}{12}, \quad g_2(\theta) = \frac{13+\cos^2\theta}{60}$$

$\langle I_f \| P^{11}_J \| I_i\rangle$ are the reduced polarizabilities for dipole photon scattering [17]. In the case of elastic dipole photon scattering (2) is reduced to

$$\frac{d\sigma}{d\Omega}\Big|_\theta = \frac{1+\cos^2\theta}{2} |P_0|^2 , \quad (3)$$

where

$$P_0 = \frac{4\pi E}{9} \sum_{ni} b_i(E1; 0^+ \to 1^-_n) \{ \frac{1}{E_{ni} - E_\gamma - i\frac{\Gamma_{ni}}{2}} + \frac{1}{E_{ni} + E_\gamma + i\frac{\Gamma_{ni}}{2}} \} - \frac{(Ze)^2}{Am}. \quad (4)$$

Here $b_i(E1; 0^+ \to 1^-_n)$ is the reduced probability of E1-transition to the ni-state, E_{ni} and Γ_{ni} are the energy and width of this state in the GDR region. The last term in (4) corresponds to the Thompson scattering. For the calculation of the energies and widths of the GDR states the strength function method [8] has been used. Since in the electromagnetic excitation of states described by the wave function (1) the main contribution comes from the one-phonon components (it can easily be seen from the structure of the electromagnetic transition operator), one needs to know the energy distribution of the strengths of such one-phonon states. Following the method described in [8], we introduce the strength function

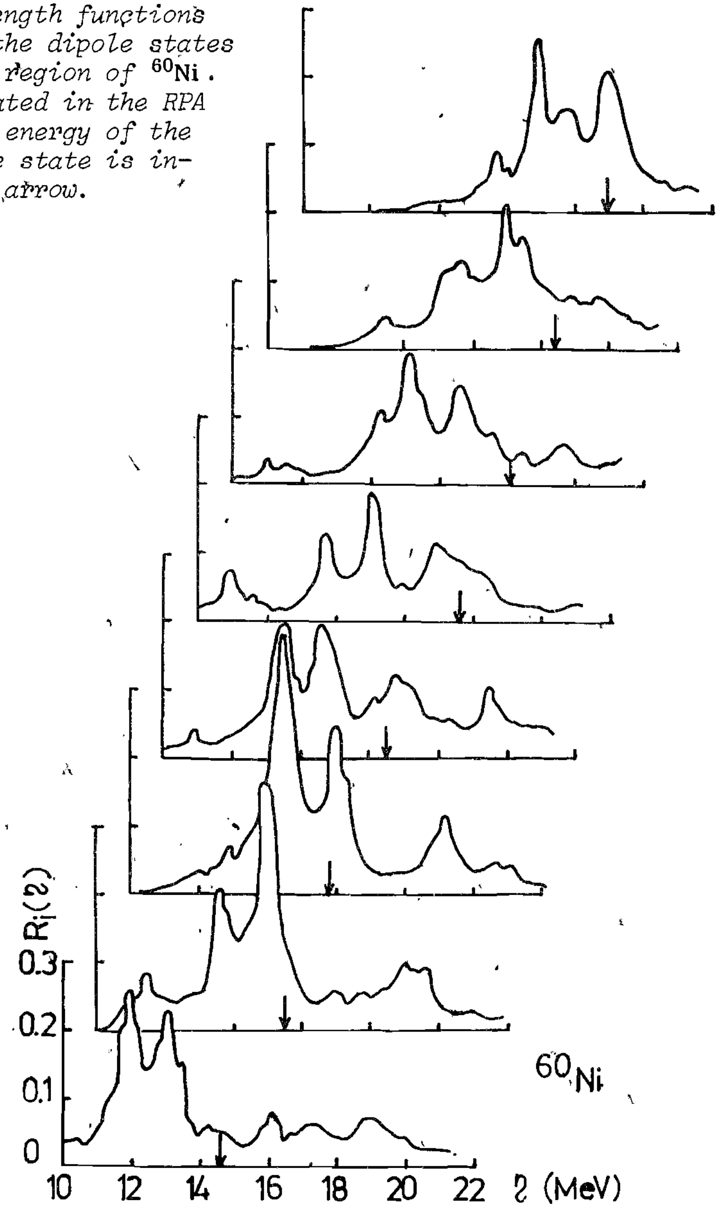
$$R_i(\eta) = \frac{1}{2\pi} \sum_\nu \frac{\Delta}{(\eta-\eta_\nu)^2 + \frac{\Delta^2}{4}} R_i^2(1\nu). \quad (5)$$

The parameter Δ can be varied so as to reproduce the fragmentation of the i-th one-phonon component of (1) in as much detail as we wish. Since the experimental energy resolution for photon dipole scattering [5,6] is about 0.2-0.6 MeV, we have taken Δ = 0.5 MeV in our calculation. The fragmentation picture for 8 collective one-phonon states forming the GDR in ^{60}Ni is shown in fig.1. The excitation energies calculated in the RPA are indicated by arrows. As one may see from fig.1 the inclusion of the two-phonon components in the wave function (1) has led to strong redistribution of one-phonon-state strengths compared to the RPA results. Further, from the strength distribution of the i-th one-phonon state we have extracted the gross structure and calculated the centroids Γ_{ni} and widths Γ_{ni} in a usual way -

$$E_{ni} = \int_{\Delta E_n} \eta R_i(\eta)\, d\eta \Big/ \int_{\Delta E_n} R_i(\eta)\, d\eta , \quad (6)$$

$$\Gamma_{ni} = 2.35\sigma , \quad \sigma^2 = \int_{\Delta E_n} (E_{ni}-\eta)^2 R_i(\eta)\, d\eta \Big/ \int_{\Delta E_n} R_i(\eta)\, d\eta . \quad (7)$$

Fig.1. Strength functions $R_i(\eta)$ for the dipole states in the GDR region of ^{60}Ni. The calculated in the RPA excitation energy of the i-th dipole state is indicated by arrow.



The dipole transition strength is integrated as

$$b_i(E1;0^+ \to 1^-_n) = |\langle 0||\mathfrak{M}(E1)\,Q^+_{1\mu i}||0\rangle|^2 \int_{\Delta E_n} R_i(\eta)\,d\eta\,, \qquad (8)$$

where $\langle 0||\mathfrak{M}(E1)Q^+_{1\mu i}||0\rangle$ is the reduced matrix element of the E1-transition operator for the 1^-_i-state calculated in the RPA, ΔE_n is the energy interval where the n-th peak of the fragmentation for the 1^- one-phonon state is localized.

Using (4)-(8) one can easily calculate the differential cross section of elastic dipole photon scattering (3).

3. DISCUSSION OF THE RESULTS

The calculated differential cross sections of elastic dipole photon scattering and the experimental data /5,6/ for ^{60}Ni at $\theta = 120°$, ^{56}Fe and ^{92}Mo at $\theta = 90°$ are shown in figs.2-4. Let us consider in detail ^{60}Ni nucleus. As can be seen from fig.2 the measured cross section shows clearly two peaks at $E_n \sim 17$ and 20 MeV. The results of our calculation for ^{60}Ni show that the GDR is formed mainly of 8 dipole RPA-states fragmented in a wide interval of energy (see fig.1). Theoretical cross sections include contributions from many peaks and are quite close to the data. The calculated widths Γ_{ni} are different for each state and range from 1 to 4 MeV. If one calculates the strength distribution of one-phonon components with a smaller Δ, there would be a fine structure in the fragmentation picture. And in such a case the fine structure would appear in the calculated cross sections too. Such a calculation corresponds to a much better energy resolution compared to the resolution available at present in the photon scattering experiments /5,6/. The results of two different calculations for ^{60}Ni are shown in fig.2. The solid line corresponds to the case when the substructures in the fragmentation of the 4th one-phonon state at 16 MeV are not taken into account. In the RPA calculation this state has a strongest probability of the E1-transition which is equal to 4.02 e^2fm^2 as much as 31.5% of the total transition strength of 8 dipole states in the GDR region, so the influence of this state on the calculated cross section is very substantial. And in the solid curve there are no clear substructures as those in fig.1 can be seen. The inclusion of substructures into the cross section calculation (the dash-dotted curve) enables one to reproduce the existence of two peaks in the energy dependence of the elastic dipole photon scattering cross section ^{60}Ni(γ,γ) as observed in the experiment. But the lower peak in our calculation is about 0.5 MeV higher than the experimental one. It should be emphasized that our microscopic calculation gives a good description of the absolute cross sections. In the calculation within DCM /6/ the widths of dipole states are taken as $\Gamma_n = \Gamma_0 (E_n/E_1)^{\delta}$, where Γ_0, E_1 and δ are determined from a least square fit to the measured elastic (γ,γ) cross sections. With these adjustable

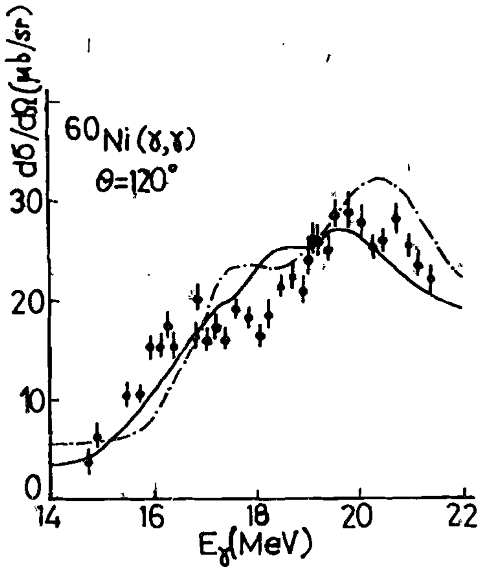


Fig. 2. Differential cross sections of elastic dipole photon scattering by the GDR in ^{60}Ni. *The points are the experimental data* [5,6]. *The solid and dash-dotted lines are the results of QPM calculations.*

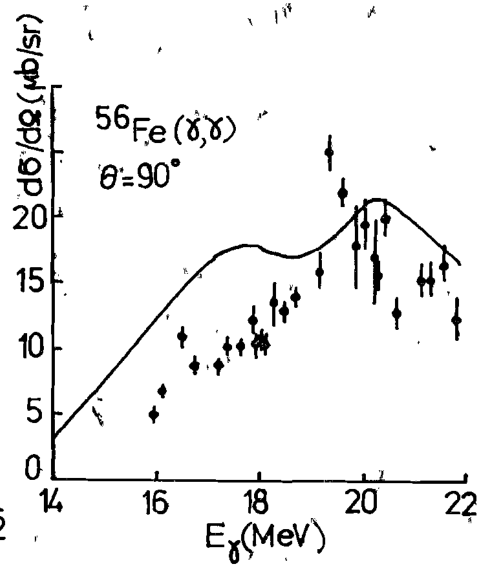
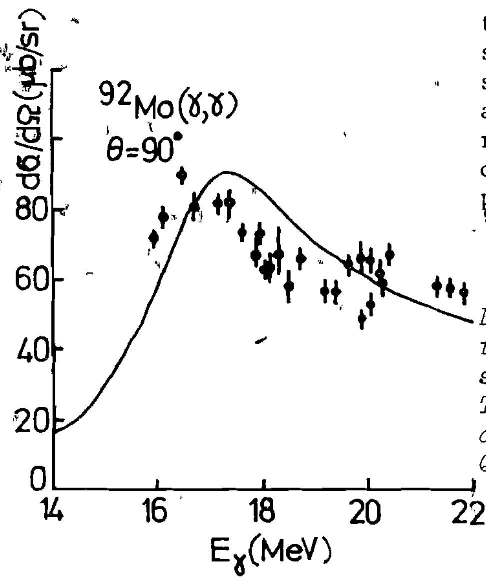


Fig. 3. Differential cross sections of elastic dipole scattering by the GDR in ^{56}Fe. *The points are the experimental data* [6]. *The solid line is the QPM calculation.*

parameters the DCM calculation describes the energy dependence of the elastic cross sections better than our calculation. But the calculated absolute cross sections do overestimate the data in all considered cases. In order to fit the elastic data, the calculated within DCM elastic cross sections have been decreased by 51% for ^{60}Ni, 47% for ^{56}Fe and 23% for ^{92}Mo [6]. The results of our calculation and the experimental data for ^{56}Fe(γ,γ) are shown in fig.3. As one can see, our results reproduce the existence of two peaks in the observed cross section for ^{56}Fe. But in the low energy region our results are somewhat higher than the data. Note, that the energy dependence in the cross section ^{56}Fe(γ,γ) is similar to that in ^{60}Ni case. In both these nuclei the anharmonic effects are quite strong, so the one-phonon components in the wave function (1) are fragmented in a wide interval of energy. And the strength distributions of these components in ^{56}Fe are like the distributions shown in fig.1 for ^{60}Ni. It is this fact that leads to similar energy dependence of the cross sections in both cases. In the ^{92}Mo case



the fragmentation of one-phonon states is weaker and has no such complicated substructures as in ^{60}Ni and ^{56}Fe cases. Our results also give rather a good description of the elastic dipole photon scattering for ^{92}Mo(γ,γ) (see fig.4).

Fig.4. Differential cross sections of elastic dipole photon scattering by the GDR in ^{92}Mo. *The points are the experimental data* [6]. *The solid line is the QPM calculation.*

4. CONCLUSION

We have shown in our calculation that within the QPM one can successfully calculate not only the integrated characteristics of the GDR [8-10], but also the differential cross sections of elastic dipole photon scattering by the GDR. It is of great interest to investigate microscopically inelastic photon scattering to the low-lying states in spherical nuclei. In such a process the two-phonon components play an important role and for the microscopic description of this process one needs to know the fragmentation of these components in the wave function of the GDR due to the interaction with more complicated configurations. This problem has not been solved yet.

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Дао Тиен Кхоа, Пономарев В.Ю., Воронов В.В. E4-85-148
Микроскопическое описание фоторассеяния на гигантских дипольных резонансах в сферических ядрах

В рамках квазичастично-фононной модели ядра рассчитаны дифференциальные сечения упругого рассеяния гамма-квантов на дипольных гигантских резонансах ^{56}Fe , ^{60}Ni и ^{92}Mo. Ширины состояний гигантских дипольных резонансов и силы переходов на них рассчитывались микроскопически. Показано, что микроскопические расчеты довольно хорошо описывают экспериментальные данные по упругому рассеянию дипольных гамма-квантов.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Dao Tien Khoa, Ponomarev V.Yu., Voronov V.V. E4-85-148
Microscopic Description of Photon Scattering by the Giant Dipole Resonances in Spherical Nuclei

The differential cross sections of elastic photon scattering in the giant dipole resonance region of ^{56}Fe, ^{60}Ni, and ^{92}Mo have been calculated within the quasiparticle-phonon nuclear model. The widths and transition strengths of the dipole states in this region have been microscopically calculated. The results of microscopic calculations are in good agreement with the experimental data for elastic photon dipole scattering.

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

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