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Фоторассеяние на гигантских резонансах в деформированных ядрах

Полумикроскопически проводится расчёт сечений фоторассеяния и фотопоглощения на гигантских резонансах в деформированных ядрах. Результаты сравниваются с экспериментальными данными.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Photon Scattering on Giant Resonances in Deformed Nuclei

The cross sections of photon scattering and photoabsorption on states of the dipole and quadrupole giant resonances are calculated for deformed nuclei within the semimicroscopic approach. Nuclear states are described in the random phase approximation. As the residual interaction, the long-range multipole forces are taken. The results of calculations are compared with experimental data.

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

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I. Introduction

A microscopic calculation of giant resonances was restricted mainly to the photoabsorption being rather simple to handle with. However, the photoabsorption allows one to investigate only the dipole resonance and only its basic properties. Therefore a more accurate check of the model description of giant resonances including the dipole one requires the consideration of other processes.

An important property of the photon scattering is the non-coincident angular dependence of different contributions to the differential cross section/1/. Thus, there appears a possibility to separate the inelastic dipole, quadrupole, and interference scattering, in particular, in the scattering of plane-polarized photons. The photon scattering is also more appropriate for testing the description of the main, coherent excitation of the dipole resonance as the scattering includes both the photoabsorption and the photoemission.

This paper deals with the semi-microscopic description of the photon quasielastic and inelastic (Raman effect) scattering on resonance levels of deformed nuclei. Effects due to the scattering of polarized photons are examined. The photoabsorption cross sections are calculated. Nuclear states are described in the microscopic approach with the residual long-range multipole forces and with pairing of particles/2/. Collective excitations are calculated within the random phase approximation (RPA). The resonance state widths, however, are taken phenomenologically. These are difficult to be calculated within the strict microscopic approach, even if the reasons for appearing widths in resonance states are clear (see, e.g., ref./3/). Thus, the absorption and scattering cross sections are not calculated strictly microscopically.

Apart from the dipole resonance, some effects due to the quadrupole isovector resonance are treated.

2. Theoretical Description

In ref./1/ it is shown that for the photon scattering in the long wave approximation the differential cross section splits into the dynamical nuclear and angular-dependent kinematical parts. With the dipole and quadrupole nuclear states the cross section is of the form/1/:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{11}}{d\Omega} + \frac{d\sigma^{22}}{d\Omega} + \frac{d\sigma^{12}}{d\Omega} \qquad (1)$$

where

$$\frac{d\sigma^{KL}}{d\Omega} = \frac{1}{2I_i+1}\,\frac{E'}{E}\sum_{\nu=0}^{2N} g_\nu^{KL}(\theta)\,\mathrm{Re}\left\{A_\nu^{(K)} A_\nu^{(L)*}\right\} \qquad (2)$$

$N = \min\{K, L\}$; E and E' are the photon initial and final energies; for the unpolarized photons the angular distributions are

$$g_0^{11}(\theta) = \frac{1}{6}\left(1+\cos^2\theta\right), \quad g_2^{11}(\theta) = \frac{1}{12}\left(13+\cos^2\theta\right),$$

$$g_0^{22}(\theta) = \frac{1}{10}\left(1-3\cos^2\theta+4\cos^4\theta\right), \quad g_0^{12}(\theta) = -\frac{\cos^3\theta}{\sqrt{15}}. \qquad (3)$$

For the plane-polarized photons one should distinguish two cases: the polarization vector is parallel to the scattering plane and perpendicular to it. Then $g_\nu^{KL}(\theta)$ break into $(g_\nu^{KL}(\theta))^{\parallel}$ and $(g_\nu^{KL}(\theta))^{\perp}$ (for a concrete form see ref./1/). Note that $(g_0^{11}(90^\circ))^{\parallel}=0$. Therefore the contribution from inelastic dipole ($\nu \neq 0$) or from quadrupole scattering can be specified by the quantity $\eta = \frac{d\sigma(90^\circ)^{\parallel}}{d\Omega} \Big/ \frac{d\sigma(90^\circ)^{\perp}}{d\Omega}$ (see, e.g. ref./4/).

The amplitudes of dipole and quadrupole scattering on even-even nuclei are expressed as follows/1/:

$$A_\nu^{(1)} = \frac{4\pi e^2 EE'}{3(\hbar c)^2}\sum_n \begin{Bmatrix}\nu & \nu & 0\\ 1 & 1 & 1\end{Bmatrix}\langle f\|Q^{(1)}\|n\rangle\langle n\|Q^{(1)}\|i\rangle\cdot\left[\frac{1}{E_n-E-i\Gamma_n/2} + \frac{1}{E_n+E'+i\Gamma_n/2}\right] + \delta_{if}\sqrt{3}\,\frac{Z^2e^2}{AMc^2}, \qquad (4)$$

$$A_\nu^{(2)} = \frac{\pi e^2(EE')^2}{15(\hbar c)^4}\sum_n \begin{Bmatrix}\nu & \nu & 0\\ 2 & 2 & 2\end{Bmatrix}\langle f\|Q^{(2)}\|n\rangle\langle n\|Q^{(2)}\|i\rangle\left[\frac{1}{E_n-E-\frac{i\Gamma_n}{2}} + \frac{1}{E_n+E'+\frac{i\Gamma_n}{2}}\right],$$

where $Q^{(\lambda\mu)}$ is the electric multipole operator, and the second term in $A_\nu^{(1)}$ stands for the Thomson scattering without excitation of internal degrees of freedom of a nucleus.

The resonance states n are treated as collective excitations in the RPA with the residual multipole-multipole forces and pairings of particles/2/. The widths Γ_n are due to the connection with continuum and due to the interaction with complex configurations.

However, the microscopic calculation allowing for both these effects cannot be performed even for spherical and light nuclei (see ref./5/). Therefore, for comparison with experimental cross sections the widths Γ_n are taken phenomenologically as a simple function of energy (see part 3), while the position and strength of resonance states are calculated microscopically.

The inelastic dipole scattering is analysed in the most important case when the final state f corresponds to the first rotational state $I^{\pi} = 2^{+}$. In deformed nuclei this corresponds to incoherent scattering, as the terms with $K=0$ and $K=1$ (K -spin projection on the symmetry axis of a nucleus) in the amplitude are of opposite sign.

The nuclear part of the problem is to calculate the function

$$F(E) = \sum_n \langle n \| Q^{(\lambda)} \| i \rangle^2 \left[\frac{1}{E_n - E - i\Gamma_n/2} + \frac{1}{E_n + E' + i\Gamma_n/2} \right]. \quad (5)$$

At this step it is convenient to apply the method proposed by Bohr and Mottelson (ref.[6], p. 297) for calculation of strength fuctions (the same method has been used for calculation of the photoabsorption cross section[7]). Assuming that $\Gamma_n = \Gamma(E_n)$ and $\langle n \| Q^{(\lambda)} \| i \rangle^2 = -\frac{f_1(E_n)}{f_2'(E_n)}$ the function (5) takes the form

$$F(E) \approx \frac{f_1(E_0)}{f_2(E_0)} \frac{1}{\left[1 - \frac{i}{2}\Gamma'(E_0)\right]}, \quad (6)$$

where E_0 obeys the condition $E_0 - E - \frac{i\Gamma(E_0)}{2} = 0$. If n is the one-phonon state and i the phonon vacuum, then[8]

$$f_1(E) = \frac{1}{\pi}\left[(e^n_{eff})^2 X_n(E) + (e^p_{eff})^2 X_p(E) - X_n(E) X_p(E)\left(\varkappa_0^{(\lambda)} + \varkappa_1^{(\lambda)}(e^n_{eff} + e^p_{eff})^2\right)\right], \quad (7)$$

$$f_2(E) = 1 - (\varkappa_0^{(\lambda)} + \varkappa_1^{(\lambda)})(X_n(E) + X_p(E)) + 4\varkappa_0^{(\lambda)}\varkappa_1^{(\lambda)} X_n(E) X_p(E),$$

where $$X_n(E) = 2 \sum_{ss'} \frac{[f^{\lambda\mu}(ss') u_{ss'}]^2 [\varepsilon(s) + \varepsilon(s')]}{[\varepsilon(s) + \varepsilon(s')]^2 - E^2};$$

$\varepsilon(s)$ is the quasiparticle energy; $u_{ss'} = u_s v_{s'} + u_{s'} v_s$;

u_s, v_s are the coefficients of the Bogolubov canonical transformation;

$$f^{\lambda\mu} = \frac{r^\lambda}{\sqrt{2}}\left[Y_{\lambda\mu} + (-1)^\mu Y_{\lambda -\mu}\right];$$

$\varkappa_0^{(\lambda)}$ and $\varkappa_1^{(\lambda)}$ are constants of the λ-multipole isoscalar and isovector interaction;

$e^n_{eff} = -\frac{Z}{A}$, $e^p_{eff} = \frac{N}{A}$ for dipole states,

$e^n_{eff} = 0$, $e^p_{eff} = 1$ for quadrupole states.

The "spurious" state originated from the translational invariance violation can be approximately eliminated by introducing the isoscalar dipole interactions[7,9]. The constant $\varkappa_0^{(1)}$ then is defined from the condition of the existence of state with zeroth energy. In general, the study of giant resonances does not require to eliminate the "spurious " states[10]. The constant $\varkappa_0^{(2)}$ can be defined from the low-lying vibrational states. The ratio $\varkappa_1^{(\lambda)}/\varkappa_0^{(\lambda)}$ is determined by the position of the corresponding isovector resonance.

3. Calculation Procedure and Discussion

As the average field the Saxon-Woods potential was taken[11]. The ratio $\varkappa_1^{(1)}/\varkappa_0^{(1)} = -1.2$ is put for all nuclei (cf. ref.[7]), and in this case $\varkappa_1^{(1)} \approx \frac{300}{A^{5/3}}$.

Figure 1 gives the strengths of levels of the dipole resonance in ^{166}Er in arbitrary units and also the absorption cross section for the width equal to 1.5 MeV for all states. Figure 2 shows the scattering cross section calculated at the same values of all parameters. From the Figures it is seen that for better fitting to experiment , the state widths should somewhat increase with state energy. No discrimination has been made among various power functions, as the resonance dipole levels are all concentrated in the interval of about 5 MeV where a power function can be approximated by a straight line within a satisfactory accuracy. Moreover, it is hardly to be expected that the level widths are described by a unique function throughout the whole energy region. In Figs. 3 and 4 the calculation results are shown for all nuclei obtained with the width $\Gamma_n = 0.2\,(E_n - 6)$ MeV . The latter dependence of Γ_n, of course, should not be extended beyond the energy range of the giant dipole resonance. From the Figures it is observed that a good description both of the scattering and absorption is achieved with the same parameters.

As to the quadrupole isovector resonance, much poor in-

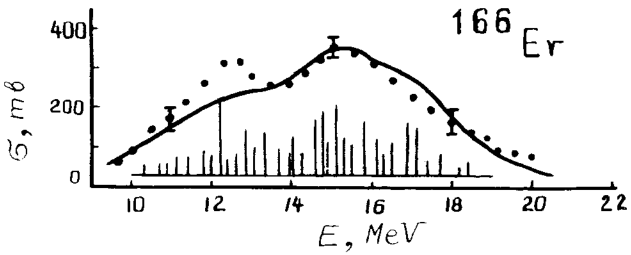

Fig.1. The absorption cross section and level strengths (in arbitrary units) for the dipole resonance in ^{166}Er. Experimental data are from ref./12/.

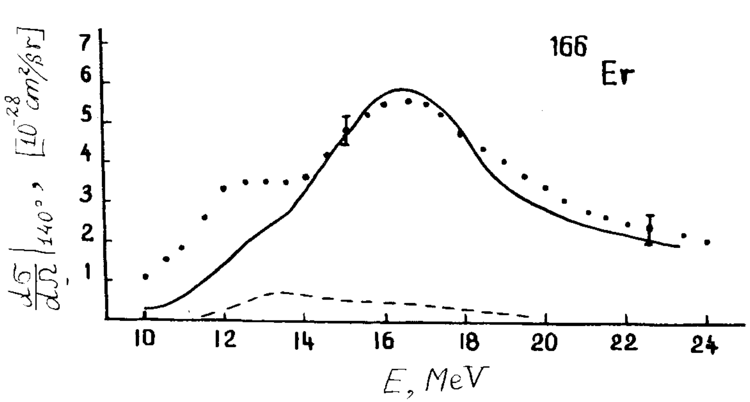

Fig.2. The scattering cross section for ^{166}Er. The dashed curve is the inelastic cross section. Experimental data are from ref./14/.

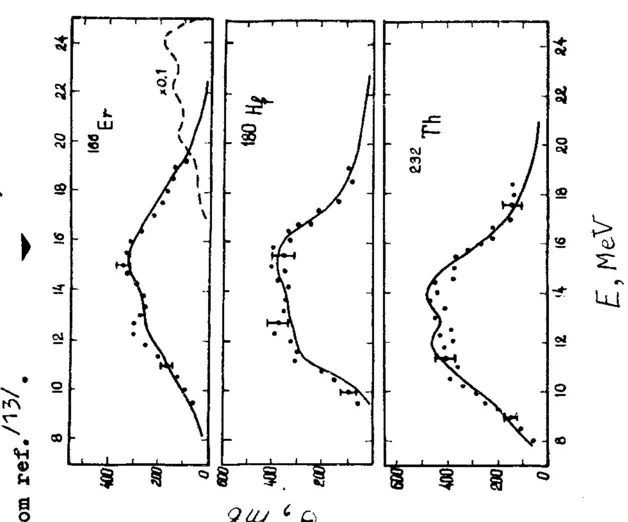

Fig.3. The absorption cross section, for ^{166}Er. The dashed curve is the cross section for the quadrupole resonance shifted down by 2 MeV. Experimental data are: for ^{166}Er from ref./12/, for ^{180}Hf and ^{232}Th from ref./13/.

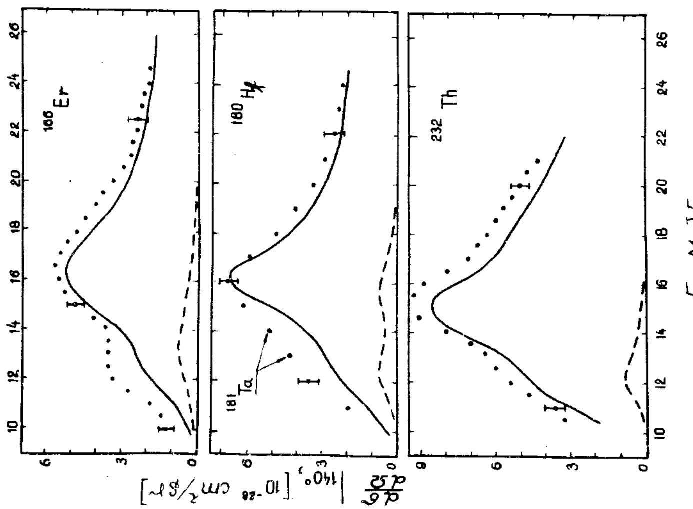

Fig.4. The scattering cross section. The dashed curve is the inelastic one. Experimental data are from ref./14/.

formation is available. As is shown in ref. /15/, the position of this resonance can be found approximately putting that $\varkappa_1^{(2)}/\varkappa_0^{(2)}=-1.5$. The results obtained at Γ_n =0.5 MeV do not contradict the existing experimental data on photoabsorption. With these parameters, the quadrupole isovector resonance has been calculated for several deformed nuclei. This choice of parameters is rather arbitrary, and the results on the quadrupole resonance should be considered methodological.

The deviation of the angular distribution of the scattering cross section from the function ($1 + \cos^2\theta$) is due to the contribution either from the inelastic dipole scattering or from the quadrupole and interference scattering. The same can be characterized by η for the polarized photon scattering.

From Fig. 5 and the Table it is seen that for nucleus at energies 13-15 MeV there is an important contribution from the tensor inelastic dipole scattering (the experimental one is slightly larger). At energies above 20 MeV the quadrupole resonance is observed. From Fig. 5 it follows that at energies 23-26 MeV the calculated interference dipole-quadrupole scattering spoils essentially the cross section angular distribution.

Table

Relation $\eta = \frac{d\sigma(90^\circ)^{\parallel}}{d\Omega} \Big/ \frac{d\sigma(90^\circ)^{\perp}}{d\Omega}$ for the scattering of polarized photons

Nucleus	E, MeV	$\eta_{exp.}$ /4/	$\eta_{calc.}$
^{186}W	15.1	0.29±0.07	0.15
	25.4		0.05
^{166}Er	15.1		0.13
	26.3		0.05
^{181}Ta	15.1	0.14±0.07	
^{180}Hf	15.1		0.10

Experimentally, the resonance interference is observed at lower energy 21 MeV. However, this low position of the quadrupole iso-

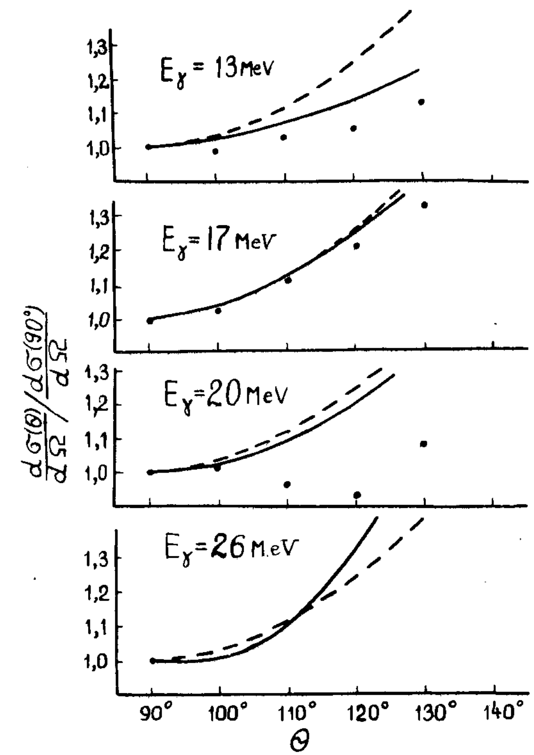

Fig.5. The angular distribution of the photon scattering cross section for ^{166}Er at various energies. The dashed curve is the function ($1 + \cos^2\theta$). Experimental data are from ref. /14/.

vector resonance contradicts the assumed A-dependence: $130A^{-1/3}$ /15/. The calculation reveals that at energies higher than 22 MeV just the quadrupole resonance is completely responsible for the non-zeroth value of η . Therefore experiments with polarized photons at such energies are useful for studying the isovector quadrupole resonance.

Thus , it may be cancluded that the applied microscopic model, under some additional assumptions, provides a rather good and unique description of the photoabsorption and photon scattering. This also enables one to describe the absolute values of cross-sections apart from their energy dependence.

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R e f e r e n c e s

1. Arenhövel H., Greiner W., Progr. Nucl.Phys., 10, 167 (1969).
2. Соловьев В.Г., Теория сложных ядер, М., Наука, 1971.
3. Dover C.B., Lemmer R.H., Hahne F.J., Ann. of Phys., 70, 458 (1972).
4. Hayward E. et al., Phys.Rev., C8, 1065 (1973).
5. Lin K.F., Nguyen Van Giai, Phys.Lett., 65B, 23 (1976).
6. Бор О., Моттельсон Б., Структура атомного ядра, М.,Мир, 1971.
7. Акулиничев С.В., Малов Л.А.,Препринт ОИЯИ,Р4-9873,Дубна, 1976.
8. Малов Л.А., Нестеренко В.О., Соловьев В.Г., Препринт ОИЯИ, Е4-10165,Дубна, 1976.
9. Petersen D.F., Veje C.J., Phys.Lett.,24B, 449 (1967).
10. Камерджиев С.П., ЯФ, 15, 676 (1972).
11. Иванова С.П., Комов А.Л., Малов Л.А., Соловьев В.Г.ЭЧАЯ,7,450, 1976; Гареев Ф.А., Иванова С.П., Соловьев В.Г., Федотов С.И. ЭЧАЯ, 4, 357 (1973).
12. Bergere R. et al., Nucl.Phys., A133, 417 (1969).
13. Гуревич Г.М., Лазарева Л.Е., Мазур В.М., Солодухов Г.В.,Письма в ЖЭТФ, 20, 741 (1974); Письма в ЖЭТФ, 23, 411 (1976).
14. Langevin M., Loiscaux J.M., Maison J.M., Nucl.Phys., 54, 114 (1964).
15. Кырчев Г., Малов Л.А., Нестеренко В.О., Соловьев В.Г., Препринт ОИЯИ, Е4-9962, Дубна, 1976.

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