High-Energy Giant Resonances and Their Particle Decay

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Abstract
A semimicroscopic approach to describe high-energy giant resonances (GRs) is briefly presented. The approach is based on the continuum-RPA method and a phenomenological treatment of the spreading effect. A realistic nuclear mean field and the Landau-Migdal particle-hole interaction are used in continuum-RPA calculations with taking the basic symmetries of the model Hamiltonian into account. Most of available experimental data concerned with properties (including the direct-nucleon-decay ones) of high-energy GRs are satisfactorily described within the approach. Properties of the non-observed high-energy GRs are also predicted.

1 Giant resonances as a phenomenon.
First- and second-order GRs

Being a universal phenomenon in nuclei, giant resonances have long been experimentally and theoretically studied (see e.g. Ref. [1]). From the microscopic point of view, GRs correspond to the collective particle-hole(p-h)-type excitations characterized by certain values of the angular momentum and parity ($J^\pi$), orbital momentum ($L = 0, 1, 2, ...$), spin ($S = 0, 1$), isospin ($T = 0, 1$) and its third projection ($T_3 = 0, \pm 1$). The multitude of giant resonances is explained by different combinations of these quantum numbers. The GRs are formed due to

i) concentration of the corresponding particle-hole (p-h) strength in a relatively narrow excitation-energy interval (that is an evidence of the shell-model structure of nuclei);

ii) coupling to the single-particle continuum (that leads to the GR particle decay and related phenomena);

iii) coupling to many-quasiparticle configurations (that leads to the spreading effect).

The well-studied GRs having relatively low excitation energy ($\simeq 10 - 20$ MeV) [1] can be considered as the main-tone, or first-order GRs. Some of these resonances are listed below. The isobaric analog resonance (IAR, $J^\pi = 0^+$, $L = 0, S = 0, T = 1, T_3 = -1$) and the Gamow-Teller
resonance (GTR, \(J^π = 1^+, L = 0, S = 1, T = 1, T_3 = -1\)) are due to the charge-exchange \(0\hbar\omega\) p-h-type excitations in the \(\beta^-\)-channel (\(\hbar\omega\) is the intershell energy distance). The familiar E1 GR, i.e. the isovector giant dipole resonance (IVGDR, \(J^π = 1^-, L = 1, S = 0, T = 1, T_3 = 0\)), is due to \(1\hbar\omega\) excitations. It is noteworthy that the \(1^-\) spurious state associated with the center-of-mass motion can be considered as the zero-energy main-tone isoscalar dipole resonance \((J^π = 1^-, L = 1, S = 0, T = T_3 = 0)\). This state is the isoscalar partner of the IVGDR. The isoscalar giant monopole and quadrupole resonances (respectively, ISGMR and ISGQR, \(J^π = 0^+\) and \(2^+, L = 0\) and \(2, S = 0, T = T_3 = 0\)) are due to \(2\hbar\omega\) excitations. Note that the isovector giant quadrupole resonance (IVGQR, \(J^π = 2, L = 2, S = 0, T = 1, T_3 = 0\)) considered below, being also due to \(2\hbar\omega\) excitations has a relatively large energy. The reason is that the p-h interaction in the \(S = 0, T = 1\) channel is repulsive, while the interaction in the \(S = 0, T = 0\) channel is attractive. The radial dependence of the first-order GR transition density is nodeless (except for the ISGMR). The low-energy GRs (except for the IAR) have a relatively small total branching ratio (less than \(10 - 15\%\)) for the direct nucleon decay. That is an evidence for weak coupling of these GRs to the single-particle continuum. In case of the IAR, the coupling is also small, but the proton branching ratio is large due to strong suppression of the spreading width caused by the approximate isospin conservation in nuclei.

Experimental and theoretical studies of high-energy GRs have been undertaken in recent years to understand better how the above-mentioned characteristics associated with the GR formation are affected with increasing the GR energy. Most of high-energy GRs are the next vibration modes (the overtones, or second-order GRs) relative to the corresponding low-energy GRs. The overtone quantum numbers \(J^π, L, S, T, T_3\) are the same as those for the corresponding main tone. The difference is in less concentration of the respective p-h strength, an extra-node radial dependence of the transition density and strong coupling to the single-particle continuum. As for the spreading effect, it seems to reveal a saturation-like energy dependence. These properties are illustrated below with a few examples.

The lowest-energy isoscalar overtone is the isoscalar giant dipole resonance (ISGDR, the overtone of the above-mentioned \(1^-\) spurious state) studied intensively in recent years via the \((\alpha,\alpha')\)-reaction (see, e.g., Ref. [2] and references therein). First indications for the excitation of the second-order isoscalar giant quadrupole resonance (ISGQR2) have recently been found [2]. As for the ISGMR2, whose existence was predicted in a number of works (see Ref. [3] and references therein), it is not found yet. The lowest-energy charge-exchange (in the \(T_3 = -1\) channel) overtones are the isovector giant monopole resonance (IVGMR, the overtone of the IAR) and the isovector giant spin-monopole resonance (IVGSMR, the overtone of the GTR). These GRs have experimentally been studied via different types of charge-exchange reactions (see, e.g., Ref. [4] and references therein). The lowest-energy isovector overtone in the \(T_3 = 0\) channel (IVGDR2, the overtone of the IVGDR and the isovector partner of the ISGDR) is not found yet.
2 Microscopic descriptions of GRs. Semimicroscopic approach.

The continuum-RPA-based microscopic approaches to description of GRs are the most advanced ones. A comprehensive study of gross properties (i.e. of the p-h strength distribution and the transition density) have been undertaken in Ref. [5] for a number of GRs. In this Ref. the Hartee-Fock method and Skyrme-type forces have been used to calculate the nuclear mean field and the p-h interaction (in the $S = 0$ channel), which are further used as input quantities for the continuum-RPA (CRPA) calculations. The spreading effect and the GR direct-nucleon-decay properties were outside the scope of the study of Ref. [5]. Attempts to incorporate the description of the spreading effect into the RPA-method have been undertaken with the use of a limited basis of 2p-2h configurations (see, e.g., Refs.[6, 7]). For obvious reasons these attempts are limited by low-energy GRs. The same is concerned with attempts to use such an approach for description of GR direct nucleon decay [6].

Being aimed to describe systematically not only the gross properties but also the GR direct nucleon decay and related phenomena, we developed a CRPA-based semimicroscopic approach to description of GRs. The partial direct+semidirect (DSD) nucleon-escape strength functions and the corresponding branching ratios for a given GR carry information on its microscopic structure, couplings to the continuum and many-quasiparticle configurations. We are also motivated by experimental studies of direct nucleon decay of high-energy GRs undertaken in recent years at KVI (Groningen) and RCNP (Osaka) (see, e.g., Refs. [2, 4] and references therein).

Within the proposed approach a realistic phenomenological isoscalar part of the nuclear mean field (including the spin-orbit term) and the Landau-Migdal p-h interaction are used as input quantities for CRPA calculations. The mean field and the p-h interaction (in the $S = 0$ channel) are related to each other by the selfconsistency conditions, which are due to the basic symmetries of the model Hamiltonian. Using these conditions, we calculate selfconsistently the isovector part of the nuclear mean field (via the phenomenological Landau-Migdal parameter $f'$), mean Coulomb field, and determine the strengths of the p-h interaction in the $S = 0, T = 0$ channel.

Within this approach we take the spreading effect into account phenomenologically. For description of high-energy GRs we do that (in the spirit of the optical model of nucleon-nucleus scattering) by introducing the energy- and radial-dependent spreading parameter into the CRPA equations (see below). Such a procedure allows us to calculate directly the energy-averaged characteristics of a given GR (the strength function, energy-dependent transition density, DSD nucleon-escape amplitudes and, therefore, DSD nucleon-escape strength functions) with taking into account the main GR relaxation modes.

To calculate the above-listed quantities for a given GR one has first to choose an appropriate single-particle probing operator (an external field) $V(x)$ with $x$ being the set of the radial, spin-angular and isospin variables. For description of first-order GRs this operator is taken proportional to the corresponding first-order multipole ($S = 0$) or spin-multipole ($S = 1$) operators with the radial dependence $r^L (L > 0)$, and $r^2$ for monopole excitations in the $T_3 = 0$
channel and 1 for the lowest monopole excitations in the $T_3 = \pm 1$ channels, i.e. the IAR and GTR [5]. For description of second-order GRs we use the corresponding second-order multipole operators with the radial dependence $r^L(r^2 - \eta_L)(L > 0), r^2(r^2 - \eta_0)$ for monopole excitations in the $T_3 = 0$ channel, and $r^2 - \eta_0$ for monopole excitations in the $T_3 = \pm 1$ channels. The scaling parameter $\eta_L$ is found from the condition of minimum overlapping of the second-order probing operator with the transition density of the corresponding first-order GR. The above-described choice of the probing operators ensures a large exhaustion of the respective p-h strength by a given second-order GR.

Differently from Ref. [5], where the CRPA equations are solved for the p-h Green function $G(x, x', \omega)$ (for the effective p-h propagator), we use the equivalent equations for the effective probing operator (for the effective external field) $\tilde{V}(x, \omega)$ ($\omega$ is the excitation energy), as is accepted within the Migdal’s finite Fermi-system theory (see, e.g., Ref. [3] and references therein). This operator determines the main characteristics of a given GR according to the following equations (given in a schematic form):

$$S_V(\omega) = -\frac{1}{\pi} \text{Im} \int V(x) G_0(x, x', \omega) \tilde{V}(x', \omega) dx dx' \equiv \left| \int \rho(x, \omega) V(x) dx \right|^2,$$

where $S_V(\omega)$ and $\rho(x, \omega)$ are, respectively, the strength function and energy-dependent transition density, $G_0(x, x', \omega)$ is the free p-h propagator;

$$M_{V,c}(\omega) = \int \psi_{\text{cont}}(x, \omega) \tilde{V}(x, \omega) \psi_{\text{bound}}(x) dx ; S_{V,c}(\omega) = |M_{V,c}(\omega)|^2,$$

where $M_{V,c}(\omega)$ and $S_{V,c}(\omega)$ are the DSD nucleon-escape amplitude and strength function, respectively, $c$ is the set of the decay-channel quantum numbers, $\psi_{\text{cont}}$ and $\psi_{\text{bound}}$ are, respectively, the single-particle continuum-state and bound-state wave functions. The substitution of $\omega$ by $\omega + (i/2) I$ in the CRPA equations ($I$ is the spreading parameter) means, in fact, using the imaginary part of the single-particle potential in calculations of the $\omega$-dependent quantities $G_0(x, x', \omega)$ and $\psi_{\text{cont}}(x, \omega)$. As a result, we are able to describe in average over the energy the gross properties (with the use of Eq. (1)) and direct-nucleon-decay properties (with the use of Eq. (2)) of a given high-energy GR. Semimicroscopic description of some low-energy GRs with the use of an alternative method of phenomenological accounting for the spreading effect is given in Ref. [8]. We remind that the description of the GR direct-nucleon-decay properties is the main subject of our study. Using Eq. (2), we are able, in particular, to evaluate the partial and total branching ratios, $b_c$ and $b_{tot} = \sum_c b_c$, respectively, for direct nucleon decay of a given GR from a certain excitation-energy interval $\delta = \omega_1 - \omega_2$:

$$b_c(\delta) = \frac{\int_{\delta} S_{V,c}(\omega) d \omega}{\int_{\delta} S_V(\omega) d \omega}.$$

The difference $1 - b_{tot}$ can be considered as the branching ratio for the GR statistical decay. Within the CRPA (i.e. in the absence of the spreading effect) $b_{tot} = 1$ for any energy interval.
(the unitary condition). Concluding the brief presentation of the CRPA equations, we note that expression for the effective field

$$\tilde{V}(x,\omega) = V(x) + \int F(x, x_1)G(x_1, x', \omega)V(x')dx_1dx'$$

(4)

$$(F(x, x_1)$$ is the p-h interaction) allows one to consider the amplitude of Eq. (2) as the semimicroscopic version of the DSD nucleon-escape amplitude. There is a number of phenomenological versions of this amplitude, which are used within the well-known DSD-model (see, e.g. Ref. [1] and references therein).

Before turning to some results of semimicroscopic description of high-energy GRs we briefly describe the choice of model parameters. The parameters of the isoscalar part of the nuclear mean field and the Landau-Migdal parameter $f'$ are so chosen that the nucleon separation energy and single-quasiparticle spectrum in closed-shell subsystems can be satisfactorily described. The parameters of the isoscalar part of the p-h interaction are found from the correct description of the $1^-$ spurious state. This state has to the zero excitation energy and exhausts most part of the isoscalar dipole strength. The strength $g'$ of the p-h interaction in the $S = 1, T = 1$ channel is so chosen that the experimental GTR energy is reproduced in the calculations. We also take effectively into account the (relatively small) contribution of the isovector momentum-dependent forces in formation of the $T = 1$ GRs using a scaling transformation of the reaction amplitudes calculated within the CRPA. The corresponding strength parameter $k_L$ (the “velocity” parameter), which describes contribution of the momentum-dependent forces in the corresponding energy-weighted sum rule, is taken so that description of the peak energy (and exhaustion of the total strength) for a given GR is improved [9]. The radial dependence of the spreading parameter is taken the same as for the isoscalar mean field, while the energy dependence is described by a function with saturation-like behavior (such a behavior is used for the imaginary part of a single-particle potential in some versions of the optical model of the nucleon-nucleus scattering):

$$I(\omega) = \frac{\alpha(\omega - \Delta)^2}{1 + (\omega - \Delta)^2/B^2}$$

(5)

Using the values of the phenomenological parameters $\alpha = 0.125$ MeV$^{-1}$, $\Delta = 3$ MeV, and $B = 7$ MeV in this expression, we describe satisfactorily the experimental strength distribution for a number of isoscalar GRs for a wide mass interval [3]. In describing the isovector GRs we occasionally change the alpha parameter a little to describe better the experimental strength distribution [9]. It should be stressed, that after the choice of the model parameters outlined above we do not use any new parameters to describe the direct-nucleon-decay properties of a given GR.
3 Semimicroscopic description of high-energy GRs

3.1 Isoscalar overtones

All the main properties of the second-order isoscalar GRs (ISGDR, ISGMR2, ISGQR2) in a few singly- and doubly-closed shell nuclei are described in Ref. [3], where the capabilities of the semimicroscopic approach in describing the gross properties of the first-order isoscalar GRs have also been checked. We have strongly been motivated by first experimental data concerned with direct nucleon decays of the ISGDR [2].

From Table XI of Ref. [3] one can see reasonable description of the experimental partial branching rates for direct proton decay of the ISGDR in $^{208}\text{Pb}$ into the ground and first three excited states of $^{207}\text{Te}$.

We note the first observation of the ISGQR2 in $^{208}\text{Pb}$ [2]. The deduced peak energy $\omega_{\text{peak}} = 26.9 \pm 0.7$ MeV and total width $\Gamma = 6.1 \pm 1.3$ MeV are satisfactorily described within the approach ($\omega_{\text{peak}} = 30.5$ MeV, $\Gamma = 6.1$ MeV [3]). One can expect observation of the ISGMR2, whose properties are close to those for the ISGQR2. Only the transition-density radial dependence of these overtones (the same as for the corresponding main tones) is different in the numbers of nodes.

In general, we are able to describe satisfactorily the total width of the isoscalar GRs with $L = 0,1,2$ [3]. That means reasonable description not only of GR coupling with the single-particle continuum, but also of the spreading effect in terms of the phenomenological spreading parameter revealing the saturation-like energy dependence of Eq. (5). As for concentration of the isoscalar particle-hole strength, it decreases with increasing GR energy. One can see the illustration of this statement in Fig. 8 of Ref. [3], where the calculated energy-weighted strength functions (normalized to the corresponding energy-weighted sum rule) are given for five isoscalar GRs in $^{208}\text{Pb}$.

3.2 Properties of the isovector spin giant monopole resonance

Among the observed overtones, the IVSGMR (in the $\beta^-$ channel) has the highest excitation energy ($\simeq$ 37 MeV in $^{208}\text{Bi}$ [4]). From a comparison of the observed and within the CRPA calculated total width ($\simeq$ 14 MeV [4] and $\simeq$ 9 MeV, respectively) one can conclude that the spreading effect for this resonance is relatively weak, while coupling to the single-proton continuum is rather strong. This observation allowed us to put forward the assumption that the spreading strength reveals a saturation-like energy dependence. We have realized this assumption in terms of an appropriate spreading parameter and evaluated the partial and total direct-proton-decay branching ratios of Eq. (3) for the above-mentioned resonance [10]. In particular, the calculated $b_{p,\text{tot}}$ value was found not much different from that deduced later by the joint analysis of the inclusive $^{208}\text{Pb}(^{3}\text{He},t)$ and coincidence $^{208}\text{Pb}(^{3}\text{He},tp)$ experiments [4]. However, the experimental distribution of the total decay probability over the partial decay channels (which are associated
with population of single-hole states $\mu^{-1}$ in $^{207}$Pb) has been found to be in a noticeable disagreement with predictions of Ref. [10]. In particular, a rather strong population of neutron deep-hole states has been unexpectedly found [4]. This fact impelled us to revise the calculations of Ref. [10] (where, in particular, the spreading effect on the continuum-state wave function in Eq. (2) has not been taken into account) and also to make predictions for some other nuclei, using the modern version of the semimicroscopic approach of Ref. [3].

As for the IVSGMR in $^{208}$Bi the experimental [4] and calculated [11] total direct proton-decay branching ratios (52(12)% and 63%, respectively) are found in satisfactory agreement. However, the disagreement with the experimental decay-probability distribution still remains (Table 3 of Ref. [11]). Similar experiments are expected for $^{90}$Zr, $^{120}$Sn target nuclei [4]. We present here the calculated total direct-proton-decay branching ratios for the IVSGMR in $^{90}$Nb and $^{120}$Sb (72% and 65%, respectively) [11].

### 3.3 Properties of the second-order giant dipole resonance

Since the semimicroscopic description of the observed second-order GRs proves to be satisfactory we turn to description of the IVGDR2 (of the lowest-energy isovector overtone in the neutral channel) [12]. The results of our prognostic analysis are shown in comparison with those obtained for the IVGDR within the same approach. Considering $^{208}$Pb as an example, we found that the second-order isovector dipole strength function reveals a well-formed resonance with $\omega_{\text{peak}} \simeq 34$ MeV and FWHM $\simeq 15$ MeV. The relative energy-weighted strength functions for both resonances are given in Fig. 2 of Ref. [12], where the difference in concentration of the corresponding p-h strength is clearly seen. The difference in the transition-density radial dependence is seen in Fig. 3 of Ref. [12], where the densities are shown at the corresponding peak energies. The strength of coupling to the continuum is also different for these resonances: $b_{n,\text{tot}} = 5.5\%$ and $48\%$, $b_{p,\text{tot}} = 0$ and $19\%$ for the IVGDR and IVGDR2, respectively. The relatively large total direct-proton-decay branching ratio allows us to suppose that the IVGDR2 can be observed in the proton-decay channel following inelastic scattering of electrons or light ions by nuclei.

### 3.4 Direct+Semidirect photoneutron and inverse reactions

The photoneutron and inverse reactions, accompanied by excitation of the EL-GRs, are closely related to the direct-neutron-decay properties of these resonances. The reaction amplitudes are proportional to the DSD neutron-escape amplitudes of Eq. (2), provided that an appropriate external field is used. Recently we applied the semimicroscopic approach to describe the above-mentioned reactions in the energy region of the IVGDR. We obtained a satisfactory description of experimental data on the neutron-radiative-capture cross sections for a number of nuclei (See Ref. [9] and references therein). In calculations of the cross sections the same set of model parameters is used as for description of the IVGDR gross properties. In particular, the adopted
values of the “velocity” parameter $k_1$ are found in agreement with the systematics of Ref. [1] ($k_1 \sim 0.1 - 0.2$). Actually, we realized a semimicroscopic version of the DSD-model without the use of any free parameters. In the “single-level” approximation one can get from Eq. (4) the expression for the reaction amplitude in the form used within the DSD-model. However, in such a case the GR form factor is proportional to the GR transition density and has no imaginary part.

As the next step in our study, we consider the backward-to-forward asymmetry of the differential cross sections of the above-mentioned reactions in the energy region of the IVGQR [13]. The asymmetry is due to an interference between the E1- and E2-reaction amplitudes and, therefore, reveals a non-monotonous energy dependence in the above-mentioned energy region. For this reason, experimental studies of the asymmetry present an indirect way to locate the IVGQR (see Ref. [1] and references therein). Considering as an example the $^{208}$Pb nucleus, we start the study from description of the main properties of the IVGQR. As a result, the peak energy (21.5 MeV) and the total width ($\simeq$ 7 MeV) for this resonance have been obtained with the use of the quadrupole “velocity” parameter value $k_2 = 0.1$. Other model parameters, used also for calculations of the transition density and direct-nucleon-decay branching ratios, are taken the same as for description of the IVGDR gross properties. Subsequently, we calculate the $(\gamma, n)$-reaction asymmetry parameter, defined as the difference-to-sum ratio of the differential cross sections taken at $55^\circ$ and $125^\circ$. Using the adopted $k_2$ parameter, we describe satisfactorily the experimental results of Ref. [14], where the $^{nat}Pb(\gamma, n)$-reaction data are obtained for population of the $^{207}$Pb final states for the excitation energy intervals $E_x < 2$ MeV and $E_x < 4$ MeV (Fig. 6 of Ref. [13]). The experimental asymmetry of the $^{208}Pb(n, \gamma_0)$-reaction cross section [15] is also satisfactorily described (Fig. 8 of Ref. [13]). It should be noted, however, that the absolute value of the $^{nat}Pb(\gamma, n)$-reaction cross section (taken at $55^\circ$, for $E_x < 4$ MeV, in the energy interval $\simeq 20 - 30$ MeV) [14] is overestimated in our calculations by a factor $\sim 1.5 - 2.0$ [13].

4 Summary

We developed a rather simple and transparent CRPA-based semimicroscopic approach to describe all the main properties of the high-energy GRs. The term “semimicroscopic” reflects two basic points of the approach. First, we use, as input quantities for CRPA calculations a realistic phenomenological isoscalar part of the nuclear mean field and the isovector (in the $S = 0$ channel) p-h interaction strength, while the mean-field isovector part (and also the mean Coulomb field) and the isoscalar (in the $S = 0$ channel) p-h interaction strength are calculated self-consistently, taking the basic symmetries of the model Hamiltonian into account. The second point is the phenomenological description of the spreading effect in terms of the radial- and energy-dependent spreading parameter, which is directly introduced in the CRPA equations. In other words, for calculation of the $\omega$-dependent quantities in these equations we use the single-particle potential having an $\omega$-dependent imaginary part. This potential is not directly related
to the optical-model potential.

Within the developed approach we are able to describe satisfactorily the most of known experimental data concerned with properties (including the direct-nucleon-decay ones) of high-energy GRs. Some of our predictions have been experimentally confirmed. As compared with properties of low-energy GRs, the concentration of the corresponding p-h strength decreases for high-energy GRs and the coupling to the continuum becomes stronger. These two modes of GR relaxation give the main contribution to the total width of high-energy GRs, while the spreading effect becomes less important revealing a saturation-like energy dependence. As a result, high-energy GRs are characterized by a large (of the order of unity) total direct-nucleon-decay branching ratio.

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References

