Direct-decay properties of Giant Resonances

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A semi-microscopic approach based on the continuum-RPA method and a phenomenological treatment of the spreading effect is developed and applied to describe direct-decay properties of a few isovector giant resonances. Capabilities of the approach to describe giant-resonance gross properties are also checked.

I. INTRODUCTION

Along with the strength distribution and transition density the direct-decay probabilities are also related to the main properties of giant resonances (GRs). In particular, the partial widths (or the partial branching ratios) for direct nucleon decay into one-hole states of the daughter nucleus carry information about the particle-hole structure of a given GR and also about its coupling to the single-particle continuum and many-quasi-particle configurations. Direct-decay properties of GRs have been studied experimentally for a long time (see, e.g., Refs. [1-4] and references therein). To describe systematically these properties we developed a semi-microscopic approach, based on the continuum-RPA (CRPA) method and a phenomenological treatment of the spreading effect. Within this approach we described satisfactorily the partial widths (partial branching ratios) for direct nucleon decay of a number of GRs. They are: the isobaric analog resonance (IAR) [5], the Gamow-Teller and isovector giant spin-dipole resonance (GTR and IVGSDR, respectively) [6], the isoscalar giant monopole resonance (ISGMR)[7], the isoscalar giant dipole resonance (ISGDR) [8]. In this work we briefly describe the approach and present recent results concerned with semi-microscopic description of direct-decay properties of a few isovector giant resonances [9-13].
II. ELEMENTS OF THE APPROACH

A. Basic CRPA equations

In our approach the CRPA equations are used in a form which is consistent with Migdal’s finite Fermi-system theory. Of particular importance is the expression for the effective single-particle probing operator (or the effective external field) \( \tilde{V}(x, \omega) \) with \( x \) being the set of radial, spin-angular, isospin variables and where \( \omega \) is the excitation energy. The difference between the effective and the bare probing operator \( V(x) \) is due to polarization effects from the quasi-particle interaction in the particle-hole (p-h) channel. Along with the strength function \( S_V(\omega) \) and transition density \( \rho(x, \omega) \) (these are related to the GR gross properties) the effective field determines also the (direct + semidirect) nucleon-escape amplitudes \( M_{V,c}(\omega) \)

\[
M_{V,c}(\omega) \sim \int \psi_{cont}(x, \omega) \tilde{V}(x, \omega) \psi_{bound}(x) dx
\]  

Here, \( \psi_{bound} \) and \( \psi_{cont} \) are, respectively, the single-particle bound-state (with an energy \( \varepsilon_\mu \)) and continuum-state (with an energy \( \varepsilon = \varepsilon_\mu + \omega \)) wave functions and \( c \) is a set of decay-channel quantum numbers. Within the CRPA the unitary condition is fulfilled: \( S_V(\omega) = \sum_c |M_{V,c}(\omega)|^2 \). (It is supposed that \( \omega > S_N \), the latter is the nucleon separation energy).

B. The spreading effect

In the present approach the spreading effect is phenomenologically taken into account in terms of an appropriate spreading parameter \( I \). In the CRPA description of low-energy (“sub-barrier”) GRs one can represent the reaction amplitudes (i.e. polarizability \( P_V(\omega) \) and amplitudes \( M_{V,c}(\omega) \)) as a sum over non-overlapping doorway-state resonances. The spreading parameter has the meaning of the averaged doorway-state spreading width and can be introduced in the expansion of the reaction amplitudes by the substitution \( \omega \rightarrow \omega + (1/2)iI \) to obtain the corresponding energy-averaged amplitudes. The parameter \( I \) is adjusted to reproduce in calculations of the energy-averaged strength function \( S(\omega) = -\frac{1}{\pi} |ImP(\omega)| \) the observed total width of a given GR. Then the partial direct-nucleon-decay branching ratios

\[
b_c = \frac{\int |M_{V,c}(\omega)|^2 d\omega}{\int S_V(\omega) d\omega}
\]
can be calculated without the use of any new parameters [6,7]. If the doorway-state resonances are overlapping (which generally is the case for high-energy “over-barrier” GRs), we take the spreading effect into account by the above-mentioned substitution of complex energies directly in the CRPA equations [8]. In this case the spreading parameter, taken radial- and energy-dependent, is, actually, the twice imaginary part of the potential used in calculations of the $\omega$-dependent single-particle quantities. Such a potential is not directly related to the optical-model potential used in description of nucleon-nucleus scattering (see, e.g., Ref. [14]). This procedure allows us to calculate directly the energy-averaged characteristics of a given GR (the strength function, energy-dependent transition density and nucleon-escape amplitudes) while taking into account all main GR relaxation modes.

C. Input quantities and model parameters

A realistic phenomenological isoscalar nuclear mean field (including the spin-orbit term) and the (momentum-independent) Landau-Migdal p-h interaction are used as input quantities for CRPA calculations. The mean field and the p-h interaction (in the non-spin-flip channel) are related to each other by self-consistency conditions, which are due to the basic symmetries of the model Hamiltonian. Using these conditions we calculate self-consistently the isovector part of the nuclear mean field (symmetry potential) via the phenomenological Landau-Migdal parameter $f'$, the mean Coulomb field, and determine the strengths of the p-h interaction in the isoscalar non-spin-flip channel. The parameters of the isoscalar part of the nuclear mean field and the parameter $f'$ are chosen such that the nucleon separation energy and single-quasi-particle spectrum in closed-shell subsystems can be described satisfactorily. The strength $g'$ of the p-h interaction in the isovector spin-flip channel is chosen such that the experimental GTR energy is reproduced in calculations. We also take into account, in an effective way, the (relatively small) contribution of isovector momentum-dependent forces in formation of the isovector GRs by using a scaling transformation of the reaction amplitudes calculated within the CRPA. The corresponding strength parameter $k_L$ (the “velocity” parameter), which describes the contribution of the momentum-dependent forces in the corresponding energy-weighted sum rule, is taken such that description of the peak energy (and exhaustion of the total strength) for given isovector GR is improved [9-13]. 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 function is used for the imaginary part of a single-particle potential in some versions
of the optical model of the nucleon-nucleus scattering). The parameters of this function
have been found in Ref. [8] from the semi-microscopic description of the total width of a few
isoscalar resonances in a number of singly- and doubly-closed shell nuclei. In the description
of the isovector GRs we occasionally change the strength of spreading parameter by a small
amount to improve the description of the experimental strength distribution [9]. It should
be stressed, that after the above-outlined choice of the model parameters we do not use any
new parameters to describe the direct-nucleon-decay properties of a given GR.

III. APPLICATIONS

A. Direct + Semidirect (DSD) photoneutron and inverse reactions

Since the excitation of electric GRs (EL-GRs) is an intermediate step in DSD reac-
tions, these reactions are closely related to the direct-decay properties of EL-GRs. In the
present approach the reaction amplitudes are proportional to the nucleon-escape amplitudes
of Eq. (1), provided that the appropriate external field is used. For a specific nucleus we
first describe the experimental photo-absorption cross section in the energy region of the
isovector giant dipole resonance (IVGDR) to obtain the spreading parameter strength $\alpha$
and the “velocity” parameter $k_1$. The values for $k_1 \simeq 0.1–0.2$ are in agreement with the sys-
tematics of Ref. [1], while the extracted values for $\alpha$ are close to the value $0.125$ MeV$^{-1}$ used
in Ref. [8]. Following this procedure the partial neutron-radiative-capture cross sections for
$^{89}$Y, $^{140}$Ce, and $^{208}$Pb target-nuclei have satisfactorily been described without the use of new
parameters [9]. Actually, the present model can be regarded as the semi-microscopic version
of the well-known phenomenological DSD-model (see, e.g., Ref. [1] and references therein).
In the “single-level” approximation one can get from Eq. (1) the expression for the reaction
amplitude in the form used within the DSD-model. The difference is that the GR form
factor is proportional to the GR transition density and has no imaginary part. In addition
the continuum-state wave function is calculated with the use of an effective optical-model
potential.

Within the same model we evaluate the total direct-neutron-decay branching ratio for
the IVGDR in a number of singly- and doubly-closed shell nuclei [9]. The value of 21.4%, obtained for $^{48}$Ca, is found to be only in qualitative agreement with the corresponding experimental value of 39(5)% [2].

As the next step, we consider the backward-to-forward asymmetry of the differential cross sections of the above-mentioned reactions in the energy region of the isovector giant quadrupole resonance (IVGQR) [11]. The asymmetry is due to an interference between the E1- and E2-reaction amplitudes and, therefore, reveals a non-monotonous energy dependence in this energy region. For this reason, experimental studies of the asymmetry presents an indirect way to locate the IVGDR (see Ref. [1] and references therein). Considering as an example the nucleus $^{208}$Pb, we satisfactorily described the experimental data on the asymmetry (defined as the difference-to-sum ratio of the differential cross sections taken at $55^\circ$ and $125^\circ$) using the “velocity” parameter value $k_2 = 0.1$. After this we calculate all the main properties of the IVGQR in $^{208}$Pb without the use of free parameters. In particular, the peak energy $\simeq 21.5$ MeV and the total width $\simeq 7$ MeV are found in agreement with the systematics of Ref. [1].

**B. Overtone of the IVGDR**

Most of high-energy GRs are the next vibration modes (overtones, or second-order GRs) relative to the corresponding low-energy GRs (main tones, or first-order GRs). The lowest energy isoscalar second-order GR is the well-studied ISGDR (the overtone of the zero-energy $1^-\!\!\!\!\!\!\!\!$ spurious state, associated with the center-of-mass motion). One can expect that in the neutral channel the lowest energy isovector second-order GR is the overtone of IVGDR (i.e. IVGDR2). The IVGDR2 is the isovector partner of the ISGDR. Considering $^{208}$Pb as an example, we performed a semi-microscopic analysis of the main properties of the IVGDR2 [12]. As an external field, the second-order dipole operator is used with a radial dependence $r(r^2 - \eta)$. The parameter $\eta$ is found from the condition of “minimum exciting” of the main-tone resonance. The isovector second-order dipole strength function reveals a well-formed resonance with a peak energy $\simeq 34$ MeV and total width $\simeq 15$ MeV. The overtone coupling to the single-particle continuum is, naturally, more intensive than the main-tone coupling: $b^{\text{tot}}_n \simeq 5.5\%$ and 48\%, $b^{\text{tot}}_p \simeq 0$ and 19\% for the IVGDR and ISVGDR2, 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.

C. Direct proton decay of the isovector giant spin-monopole resonance

Among the observed GRs the charge-exchange (in the $\beta^-$ channel) giant spin-monopole resonance (IVGSMR$^{(-)}$, the overtone of the GTR) has the highest excitation energy ($\simeq 37$ MeV in $^{208}$Bi [3]). From comparison of the observed and calculated total width ($\simeq 14$ MeV [3] and $\simeq 11$ MeV, respectively) one can conclude that the spreading effect for this resonance is relatively weak, while the coupling to the (single-proton) continuum is rather strong. This observation allowed us to put forward the assumption that the spreading effect reveals a saturation-like energy dependence. This assumption was successfully applied in Ref. [15], where the partial and total direct-proton-decay branching ratios were calculated for the IVGSMR$^{(-)}$. In particular, the calculated $b_p^{\text{tot}}$ value was found to be close to the corresponding value deduced later from the joint analysis of the inclusive $^{208}$Pb($^3$He,t) and coincidence $^{208}$Pb($^3$He,tp) experiments [3]. 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. [15]. In particular, a rather strong population of neutron deep-hole states has been unexpectedly found [3]. Recently, we have revised the calculations of Ref. [15] (where, in particular, the spreading effect on the continuum-state wave function of Eq. (11) has not been taken into account) [13]. Although the calculated and experimental total proton branching ratios are found to be rather close (63% and 52(12)% [3], respectively), the disagreement with the experimental decay-probability distribution still remains. The reasons for this disagreement are not clear now. Being motivated by forthcoming experimental results, we made some predictions for decay properties of the IVGSMR$^{(-)}$ in $^{90}$Nb and $^{120}$Sb [13]. In particular, the $b_p^{\text{tot}}$ values (72% and 65%, respectively) have been obtained for these GRs.
D. Direct decays of isolated 1− IAR

The isospin splitting of the IVGDR into two components takes place for nuclei having not-too-large neutron excess \( (N - Z) = 2T \) (\( T \) is the value of the ground-state isospin). The \( T = T + 1 \) component of the IVGDR (i.e. IVGDR\(_{>}\)) is the isobaric analog of the charge-exchange (in the \( \beta^{(+)} \) channel) IVGDR (i.e. of the IVGDR\(^{(+)}\)) and presents the specific double GR (see, e.g., Ref. [1]). Assuming that the isobaric analog state exhausts 100% of the Fermi strength, one can express the IVGDR\(_{>}\) strength function (corresponding to \( V(x) \sim -(1/2)\tau^{(3)} \)) via the IVGDR\(^{(+)}\) strength function (corresponding to \( V(x) \sim \tau^{(+)}) \)

\[
S_{>}(\omega) = (2T + 2)^{-1}S^{(+)}(\omega - \Delta C) \tag{2}
\]

where \( \Delta C \) is the Coulomb displacement energy. CRPA calculations of the \( S^{(+)} \) strength function, performed in Ref. [10] for the \(^{48}\)Ca and \(^{90}\)Zr parent nuclei, show that in accordance with Eq. (2) the low-energy part of the IVGDR\(_{>}\) strength function contains a few isolated resonances (1− IAR). Since the cross section of photo-absorption, accompanied by excitation of the IVGDR\(_{>}\), is proportional to \( S_{>}(\omega) \), one can evaluate the partial radiative width \( \Gamma_{\gamma_0} \) of each mentioned 1− IAR [10].

Being motivated by the experimental results of Ref. [16], where one of 1− IAR in \(^{90}\)Zr (with \( E_x = 16.28 \) MeV) has been studied via the \((e,e'p)\)-reaction, the authors of Ref. [10] attempted to evaluate the partial protons widths of this IAR for decay into one-hole states of \(^{89}\)Y. They used the expression for the partial amplitude of the \((\gamma,p)\)-reaction accompanied by excitation of IVGDR\(_{>}\) [10]. This expression, derived using the above-mentioned assumption regarding the properties of the isobaric analog state, can be presented as (compare with Eq. (1), both Eqs. are given in a rather schematic form):

\[
M^>(\omega) \sim (2T + 2)^{-1} \int \psi_{cont}(x,\omega)v(x) \times \\
\quad \times g_{n}(x,x',\epsilon')\tilde{V}^{(+)}(x',\omega')\psi_{bound}(x')dx dx' . \tag{3}
\]

Here, \( v(x) \) is the symmetry potential; \( g_{n}(x,x',\epsilon') \) is the neutron Green’s function \( (\epsilon' = \epsilon - \Delta C) \); \( \tilde{V}^{(+)}(x',\omega') \) is the effective charge-exchange dipole field \( (\omega' = \omega - \Delta C) \). The poles in the omega-dependence of the amplitude \( M_{e} \) correspond to the 1− IAR, while the pole residue is proportional to the product \( (\Gamma_{\gamma_0})^{1/2}(\Gamma_{p})^{1/2} \). Therefore, the joint analysis of Eqs. (2) and (3) allows one to evaluate within the CRPA the partial proton widths, \( \Gamma_{p} \), of each 1− IAR. Among these resonances in \(^{90}\)Zr one 1− IAR with the energy \( \simeq 16 \) MeV can be related
TABLE I: Partial widths for decay of $1^-$ IAR in $^{90}$Zr ($E_x \approx 16$ MeV). $\Delta_p$ is the proton energy-gap parameter. The decay channels $p_{0-3}$ correspond to population of the $2p_{1/2}$, $1g_{9/2}$, $2p_{3/2}$, $1f_{5/2}$ one-hole states $\mu^{-1}$ in $^{89}$Y.

| $\Delta_p$ (MeV) | $\Gamma_{\gamma_0}$ (eV) | $\Gamma_{p_0}$ | $\Gamma_{p_1}$ | $\Gamma_{p_2}$ | $\Gamma_{p_3}$ (keV) |
|------------------|---------------------|--------|--------|--------|-----------------|
| $\Delta_p = 0$   | 170                 | 55     | –      | 25     | –               |
| $\Delta_p = 1$   | 110                 | 55     | 1.7    | 10.5   | 0.1             |
| exp. [16]        | 108 (35)            | 54 (18)| < 2    | 20 (5) | 7 (2)           |

to the one studied in Ref. [16]. In the Tab. 1 the partial widths calculated for this resonance are shown in comparison with the corresponding experimental values. To understand the role of proton pairing in the formation of the $1^-$ IAR we take pairing into account by simply substituting in the CRPA equations the occupation numbers by the Bogoluybov coefficients $v^2$. This can be done in an isospin-self-consistent way [5]. The results are also shown in the Table 1 and demonstrate a satisfactory agreement with the data of Ref. [16].

IV. CONCLUSION

The semi-microscopic approach presented here is relatively simple to use and at the same time is able to give a satisfactorily description of most of several different experimentally measurable quantities related to the direct-decay properties of giant resonances in singly- and doubly-closed-shell nuclei.

The current problems with developing the approach are related to correct description of the non-resonance part of the reaction amplitudes and taking nucleon pairing into account (in the spirit of Ref. [17]).

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