Damping parameters of charge-exchange giant monopole resonances within a semi-microscopic approach

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Abstract. The recently proposed semi-microscopic approach, which consists in incorporating the "Coulomb description" of isospin-forbidden processes into the particle-hole dispersive optical model, is implemented to evaluate the main damping parameters of charge-exchange giant monopole resonances (including isobaric analog resonances) in medium-heavy spherical nuclei. The calculation results obtained for the ^{208}Pb and ^{209}Pb parent nuclei are compared with available experimental data.

1 Introduction

The problem in evaluating the main parameters of damping an arbitrary giant resonance consists in a necessity to describe together coupling the corresponding particle-hole type states to the single-particle (s.-p.) continuum, and to many-quasiparticle configurations (the spreading effect). As applied to medium-heavy spherical nuclei, a solution of this problem is proposed within the newly developed particle-hole dispersive optical model (PHDOM) [1]. The model is a microscopically-based extension of the standard and non-standard continuum-RPA (cRPA) versions on taking the spreading effect into account. In this semi-microscopic model, a mean field and the particle-hole interaction responsible for long-range correlations are described microscopically, while the spreading effect is treated phenomenologically in terms of the strength of an energy-averaged particle-hole self-energy term. The imaginary part of this term determines the real part via a proper dispersive relationship.

The specific feature of high-energy charge-exchange monopole excitations is the presence of isobaric analog resonances (IARs), whose properties are closely related to approximate isospin-symmetry conservation in nuclei. The main parameters of IAR damping (the spreading width, partial proton-escape widths, so-called mixing phase determining the IAR asymmetry in proton-induced resonance-reaction cross sections) do exist due to isospin mixing. In medium-heavy nuclei, the main mixing mechanism consists in IAR coupling to its overtone (the isovector monopole giant resonance in the $\beta^{(-)}$-channel, (IVMGR$^{(-)}$)) via a spatially variable part of the mean Coulomb field (see, e.g., Ref. [2]). In our previous work [3] for describing above-mentioned excitations, we proposed the semi-microscopic approach, which consists in incorporating the "Coulomb description" of isospin-forbidden processes [4, 5] into the PHDOM. In Ref. [3], implementation of the proposed approach has been limited by a quantitative estimation of the spreading width for the IARs based on the ^{208,209}Pb parent-nuclei ground state. We extend this study and present the results of implementations of the semi-microscopic approach to a quantitative estimation of the main damping parameters for the above-mentioned IARs, and also of the partial branching ratios for direct one-proton (one-neutron) decay of the IVMGR$^{(-)}$ (IVGMR$^{(+)}$) based on the ^{208}Pb parent-nucleus ground state (the IVMGR$^{(+)}$ is the isobaric partner of the IVMGR$^{(-)}$).

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2 Basic relationships

We start from brief presentation of the equations derived in Ref. [3]. Within the semi-microscopic approach mentioned in Introduction, the IAR total width, Γ_A, is determined by the equation

$$\Gamma_A = \frac{2\pi}{S_A} S_C^{(-)}(\omega_A) \tag{1}$$

Here, S_A is the IAR Fermi strength; $S_C^{(-)}(\omega)$ is the energy-averaged strength function related to the "charge-exchange Coulomb" external field (probing operator) $V_C^{(-)} = V_C(r)\tau^{(-)}$ with $V_C(r) = U_C(r) - \omega_A + (i/2)\Gamma_A$, where $U_C(r)$ is the mean Coulomb field and ω_A is the IAR excitation energy counted off from the parent-nucleus ground-state energy. In absence of the spreading effect (i. e., within the cRPA) the strength S_A and energy $\omega_A^{(0)}$ can be evaluated from describing the IAR by means of the Fermi strength function (related to the Fermi probing operator $V_F^{(-)} = \tau^{(-)}$). In further consideration, we suppose $\omega_A = \omega_A^{(0)}$, neglecting by a small IAR spreading shift (the expression for this shift is given in Ref. [3]).

The "s.-p." partial width for IAR direct one-proton decay accompanied by population of the neutron one-hole state ν^{-1} in the product nucleus, $\Gamma^{\uparrow}_{A,\nu}$, is determined by the partial escape "charge-exchange Coulomb" strength function, $S^{(-),\uparrow}_{C,\nu}(\omega)$ [3, 5]

$$\exp\left[2i\xi_{(\pi)}(\varepsilon_A)\right]\Gamma^{\uparrow}_{A,\nu} = \exp\left[2i\xi_{(\pi)}(\varepsilon_A)\right]\frac{2\pi}{S_A}S^{(-),\uparrow}_{C,\nu}(\omega_A) = \frac{2\pi}{S_A}N_\nu\delta_{(\pi)(\nu)}\int \chi^{(-)*}_{\varepsilon_{A,\nu},(\pi)}(r)\tilde{V}^{(-)}_C(r,\omega_A)\chi_\nu(r)dr\times \int \chi_\nu(r)\tilde{V}^{(-)*}_C(r,\omega_A)\chi^{(+)}_{\varepsilon_{A,\nu},(\pi)}(r)dr. \quad (2)$$

Here, $\nu = \{\varepsilon_\nu, j_\nu, l_\nu\}$ ($(\nu) = \{j_\nu, l_\nu\}$) is the set of s.-p. bound-state quantum numbers; N_ν is the number of neutrons filling the single-particle level ν; $r^{-1}\chi_\nu(r)$ is the radial bound-state wave function; $r^{-1}\chi^{(\pm)}_{\varepsilon,(\pi)}(r)$ is the radial optical-model-like continuum-state proton wave function taken at the energy $\varepsilon = \varepsilon_{A,\nu} = \varepsilon_\nu + \omega_A$; $\xi_{(\pi)}$ is the real part of the proton-scattering phase $\delta_{(\pi)} = \xi_{(\pi)} + i\eta_{(\pi)}$ determined by the mentioned continuum-state wave function. The effective field in Eq. (2), $\tilde{V}^{(-)}_C(r,\omega)$, is related to the above-given radial part of the "charge-exchange Coulomb" field $V_C(r)$ and satisfies the corresponding integral equation, which is valid in a wide excitation-energy interval, including the IAR and IVGMR$^{(-)}$ [3]. This equation (related to a couple-channel approach) contains the isovector part of the Landau-Migdal p-h interaction and the respective charge-exchange part of the energy-averaged "free" p-h propagator determined within PHDOM with taking the s.-p. continuum and spreading effect into account. The mentioned effective field determines the total "charge-exchange Coulomb" strength function (see Eq. (1)) also in a wide excitation energy interval [3].

The main parameters of IAR damping can be found from Eqs. (1) and (2). The spreading width is determined, as follows:

$$\Gamma^{\downarrow}_A = \Gamma_A - \Gamma^{\uparrow}_A; \qquad \Gamma^{\uparrow}_A = \sum_\nu \Gamma^{\uparrow}_{A,\nu}. \quad (3)$$

Since the proton-escape widths are strongly dependent on the potential-barrier penetrability, for a comparison with the corresponding experimental data we recalculate the partial widths of Eq. (2) from the energy $\varepsilon = \varepsilon_{A,\nu}$ to the respective experimental energy $\varepsilon^{exp}_{A,\nu}$

$$\check{\Gamma}^{\uparrow}_{A,\nu} = \frac{T_{(\pi)}(\varepsilon^{exp}_{A,\nu})}{T_{(\pi)}(\varepsilon_{A,\nu})}\Gamma^{\uparrow}_{A,\nu}; \quad T_{(\pi)}(\varepsilon) = 1-\exp\left[-4\eta_{(\pi)}(\varepsilon)\right]. \quad (4)$$

Here, $T_{(\pi)}(\varepsilon)$ is the optical-model penetrability (transmission coefficient) determined by the scattering-phase imaginary part. The real part of the scattering phase of Eq. (2), $\xi_{(\pi)}(\varepsilon)$, determines the so-called mixing phase, $\phi_{(\pi)}(\varepsilon)$

$$\phi_{(\pi)}(\varepsilon) = \xi_{(\pi)}(\varepsilon) - \xi^{bkg}_{(\pi)}(\varepsilon). \quad (5)$$

Here, $\xi^{bkg}_{(\pi)}(\varepsilon)$ is the real part of the background-scattering phase deduced from the description of proton scattering within the standard optical model in a vicinity of the IAR (Within the PHDOM, there appears an effective optical-model potential [1]). The mixing phase of Eq. (5) determines the asymmetry of the IAR in the energy dependence of the proton-induced resonance-reaction cross sections [6]. This statement follows from the single-level parameterization of the energy-averaged S-matrix for proton scattering accompanied by IAR excitation. In case of scattering by the "ν_0^{-1} neutron-hole" nucleus, the S-matrix elements corresponding to 0^+-IAR excitation can be presented in the form:

Table 1. Energies and widths of the IVGMR$^{(\mp)}$ based on the ^{208}Pb ground state in comparison with the corresponding experimental data [8] (in MeV)

GR	ω_M	ω^{exp}_M	Γ_M	Γ^{exp}_M
IVGMR$^{(-)}$	42.1	37.0 ± 3.5	16.4	15.0 ± 6.0
IVGMR$^{(+)}$	16.6	12.0 ± 2.8	4.35	11.6 ± 7.1

$$S_{(\pi)(\pi_0)}(\varepsilon) = \exp\left[2i\left(\xi^{bkg}_{(\pi_0)} + i\eta^{bkg}_{(\pi_0)}\right)\right]\delta_{(\pi)(\pi_0)} - \exp\left[i\left(\xi_{(\pi)} + \xi_{(\pi_0)}\right)\right]\frac{i\left(\Gamma^{\uparrow}_{A,\nu}\Gamma^{\uparrow}_{A,\nu_0}\right)^{1/2}}{\varepsilon - \varepsilon_{A,\nu_0} + \frac{i}{2}\Gamma_A}\delta_{(\pi)(\nu)}\delta_{(\pi_0)(\nu_0)}. \quad (6)$$

In particular, the energy dependence of the generalized transmission coefficient $\tilde{T}_{(\pi_0)}(\varepsilon) = 1 - \sum_{(\pi)}\left|S_{(\pi)(\pi_0)}(\varepsilon)\right|^2$, which determines the resonance (p, n_{tot})-reaction cross section, exhibits the above-mentioned asymmetry. In the cRPA limit (i.e., in neglecting the spreading effect) the asymmetry tends to zero. A microscopic consideration of the mixing-phase problem in applying to IARs has been given in Ref. [7]. It is worth noting here that within PHDOM-based approach the isospin mixing mechanism is considered without its dividing into "internal" and "external" parts.

Being considered in a wide excitation energy interval, the energy-averaged "charge-exchange Coulomb" strength functions $S^{(-)}_C(\omega)$, $S^{(-),\uparrow}_{C,\nu}(\omega)$ (and their isobaric partners $S^{(+)}_C(\omega)$, $S^{(+),\uparrow}_{C,\pi}(\omega)$) exhibit a maximum, corresponding to the IVMGR$^{(-)}$ (IVGMR$^{(+)}$). This point allows one to use these strength functions for evaluating the partial branching ratios, $b^{(-),\uparrow}_{C,(\nu)}$ ($b^{(+),\uparrow}_{C,(\pi)}$), for direct one-proton (one-neutron) decay of the mentioned giant resonances

$$b^{(-),\uparrow}_{C,\nu} = \int_{\delta^{(-)}} S^{(-),\uparrow}_{C,\nu}(\omega)d\omega \Bigg/ \int_{\delta^{(-)}} S^{(-)}_C(\omega)d\omega\,, \quad (7)$$

$$b^{(+),\uparrow}_{C,\pi} = \int_{\delta^{(+)}} S^{(+),\uparrow}_{C,\pi}(\omega)d\omega \Bigg/ \int_{\delta^{(+)}} S^{(+)}_C(\omega)d\omega\,. \quad (8)$$

Here, $\delta^{(-)}$ ($\delta^{(+)}$) is the excitation energy interval in a vicinity of the IVMGR$^{(-)}$ (IVGMR$^{(+)}$), and the total "charge-exchange Coulomb" strength functions $S^{(\mp)}_C(\omega)$ obey the respective non-energy-weighted sum rule

$$NEWSR_C = \int S^{(-)}_C(\omega)d\omega - \int S^{(+)}_C(\omega)d\omega = \int |V_C(r)|^2\, n^{(-)}(r)d^3r, \quad (9)$$

where $n^{(-)}(r)$ is the neutron-excess density. The total branching ratio for direct one-proton (one-neutron) decay, $b^{(-),\uparrow}_C = \sum_\nu b^{(-),\uparrow}_{C,\nu}$ ($b^{(+),\uparrow}_C = \sum_\pi b^{(+),\uparrow}_{C,\pi}$), determines the branching ratio for statistical (mainly neutron) decay of the IVMGR$^{(-)}$ (IVGMR$^{(+)}$)

$$b^{(-),\downarrow}_C = 1 - b^{(-),\uparrow}_C \qquad \left(b^{(+),\downarrow}_C = 1 - b^{(+),\uparrow}_C\right). \quad (10)$$

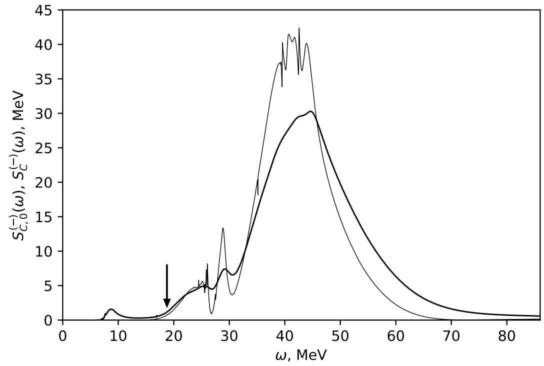

Figure 1. The "charge-exchange Coulomb" strength functions $S_{C,0}^{(-)}(\omega)$ and $S_C^{(-)}(\omega)$ (in MeV) calculated for the ^{208}Pb parent nucleus within the cRPA (thin line) and PHDOM (bold line). The arrow marks the IAR energy.

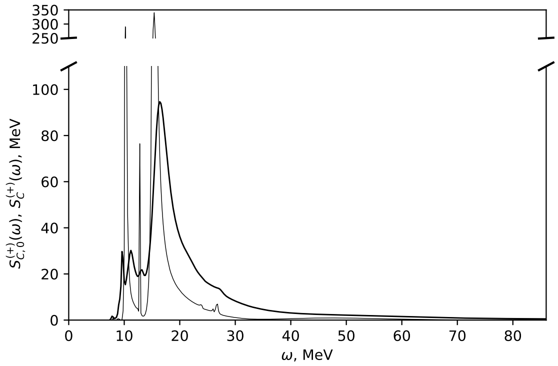

Figure 2. The "charge-exchange Coulomb" strength functions $S_{C,0}^{(+)}(\omega)$ and $S_C^{(+)}(\omega)$ (in MeV) calculated for the ^{208}Pb parent nucleus within the cRPA (thin line) and PHDOM (bold line).

In absence of the spreading effect (i.e., within the cRPA), these branching ratios tend to zero.

3 Input quantities. Calculation results

The input quantities for the PHDOM version, used in the present work to implement the semi-microscopic approach, are the following. (i) A realistic partially self-consistent phenomenological mean field (Woods-Saxon-type) which is described in details in [9]. Essential for a description of considered excitations terms, namely, the mean Coulomb field $U_C(r)$ and the symmetry potential $v(r) = 2F'n^{(-)}(r)$, are calculated self-consistently. (ii) The strength F' of the isovector part of the Landau-Migdal p-h interaction, which is an element of the above-mentioned mean field. (iii) The strength α of the imaginary part of the energy-averaged p-h self-energy term.

We start quantitative estimation of the damping parameters of the charge-exchange giant monopole resonances based on the ^{208}Pb ground state from the solution of Eq. (1) for the IAR total width. This quantity depends on the above-mentioned strength parameter α, which is adjusted to describe within the approach the IVGMR$^{(-)}$ total width experimentally known with low accuracy. The "charge-exchange Coulomb" strength functions $S_C^{(\mp)}(\omega)$ calculated in a vicinity of the IVGMR$^{(\mp)}$ in the mentioned nucleus with the use of the adopted value $\alpha = 0.07$ MeV^{-1} are shown in Figs. 1, 2. (So chosen α value is close to those used within the PHDOM description of the isovector dipole and isoscalar monopole giant resonances (Refs. [10] and [11], respectively). The calculated "charge-exchange Coulomb" strength functions exhaust 99% of the sum rule of Eq. (8). The experimental and calculated energy ω_M and total width Γ_M of each giant resonance are given in Table 1. The partial and total branching ratios for direct one-nucleon decay calculated for the considered IVGMR$^{(\pm)}$ are given in Table 2. In accordance with Eq. (9), the mentioned total branching ratios can be considered as a measure of contribution of the s.-p. continuum to formation of these resonances. It is worth to note, that the evaluated total branching ratio for the direct one-proton decay of the considered IVGMR$^{(-)}$ is close to the experimental value $52 \pm 12\%$ found for the respective charge-exchange spin-monopole giant resonance in the same nucleus [12]. It is not surprising, because both giant resonances have similar microscopic structure.

As in Ref. [3], the spreading width $\Gamma_A^{\downarrow} = 60$ keV, evaluated for the IAR based on the ^{208}Pb ground state in accordance with Eqs. (1)–(3), is found in acceptable agreement with the corresponding experimental quantity $\Gamma_{A,exp}^{\downarrow} = 78 \pm 8$ keV [13]. The partial widths for direct one-proton decay of the considered IAR evaluated and recalculated to the respective experimental energies in accordance with Eqs. (2) and (4) are given in Table 3 in comparison with the respective experimental width data. Strictly speaking, for such a comparison each calculated s.-p. escape width $\check{\Gamma}_\nu$ should be multiplied by the spectroscopic factor SF_ν of the corresponding s.-p. state of the parent nucleus. For most of the considered channels the experimental values of SF_ν are close to unity and not taken into account. Only for the $\nu = 2f_{7/2}$ s.-p. state $SF_{2f_{7/2}} = 0.7$ [14]. The respective escape width is multiplied by this experimental spectroscopic factor, whereas the calculated within the model value is given in brackets.

In applying to the IAR based on the single-neutron state ν_0 of the closed-shell+valence-neutron parent nucleus ^{209}Pb, Eqs. (1)–(3) (with $N_{\nu_0} = 1$) are valid. The s.-p. elastic partial proton width calculated for this IAR and recalculated to the respective experimental energy is given in Table 3 in comparison with corresponding experimental value. As in Ref. [3], the spreading width calculated for the IAR ($\nu_0 = 2g_{9/2}$), $\Gamma_A^{\downarrow} = 67$ keV, is found in acceptable agreement with the corresponding experimental quantity $\Gamma_{A,exp}^{\downarrow} = 75 \pm 7$ keV [13].

In evaluation of the mixing phases of Eq. (5) (Table 3) we take the optical-model parameters systematic from [15] to calculate the background scattering phases $\xi_{(\pi)}^{bkg}$.

4 Conclusive remarks

In this talk, we extend implementation of the semi-microscopic approach proposed in the previous work and

Table 2. Branching ratios for IVGMR$^{(\mp)}$ based on the ^{208}Pb ground state

IVGMR$^{(-)}$			IVGMR$^{(+)}$		
ν	$b^{(-),\uparrow}_{C,\nu}$ (cRPA), %	$b^{(-),\uparrow}_{C,\nu}$ (PHDOM), %	π	$b^{(+),\uparrow}_{C,\pi}$ (cRPA), %	$b^{(+),\uparrow}_{C,\pi}$ (PHDOM), %
$3p_{1/2}$	4.1	2.2	$3s_{1/2}$	7.5	2.1
$2f_{5/2}$	10.1	5.1	$2d_{3/2}$	16.7	3.6
$3p_{3/2}$	7.9	4.3	$1h_{11/2}$	49.7	9.9
$1i_{13/2}$	20.5	10.7	$2d_{5/2}$	13.2	4.0
$2f_{7/2}$	13.0	6.5	$1g_{7/2}$	8.1	2.9
$1h_{9/2}$	9.1	4.4	$1g_{9/2}$	2.1	1.5
$3s_{1/2}$	2.5	1.0	$2p_{1/2}$	0.4	0.3
$1h_{11/2}$	10.4	5.2	$2p_{3/2}$	0.7	0.5
Others	22.6	10.4	Others	1.6	1.2
Total	100.0	49.9	Total	100.0	26.1

Table 3. Escape-proton energies, partial direct one-proton decay widths, mixing phases and corresponding experimental data for the IAR based on the ^{208,209}Pb parent nuclei.

ν	$\varepsilon_{A,\nu}$, MeV	$\varepsilon^{exp}_{A,\nu}$, MeV	$\Gamma^{\uparrow}_{A,\nu}$, keV	$\check{\Gamma}^{\uparrow}_{A,\nu}$, keV	$\Gamma^{\uparrow,exp}_{A,\nu}$, keV	$\phi_{(\pi)}$	$\phi^{exp}_{(\pi)}$
p+^{207}Pb							
$3p_{1/2}$	11.1	11.5	54.7	71.6	51.9 ± 1.6	0.051	0.087 ± 0.035
$2f_{5/2}$	10.2	10.9	11.4	24.3	26.4 ± 2.0	0.011	–
$3p_{3/2}$	10.1	10.6	49.5	86.4	64.7 ± 3.4	0.039	–
$1i_{13/2}$	9.1	9.7	<0.1	0.1	–	<0.001	–
$2f_{7/2}$	7.5	9.2	0.5	4.9 (7.0)	4.2 ± 0.6	<0.001	–
$1h_{9/2}$	6.8	8.0	<0.1	<0.1	–	<0.001	–
p+^{208}Pb							
$2g_{9/2}$	14.618	14.460	30.7	27.1	22.7 ± 0.6	0.062	0.022 ± 0.011

used there only for a description of the IAR spreading width. Methods for evaluating within this approach the main damping parameters of charge-exchange giant monopole resonances in closed-shell and closed-shell + valence-neutron parent nuclei are presented. The methods are realized for the the description of partial proton widths and mixing phases together with the spreading widths for the IARs based on the ^{208,209}Pb parent-nucleus ground state. The calculation results are found in an acceptable agreement with available experimental data. Also, the partial branching ratios for direct one-proton (one-neutron) decay of the IVGMR$^{(-)}$ (IVGMR$^{(+)}$) in the ^{208}Pb parent nucleus are predicted. As applied to other appropriate medium-heavy nuclei, the study presented in this talk is planned to be continued.

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