Dedicated to the 100-th anniversary
of the birth of Academician
Arkady Benedictovich
Migdal

Giant-resonance damping: semimicroscopic description

(methods, results, perspectives)

M.G. Urin

National Research Nuclear University "MEPhI", Moscow, Russia

Collaborators: M.L. Gorelik, S.Yu. Igashov, S.E. Muraviev, V.A. Rodin, V.S. Rykovanov, I.V. Safonov, B.A. Tulupov, and G.A. Chekomazov

1. General remarks

- Being an universal phenomenon, GRs correspond to collective (p-h)-type excitations of low multipolarity (to specific door-way states (DWS)). Different combinations of the DWS quantum numbers (J^{π}, L, S, T, T_3) lead to a wide variaty of GRs.

  A lot of observables (a collection is given by Harakeh and Van der Woude, Oxford, 2001) need for an unified theoretical description. In particular, it's concerned with GR damping.

- GR main relaxation modes:
  (i) distribution of the proper p-h strength (Landau damping) is the result of the nucleus shell structure $\rightarrow \Delta\Gamma$
  (ii) DWS coupling to s-p continuum leads to direct particle decay and related phenomena $\rightarrow \Gamma^{\uparrow}$
  (iii) DWS coupling to many-quasiparticle configurations (mqpc) leads to the spreading effect $\rightarrow \Gamma^{\downarrow}$

Very schematically:

$$\Gamma = \Delta\Gamma + \Gamma^{\uparrow} + \Gamma^{\downarrow}.$$

Actually, an interplay of main relaxation modes, which is changed with increasing of excitation energy, takes place in the GR phenomenon.

- GR main properties:
  (i) gross properties (strength distribution, transition density) are the integral characteristics;
  (ii) direct-decay properties (partial direct-nucleon-decay branching ratios and related phenomena) are the differential characteristics.

2. Theoretical approaches

   RPA-based microscopic and semimicroscopic approaches are the most advanced in description of GR properties (a mean field and p-h interaction are the input quantities).

- Landau damping + s.p. continuum → continuum-RPA (cRPA). Shlomo and Bertsh, NPA'75.
  - No description of the spreading effect and partial particle decays.
- cRPA+DWS coupling with a limited number of 2p-2h states. Kamerdziev et al., Phys. Rep'04.
  - No "termalization" of DWS that leads to interaction of different DWS via 2p-2h states in a contradiction with the statistical assumption.
  - No description of partial particle decays.
- cRPA + a phenomenological treatment of the spreading effect (in spirit of an optical model) → outlined below semimicroscopic description of GR damping. U., NPA'08 (a brief review), PAN'11 (in press).
  - A statistical assumption is supposed to be valid.
  - A method to describe direct particle decays is developed and widely implemented.

1. Standard elements of the cRPA
   - The (local) p.-h. Green function $A(x,x_1;\omega)$ taken in coordinate representation is the basic quantity and satisfies the spectral expansion:

$$A(x,x_1;\omega)=\sum_s\left\{\frac{\rho_s^*(x)\rho_s(x_1)}{\omega-\omega_s+i0}-\frac{\rho_s^*(x_1)\rho_s(x)}{\omega+\omega_s-i0}\right\}.$$

Here, $\omega_s=E_s-E_0$ and $\rho_s(x)=\langle s|\hat{\Psi}^+(x)\hat{\Psi}(x)|0\rangle$ are the excitation energy and transition density, respectively. $\hat{\Psi}^+(x)$ is the s.p. creation operator.

In the continuum region ($\omega>B_N$, B_N — nucleon separation energy)

$$-\frac{1}{\pi}\mathrm{Im}A(x=x_1;\omega)=|\rho(x,\omega)|^2,\qquad \rho(x,\omega)=\rho_s(x)|_{\omega=\omega_s}$$ is the energy-dependent transition density.

- The strength function $S_{V_0}(\omega) = \sum_s |\hat{V}_{s0}|^2 \delta(\omega - \omega_s)$ for a local s.p. external field (probe operator)

  $$\hat{V} = \sum_a V_0(x_a) = \int \hat{\Psi}^+(x) V_0(x) \hat{\Psi}(x) dx \equiv \left[\hat{\Psi} V_0 \hat{\Psi} \right]$$ is

  determined by A:

  $$S_{V_0}(\omega) = -\frac{1}{\pi} \mathrm{Im} \left[V_0^+ [[A V_0]] \right],$$ ([...] means proper integration).

  $$S_{V_0}(\omega) = | \left[V_0^+ \rho(\omega) \right] |^2$$ at $\omega > B_N$.

- The Bethe-Goldstone integral equation for $A(x, x_1; \omega)$ contains within the RPA the p-h interaction $F(x, x_1) \to F(x) \delta(x - x_1)$, which leads to GR formation ($|s\rangle \to |d\rangle$ — DWS w.f.):

  $$A_{RPA}(\omega) = A_0(\omega) + [A_0(\omega) F A_{RPA}(\omega)],$$

  where $A_0(x, x_1; \omega)$ is the free local p-h propagator.

- Alternative formulation of the cRPA in terms of an effective field (effective probe operator) $V(x,\omega)$ defined as $[V_0 A_{RPA}(\omega)] = [V(\omega)A_0(\omega)]$ and satisfying the integral equation:

  $V(\omega) = V_0 + F\,[A_0(\omega)V(\omega)]$, so that

  $S_{V_0}(\omega) = -\frac{1}{\pi}\mathrm{Im}\left[V_0^+\,[A_0(\omega)V(\omega)]\right]$ and

  $\rho(x,\omega) = -\frac{1}{\pi}\mathrm{Im}\,V(x,\omega)/F(x)S_{V_0}^{1/2}(\omega)$.

  This formulation is used within the Migdal's FFST.

- Free p-h propagator $A_0(x, x_1; \omega)$ is determined by a mean field via the bound-state wave functions $\Phi_\mu(x)$, single-particle Green functions $g(x, x_1; \varepsilon = \varepsilon \pm \omega)$, and occupation numbers n_μ with taking the full single-particle basis into account:

$$
\begin{aligned}
A_0(x, x_1; \omega) &= \sum_\mu n_\mu \{\Phi^*_\mu(x)\Phi_\mu(x_1) g(x, x_1; \varepsilon_\mu + \omega) \\
&+ \Phi^*_\mu(x_1)\Phi_\mu(x) g(x_1, x; \varepsilon_\mu - \omega)\};
\end{aligned}
$$

$$(H(x) - \varepsilon_\mu)\Phi_\mu(x) = 0; \qquad (H(x) - \varepsilon) g(x, x_1; \varepsilon) = -\delta(x - x_1);$$

$H(x)$—a single-particle Hamiltonian.

2. Nonstandard elements of the cRPA

- Direct-nucleon-decay probabilities can be described with the use of an alternative expression for $S_V(\omega)$ at $\omega > B_n$:

$$S_{V_0}(\omega) = -\frac{1}{\pi}\mathrm{Im}\left[V^+(\omega)\left[A_0(\omega)V(\omega)\right]\right] = \sum_\mu |M_{V_0,\mu}(\omega)|^2 \rightarrow$$

a kind of the optical theorem.

$M_{V_0,\mu} = n_\mu^{1/2}\left[\psi_{\mu,0}^{(+)}(\omega)V(\omega)\right]$ with $\psi_{\mu,0}^{(+)} = \phi_{\varepsilon=\varepsilon_\mu+\omega}^{(+)}(x)\phi_\mu(x)$ being the free decay-channel wave function and $\phi_{\varepsilon>0}^{(+)}(x)$ being the continuum-state wave function.

$M_{V_0,\mu}$ is the amplitude of a "direct+semidirect" (DSD) nucleon-escape reaction induced by the external field $V_0(x)$.

Partial branching ratio for direct decay from the excitation-energy interval $\delta = \omega_2 – \omega_1$ with population of one-hole state μ^{-1} of the product nucleus is determined as:

$$b_\mu(\delta) = \int_{(\delta)} |M_{V_0,\mu}(\omega)|^2 d\omega / \int_{(\delta)} S_{V_0}(\omega) d\omega.$$

Unitary condition $\sum_\mu b_\mu(\delta) = 1$ is valid independently of δ.

- Alternative description of GR particle decay within the cRPA

  The scattering amplitude $\Gamma(x, x_1; \omega)$ is the basic quantity.
  Definitions $[A(\omega)F] = [A_0(\omega)\Gamma(\omega)]$ and
  $[\Gamma(\omega)\psi^{(+)}_{\mu,0}] = [F\psi^{(+)}_\mu(\omega)]$
  result in equations:
  $\Gamma(\omega) = F + [FA_0(\omega)\Gamma(\omega)]$ and
  $\psi^{(+)}_\mu(\omega) = \psi^{(+)}_{\mu,0} + [A_0(\omega)F\psi^{(+)}_\mu(\omega)]$
  $\psi^{(+)}_\mu(\omega)$—the effective decay-cannel w.f.

Consequences:

(i) DSD-reaction amplitude: $M_{V_0,\mu}(\omega) = [\psi_\mu^{(+)}(\omega)V_0]$;

(ii) S-matrix for nucleon-nucleus scattering:

$$S_{\mu'\mu}(\omega) = S^{pot}_{\mu'\mu}\delta_{\mu'\mu} - 2\pi i\Gamma_{\mu'\mu}(\omega),$$

$$\Gamma_{\mu'\mu}(\omega) = [\psi^{(-)*}_{\mu',0}F\psi^{(+)}_\mu(\omega)];$$

(iii) unitary conditions: $\sum_{\mu'}|S_{\mu'\mu}(\omega)|^2 = 1$, or

$$-\left(\frac{1}{\pi}\right)\mathrm{Im}S^{pot*}_{\mu\mu}\Gamma_{\mu\mu}(\omega) = \sum_{\mu'}|\Gamma_{\mu'\mu}(\omega)|^2;$$

(iv) partial branching ratios:

$$b_{\mu'}(\delta) = \int_{(\delta)}|\Gamma_{\mu'\mu}(\omega)|^2\,d\omega \Big/ \int_{(\delta)}\sum_{\mu''}|\Gamma_{\mu''\mu}(\omega)|^2\,d\omega\,.$$

- "Pole" approximation for the main cRPA quantities is valid for low-energy ("subbarrier") GRs at their maximum. DWS resonances are nonoverlapped ($R_d(\omega) \equiv (\omega - \omega_d + \frac{i}{2}\Gamma^{\uparrow}_{d})^{-1}$):

$$A_{RPA}(x, x_1; \omega) \cong \sum_d \rho^*_d(x)\rho_d(x_1)R_d(\omega);$$

$$S_{V_0}(\omega) \cong -\frac{1}{\pi}\mathrm{Im}\sum_d S_d R_d(\omega);$$

$$V(x, \omega) \cong \sum_d S_d^{1/2} v_d(x)R_d(\omega);$$

$$|M_{V_0,\mu}(\omega)| \cong \frac{1}{\sqrt{2\pi}}\left|\sum_d S_d^{1/2}(\Gamma^{\uparrow}_{d,\mu})^{1/2}R_d(\omega)\right|;$$

$$\Gamma(x, x_1; \omega) \cong \sum_d v^*_d(x)v_d(x_1)R_d(\omega);$$

$$\Gamma_{\mu'\mu}(\omega) \cong \frac{1}{2\pi}\left|\sum_d \left(\Gamma^{\uparrow}_{d,\mu'}\Gamma^{\uparrow}_{d,\mu}\right)^{1/2} R_d(\omega)\right|.$$

Here, $\rho_d(x)$ and $v_d(x) = F(x)\rho_d(x)$ are, respectively, the DWS transition density and transition potential;

$S_d = |[V_0^+ \rho_d]|^2$—the DWS strength;

$\Gamma^{\uparrow}_{d,\mu} = 2\pi n_\mu |[\psi^{(+)}_{\mu,0} v_d]|^2$—the DWS partial width for direct nucleon decay;

$\Gamma^{\uparrow}_d = \sum_\mu \Gamma^{\uparrow}_{d,\mu}$—the total (escape) width;

$b_\mu = \sum_d S_d(\Gamma^{\uparrow}_{d,\mu}/\Gamma^{\uparrow}_d)/\sum_d S_d$—the partial branching ratio.

All these values can be evaluated within the cRPA. For high-energy GRs (DWS resonances are overlapped) only $S_{V_0}(\omega)$, $\rho(x,\omega)$, $\Gamma_{\mu'\mu}(\omega)$, and $b_\mu(\delta)$ can be evaluated.

3. Phenomenological treatment of the spreading effect

- In the "pole" approximation the spreading effect on the energy-averaged GR characteristics can be first taken into account in terms of the DWS spreading width under reasonable statistical assumption:

$$2\pi\langle d'|\hat{H}'|m\rangle\langle m|\hat{H}'|d\rangle\rho_m = \Gamma_d^{\downarrow}\delta_{dd'}.$$

Here ρ_m is the mqps density, $\hat{H}'$ is a "residual" interaction. Thus:

$$R_d(\omega) \to \bar{R}_d(\omega) = (\omega - \omega_d + \frac{i}{2}\Gamma_d^{\uparrow} + \frac{i}{2}\Gamma^{\downarrow}),$$

where $\Gamma^{\downarrow} = \langle\Gamma_d^{\downarrow}\rangle$ is the mean DWS spreading width. As a result, for the energy-averaged quantities $\bar{S}_F(\omega)$, $\bar{M}_V(\omega)$ we get a superimposition of the generally overlapped DWS resonances. The width $\Gamma^{\downarrow}$ is adjusted to reproduce in calculations of $\bar{S}_V(\omega)$ the experimental total width. Then the direct-decay properties (in particular, $\bar{b}_\mu(\delta)$) are described without use of free parameters.

- An alternative way for using the cRPA as a base for taking the spreading effect into account consists in the substitution

$$\omega \to \omega + \frac{i}{2} I(r,\omega)$$

directly in the cRPA equations for energy-averaged quantities $\bar{V}$, $\bar{M}_V$. It means that the ω-dependent single-particle quantities (Green function, $\bar{g}(x, x_1; \varepsilon_\mu \pm \omega)$, continuum-state wave function $\bar{\phi}^{(+)}_{\varepsilon=\varepsilon_\mu+\omega}(x)$) are determined by the single-particle potential having an imaginary part:

$$\left(H(x) - (\varepsilon_\mu \pm \omega \pm \frac{i}{2} I(r,\omega)) \right) \bar{g}(x, x_1; \varepsilon_\mu \pm \omega) = -\delta(x - x_1),$$

$$\left(H(x) - (\varepsilon_\mu + \omega + \frac{i}{2} I(r,\omega)) \right) \bar{\phi}^{(+)}_{\varepsilon_\mu+\omega}(x) = 0.$$

This way allows us to take spreading effect into account in the same manner for low- and high-energy GRs. Actually, we use an effective ω-dependent single-particle optical-model potential.

4. Practical realizations

- Phenomenological Landau-Migdal forces are taken as the p-h interaction ($C = 300$ MeV fm^3):

$$F(x_1, x_2) = C\,\{(f(r_1) + f'\vec{\tau}_1\vec{\tau}_2) + (g + g'\vec{\tau}_1\vec{\tau}_2)\vec{\sigma}_1\vec{\sigma}_2\}\,\delta(\vec{r}_1 - \vec{r}_2).$$

The dimensionless intensities are taken as follows:

(i) the isoscalar strength $f(r)$ — from the translation-invariance conditions (the 1^- spurious state has the zero energy and exhausts almost the total isoscalar dipole EWSR);

(ii) the isovector strength — from the isospin-selfconsistent description of the mean-field isovector part;

(iii) the spin-isovector strength g' — from the experimental Gamow-Teller resonance (GTR) energy;

(iv) the spin-isoscalar strength $g \simeq 0$ wasn't used in implementations of the semimicroscopic approach

- A partially self-consistent phenomenological mean field contains isoscalar, isovector, and Coulomb parts:

$$U(x) = U_0(x) + U_1(x) + U_C(x), \quad \text{with} \quad U_0(x) = U_0(r) + U_{SO}(\vec{r}),$$

$$U_0(r) = -U_0 f_{WS}(r, R, a), \; R = r_0 A^{1/3}, \; U_{SO}(r) = U_{SO} \frac{1}{r} \frac{df_{WS}}{dr} \vec{l}\vec{s},$$

$$U_1(x) = \frac{1}{2} v(r) \tau^{(3)}, \qquad U_C(x) = \frac{1}{2}(1 - \tau^{(3)}) U_C(r).$$

The symmetry potential $v(r) = 2Cf' n^{(-)}(r)$ and the mean Coulomb field are calculated selfconsistently via the neutron-excess density $n^{(-)} = n^n - n^p$ and proton density n^p, respectively. Only five phenomenological parameters (U_0, f', U_{SO}, r_0, a) are used and adjusted to reproduce the experimental single-quasiparticle spectra in doubly-closed-shell nuclei. These parameters determine also the values f^{ex} and f^{in} in the radial dependence of the isoscalar p-h strength $f(r)$.

- The spreading parameter (the imaginary part of an effective optical-model potential) is parameterized similarly to some versions of the single-particle optical model:

$$I(r,\omega) = I(r)I(\omega), \text{ where}$$

$$I_{vol}(r) = f_{WS}(r,R,a), \qquad \text{or} \qquad I_{surf}(r) = -4a\frac{df_{WS}}{dr}.$$

Using the volume "absorption" we revealed the saturation-like energy dependence of $I(r,\omega)$ from description of the experimental total width for different GRs from a wide energy interval:

$$I_{vol}(\omega \geq \Delta) = \alpha_{vol}\frac{(\omega-\Delta)^2}{1+(\omega-\Delta)^2/B^2}, \qquad \text{where}$$

the intensity $\alpha_{vol} \simeq 0.125$ MeV^{-1}, the "gap" parameter $\Delta = 3$ MeV, the "saturation" parameter $B = 7$ MeV. In description of charge-exchange GRs ω is replaced by the excitation energy of the final nucleus $E_x = \omega - Q$.

No adjusted parameters in description of the GR direct decays!

1. Previous results (referred and partially described in U., NPA'08, PAN'11) are related to direct-nucleon-decay properties of various isoscalar ($T = 0$) and isovector ($T = 1$) GRs. the results are mainly concerned with the GRs studied experimentally.
   (i) ISGMR (partial proton widths), ISGDR (partial direct-proton(neutron)-decay branching ratios);
   (ii) charge-exchange ($T_3 = -1$) GRs: GTR (partial proton widths), IVGSDR$^{(-)}$ and IVGSMR$^{(-)}$ (partial direct-proton-decay branching ratios). IAR (partial proton widths have been analysed without taking the isospin-forbidden spreading effect into account);
   (iii) the isovector $T_3 = 0$ GRs: photo-absorption, DSD photo-neutron and inverse reactions accompanied by excitation of the IVGDR and IVGQR, IVGDR2—the overtone of the IVGDR (partial neutron and proton branching ratios).

In the main, satisfactory description of the available experimental data has been obtained. Some results are under revision due to the necessity to satisfy the experimental conditions known later and/or to improve the methods.

2. New results

2.1 "Coulomb" description of the main relaxation parameters of the IAR and $\mathrm{IVSGMR}^{(-)}$ (IAR overtone). Gorelik, Rykovanov, U., PAN'10.

- The IAR properties are closely related to the isospin SU(2)-symmetry in nuclei. This symmetry is weakly broken mainly by the mean Coulomb field $U_C(r)$. To avoid spurious contributions, we describe the main relaxation parameters of IAR (and also of $\mathrm{IVGMR}^{(-)}$) in terms of U_C.

- Starting relationship

$$[\hat{H}, \hat{\mathcal{T}}^{(-)}] = \hat{U}_C^{(-)} \quad (\hat{\mathcal{T}}^{(-)} = \sum_a \tau_a^{(-)}, \quad \hat{U}_C^{(-)} = \sum_a U(r_a)\tau_a^{(-)}),$$

which is valid within the RPA under the afore-mentioned self-consistency condition $v(r) = 2F' n^{(-)}(r)$, allows to get the basic equation:

$$S_F(\omega) = \frac{S_C^{(-)}(\omega)}{|\omega - \Delta_C|^2}.$$

Here, $S_F(\omega)$ is the Fermi strength function corresponding to $V_{F,0}(x) = \tau^{(-)}$; $S_C^{(-)}(\omega)$ is the Coulomb strength function corresponding to $V_{C,0}^{(-)}(x) = V_C(r)\tau^{(-)}$, where $V_C(r) = U_C(r) - \Delta_C$ is the "variable" part of U_C.

Being also valid for the energy-averaged quantities, the basic equation can be parametrized as (experiment!):

$$\bar{S}_F(\omega) = \frac{1}{2\pi} \frac{S_A \Gamma_A}{(\omega - \omega_A)^2 + \frac{1}{4}\Gamma_A^2}$$

with $S_A \simeq (N - Z)$, ω_A, and $\Gamma_A = \Gamma_A^{\downarrow} + \bar{\Gamma}_A^{\uparrow}$ being, respectively, the IAR Fermi strength, energy, and total width.
From comparison of the above equations we get:

$$\Delta_C = \omega - \frac{i}{2}\Gamma_A, \quad \text{and} \quad \Gamma_A = 2\pi S_A^{-1} \bar{S}_C^{(-)}(\omega = \omega_A).$$

The nonlinear equation for Γ_A (!) can be solved provided the ω_A and S_A values are found from cRPA description of $S_F(\omega)$.
Very schematically: $\Gamma_A = \beta_{MA}^2 \Gamma_M(\omega = \omega_A)$, where $\Gamma_M(\omega)$ is the IVSGMR$^{(-)}$ total width, β_{MA} is the amplitude of the Coulomb mixing $T_>$-IAR and $T_<$-IVGMR$^{(-)}$.

- Within the approach (Section 2) the IAR partial width for direct proton decay into the neutron one-hole state μ^{-1} of the product nucleus is determined by the "reaction amplitude" $\bar{M}_{V_C^{(-)},\mu}(\omega)$:

  $\bar{\Gamma}^{\uparrow}_{A,\mu} = 2\pi S_A^{-1} |\bar{M}_{V_C^{(-)},\mu}(\omega = \omega_A)|^2, \qquad \bar{M}_{V_C^{(-)},\mu} = n_\mu^{1/2}[\bar{\psi}^{(+)}_{\mu,0} \bar{V}_C^{(-)}].$

  Finally, the calculated spreading width

  $$\Gamma_A^{\downarrow} = \Gamma_A - \sum_\mu \bar{\Gamma}^{\uparrow}_{A,\mu}$$

  (tends to zero without "absorption") and the reduced partial proton widths

  $$\check{\bar{\Gamma}}^{\uparrow}_{A,\mu} = S_\mu \bar{\Gamma}^{\uparrow}_{A,\mu} P\mu(\varepsilon^{exp})/P\mu(\varepsilon = \varepsilon_\mu + \omega_A)$$

  (S_μ — the spectroscopic factor of the μ^{-1} state, $P_\mu(\varepsilon)$ — potential-barrier penetrability for protons) can be compared with the corresponding experimental data (Table 2).

- The Coulomb strength function $\bar{S}^{(-)}_{V_C}(\omega)$ exhibits an almost "single-level" resonance corresponding to the IVGMR$^{(-)}$ (Fig. 1). Only one specific parameter α_S (taken to describe the experimental IVGMR$^{(-)}$ total width) is used for description of the IAR and IVGMR$^{(\mp)}$ main relaxation modes. The contribution of the spreading effect in formation of the high-energy IVGMR$^{(-)}$ is relatively low (Fig. 1). It leads to the large (about 0.5) total direct-proton-decay branching ratio for this GR.

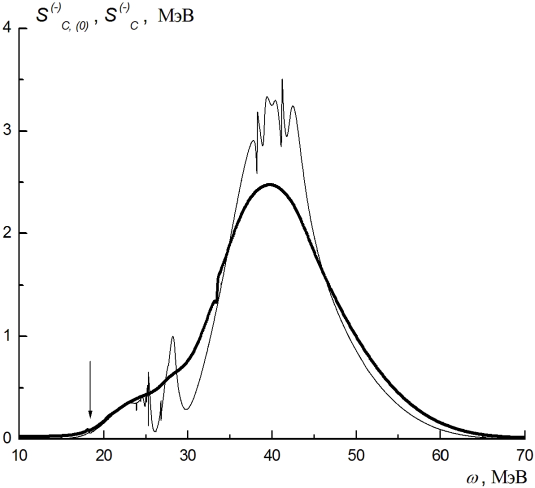

Figure 1

Table 1. The calculated and experimental IVGMR$^{(\mp)}$ parameters

Nucleus	$\omega^{(-)}_{M,\,exp}$	$\omega^{(-)}_{M}$	$\Gamma^{(-)}_{M,\,exp}$	$\Gamma^{(-)}_{M}$	α_S	$b^{(-)}_{tot}$
^{90}Zr	34.6±2.9	36.6	18.9±4.1	18.8	0.06	73
^{140}Ce	35.4±3.5	37.8	16.6±4.2	18.6	0.11	41
^{208}Pb	37.2±3.5	39.7	15.0±6.0	15.8	0.09	51
	(MeV)	(MeV)	(MeV)	(MeV)	(MeV^{-1})	(%)

Nucleus	$\omega^{(+)}_{M,\,exp}$	$\omega^{(+)}_{M}$	$\Gamma^{(+)}_{M,\,exp}$	$\Gamma^{(+)}_{M}$
^{90}Zr	22.0±2.0	19.8	15.0±2.1	8.0
^{140}Ce	19.9±2.4	17.3	8.5±4.5	8.0
^{208}Pb	12.2±2.8	14.4	11.6±7.1	3.4
	(MeV)	(MeV)	(MeV)	(MeV)

Table 2. The calculated and experimental IAR-decay parameters

ν, ^{207}Pb	$S_{\nu,\,exp}$	ε_{exp}	$\varepsilon_\nu + \omega_A$	$\Gamma^\uparrow_{A,\,\nu,\,exp}$	$\check{\Gamma}^\uparrow_{A,\,\nu}$	$\Gamma^\downarrow_{A,\,exp}$	$\Gamma^\downarrow_A$
$3p_{1/2}$	1.0	11.46	11.12	51.9±1.6	51.5		
$2f_{5/2}$	0.98	10.91	10.35	26.4±2	17.7	78±8	71
$3p_{3/2}$	1.0	10.59	9.89	64.7±3.4	64.0		
$2f_{7/2}$	0.7	9.15	7.26	4.2±0.6	3.1		
		(MeV)	(MeV)	(keV)	(keV)	(keV)	(keV)

Nucl.	ν	$S_{\nu,\,exp}$	ε_{exp}	ε	$\Gamma^\uparrow_{A,\,\nu,\,exp}$	$\check{\Gamma}^\uparrow_{A,\,\nu}$	$\Gamma^\downarrow_{A,\,exp}$	$\Gamma^\downarrow_A$
^{91}Zr	$2d_{5/2}$	0.89	4.67	4.20	4.0±0.5	0.93	20±2	21.6
^{141}Ce	$2f_{7/2}$	0.80	9.68	9.55	11±1	11.9	51±4	47.7
^{209}Pb	$2g_{9/2}$	0.78	14.83	14.06	22.7±0.6	20.3	75±7	84.5
			(MeV)	(MeV)	(keV)	(keV)	(keV)	(keV)

2.2 Particle decay of the IVGSMR$^{(\mp)}$. Safonov, U., Bull. RAS. (phys), '09.

- In accordance with the p-h structure, the GTR and IVGSMR$^{(-)}$ are the spin-flip partners of the IAR and IVGMR$^{(-)}$, respectively.
- In connection with the rather unexpected experimental data (Zegers et al., PLB'03), we (i) slightly revised previous calculations of the partial direct-proton-decay branching ratios for the IVGSMR$^{(-)}$ (Tables 3,4), (ii) evaluated the partial direct-neutron-decay branching ratios for the IVGSMR$^{(+)}$ (Table 4).
- Results: (i) a contradiction with the experimental data of Zegers et al. concerned with the partial (not total) direct-proton-decay branching ratios for the IVGSMR$^{(-)}$ in ^{208}Bi still remains; (ii) found in calculations a large total direct-neutron-decay branching ratios for the IVGSMR$^{(+)}$ can be apparently observed (Harakeh, private communication).

Table 3. Calculated partial branching ratios (in %) for the direct proton decay of the IVGSMR$^{(-)}$ in ^{208}Bi. The results are given for the decays from the excitation-energy range $E_x \simeq$ 31–50 MeV. The experimental data are taken from Zegers et al., PLB'03

μ^{-1}	$3p_{1/2}$	$2f_{5/2}$	$3p_{3/2}$	$1i_{13/2}$	$2f_{7/2}$	$1h_{9/2}$	$1h_{11/2}$
b_μ^{theor}	1.44	3.93	3.22	16.37	6.97	4.33	8.85
b_μ^{exp}					13 ± 5		22 ± 8
μ^{-1}	$3s_{1/2}$	$2d_{3/2}$	$2d_{5/2}$	$1g_{7/2}$	$1g_{9/2}$		$\sum b_\mu$
b_μ^{theor}	1.16	1.77	3.55	2.02	4.01		54.62
b_μ^{exp}				17 ± 8			52 ± 12

Table 4. Calculated partial branching ratios (in %) for the direct neutron decay of the IVGSMR$^{(+)}$ in ^{208}Tl. The results are for the decays from the excitation-energy range $E_x \simeq$ 9–14 MeV.

μ^{-1}	$3s_{1/2}$	$2d_{3/2}$	$1h_{11/2}$	$2d_{5/2}$	$1g_{7/2}$	$1g_{9/2}$	$2p_{1/2}$	$2p_{3/2}$	$\sum b_\mu$
b_μ	1.49	2.66	32.82	4.76	3.26	0.80	0.14	0.13	46.06

2.3 Photoabsorption and DSD neutron radiative capture cross sections. Tulupov, U., EMIN-2009 (Moscow), ICNP-2010.

An unified semimicroscopic description of these quantities in the IVGDR region is possible . Because the p-h interaction isovector strength f' is fixed, we add the isovector (separable) momentum-dependent forces

$$F_{m-d}(x_1, x_2) = \frac{1}{mA} k'(\vec{\tau}_1 \vec{\tau}_2)(\vec{p}_1 \vec{p}_2)$$

to reproduce in calculations of the photoabsorption cross section $\sigma_a(\omega)$ the experimental IVGDR energy.

$$\sigma_a(\omega) = \frac{16\pi^3}{3} \frac{e^2}{\hbar c} \omega S_{V_0^{(3)}}(\omega), \qquad V_0^{(3)}(x) = -\frac{1}{2}\tau^{(3)} r Y_1.$$

In such a case $\sigma_a^{int} = (\sigma_a^{int})_{TRK}(1 + k')$. The "absorption" intensity is adjusted to describe the $\sigma_a^{exp}(\omega)$ shape line (Fig. 2). The partial DSD $(n\gamma)$-reaction cross sections, calculated without the use of free parameters (Fig. 3), are in satisfactory agreement with the corresponding experimental data.

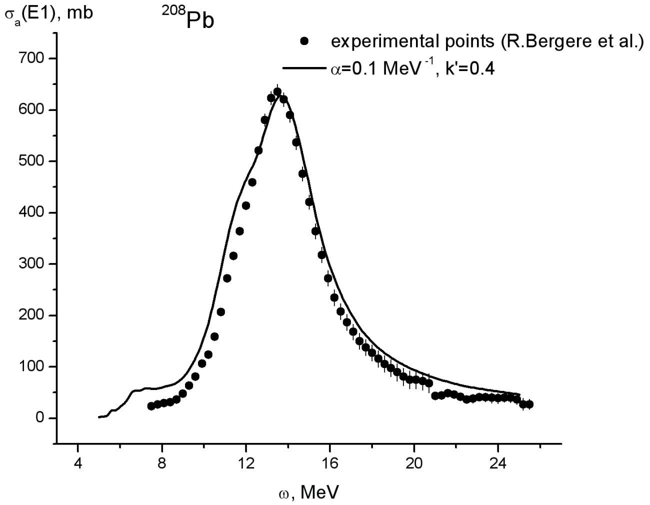
σa(E1), mb
208Pb
experimental points (R.Bergere et al.)
α=0.1 MeV -1, k'=0.4
700
600
500
400
300
200
100
0
4
8
12
16
20
24
ω, MeV

Figure 2

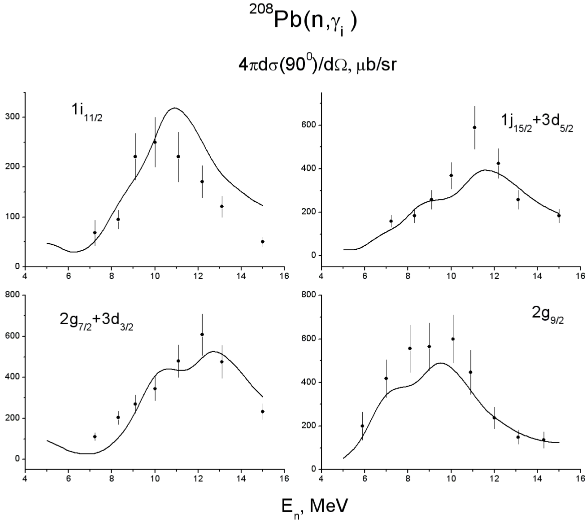
208Pb(n,γi)
4πdσ(90⁰)/dΩ, μb/sr
1i11/2
1j15/2+3d5/2
2g7/2+3d3/2
2g9/2
En, MeV

Figure 3

1. P-h optical model for phenomenological description of the spreading effect on (p-h)-type excitations at arbitrary (but high enough) excitation energies. U., PAN, '10; arXiv: 1005.2349v2 [nucl-th], PAN'11 (in press).

   - The shortcomings of the "$\omega + \frac{i}{2}I$" method. It is (i) physically clear but not-well-grounded enough; (ii) valid in the "pole" approximation, i.e. only in the GR energy region (in implementations far low- and/or high-energy "tails" are the subject of interest).
   - An analogy with formulation of the single-particle optical model has been used in formulation of the p-h optical model. Below we consider the basic equations and ways for practical realization of the model.

- The basic quantity is the p-h nonlocal Green function $\mathcal{A}(x,x';x_1,x_1';\omega)$, whose spectral expansion is similar to the afore-shown expansion for the local Green function $A(x,x_1;\omega)=\mathcal{A}(x=x';x_1=x_1';\omega)$:

$$\mathcal{A}(x,x';x_1,x_1';\omega)=\sum_s\left\{\frac{\rho_s^*(x,x')\rho_s(x_1,x_1')}{\omega-\omega_s+i0}-\frac{\rho_s^*(x_1,x_1')\rho_s(x,x')}{\omega+\omega_s-i0}\right\}$$

with $\rho_s(x,x')=\langle s|\hat{\Psi}^+(x)\Psi(x')|0\rangle$ being the transition matrix density. This specific feature of $\mathcal{A}$ allows us to realize the statistical assumption in description of the spreading effect.

- The strength function for a (nonlocal) external field $\mathcal{V}_0(x,x')$:

$$S_{\mathcal{V}_0}(\omega)=-\frac{1}{\pi}\mathrm{Im}[\mathcal{V}_0^+\mathcal{A}(\omega)\mathcal{V}_0].$$

- Specific quantities
  (i) the free p-h nonlocal Green function $\mathcal{A}_0$ is determined by a mean field:

$$\omega_s \to \omega_s^{(0)} = \varepsilon_\nu - \varepsilon_\lambda,\ \rho_s \to \rho_s^{(0)} = \phi_\nu^*(x)\phi_\lambda(x'), [\rho_s^{(0)*}, \rho_{s'}^{(0)}] = \delta_{ss'}(!);$$

  (ii) the RPA nonlocal Green function $\mathcal{A}_{RPA}$ is determined also by a (nonlocal) p-h interaction $\mathcal{F}(x, x'; x_1, x_1')$:

$$\mathcal{A}_{RPA}(\omega) = \mathcal{A}_0(\omega) + [\mathcal{A}_0(\omega)\mathcal{F}\mathcal{A}_{RPA}(\omega)],$$

  within the discrete RPA (dRPA):

$$\omega_s \to \omega_d, \quad \rho_s \to \rho_d, \quad [\rho_d^*, \rho_d] \simeq \delta_{dd'};$$

  (iii) the local p-h Green function A (Sect. 2.1) is determined by a local p-h interaction:

$$\mathcal{F}(x, x'; x_1, x_1') \to F(x, x_1)\delta(x - x')\delta(x_1 - x_1').$$

- An additional p-h interaction $\mathcal{T}(x,x';x_1,x_1';\omega)$ takes place due to DWS coupling to mqps. Having high-density poles corresponding to virtual excitations of mpqs, $\mathcal{T}$ is a sharp function of ω and, therefore, only the energy-averaged quantity $\bar{\mathcal{T}}(\omega) = \mathcal{T}(\omega + iJ)$ $(J \gg \rho_m^{-1})$ can be reasonably parametrized:

$$\bar{\mathcal{T}}(x,x',x_1,x_1';\omega) = \{-i\mathcal{W}(x,x';\omega) + \mathcal{P}(x,x'\omega)\}\,\delta(x-x_1)\delta(x'-x_1').$$

  The δ-functions here are due to a large ($\sim p_F$) momentum transfer at "decay" DWS to mqps.

- P-h optical-model basic equations

$$\bar{A}(\omega) = \mathcal{A}_{RPA}(\omega) + [\mathcal{A}_{RPA}(\omega)\bar{\mathcal{T}}(\omega)\bar{A}(\omega)] \quad \text{or}$$

$$\bar{A}(\omega) = \mathcal{A}_0(\omega) + [\mathcal{A}_0(\omega)(\mathcal{F} + \bar{\mathcal{T}}(\omega))\bar{A}(\omega)],$$

$$\bar{S}_{\mathcal{V}_0}(\omega) = -\frac{1}{\pi}\mathrm{Im}[\mathcal{V}_0^+\bar{A}(\omega)\mathcal{V}_0]$$

  can be formally solved, using a phenomenological value of $\mathcal{W}(\omega)$. $\mathcal{P}(\omega)$ is determined by $\mathcal{W}(\omega)$ via a proper dispersive relationship (Sect. 4.2).

- The statistical assumption can be simply realized, considering "the dRPA+"pole" approximation" as an example. This assumption is valid under the conditions:
  - (i) $\bar{\bar{\pi}}$ is nearly constant within the nucleus volume, i.e.

$$-i\mathcal{W}(x,x';\omega)+\mathcal{P}(x,x';\omega)\to -i\mathcal{W}(\omega)+\mathcal{P}(\omega),$$

  - (ii) dRPA transition matrix densities $\rho_d(x,x')$ are orthonormalized. In such a case, the solution of the B.-G. eq. is:

$$\bar{\mathcal{A}}(\omega)=\mathcal{A}_{RPA}(\omega+i\mathcal{W}(\omega)-\mathcal{P}(\omega)),$$

and the strength function is a superimposition of DWS resonances:

$$\bar{S}_{\mathcal{V}_0}(\omega)=-\frac{1}{\pi}\mathrm{Im}\sum_d |[\mathcal{V}_0^+\rho_d]|^2(\omega-\omega_d+i\mathcal{W}(\omega)-\mathcal{P}(\omega))^{-1}.$$

- The alternative presentation of the basic eqs. (corresponds to "the model of interacting and damping quasiparticles"):

$$\bar{\mathcal{A}}(\omega) = \bar{\mathcal{A}}_0(\omega) + \left[\bar{\mathcal{A}}_0(\omega)\mathcal{F}\bar{\mathcal{A}}(\omega)\right], \qquad \text{where}$$

$$\bar{\mathcal{A}}_0(\omega) = \mathcal{A}_0(\omega) + \left[\mathcal{A}_0(\omega)\bar{\bar{\pi}}(\omega)\bar{\mathcal{A}}_0(\omega)\right].$$

The solution of the last eq.:

$$\bar{\mathcal{A}}_0(x,x';x_1,x_1';\omega) = \sum_{\nu\lambda}\phi_\nu(x)\phi^*_\lambda(x')\phi_\lambda(x_1')\phi^*_\nu(x_1)\bar{A}_{\nu\lambda}(\omega), \text{ where}$$

$$\bar{A}_{\nu\lambda}(\omega) = \frac{n_\nu - n_\lambda}{\varepsilon_\nu - \varepsilon_\lambda - \omega + (n_\nu - n_\lambda)(i\mathcal{W}(\omega) - \mathcal{P}(\omega))\mathcal{W}_{\nu\nu,\lambda\lambda}},$$

$$\mathcal{W}_{\nu\nu,\lambda\lambda}\delta_{\nu\nu'}\delta_{\lambda\lambda'} \simeq \int \phi^*_\nu(x)\phi_{\nu'}(x)\mathcal{W}(x,x')\phi_\lambda(x')\phi^*_{\lambda'}(x')dxdx' \rightarrow$$

$$\rightarrow \text{statistical assumption (!)}, \qquad \left(\rho_s^{(0)}(x,x') = \bar{\rho}_s^{(0)}(x,x')\right).$$

$$\mathcal{W}(x,x') \rightarrow f_{WS}(r)f_{WS}(r'), \quad (f_{WS})_{\mu\mu} \equiv f_\mu, \quad \mathcal{W}_{\nu\nu,\lambda\lambda} = f_\nu f_\lambda.$$

After coming to the local limit, i.e.

$$\bar{\mathcal{A}}_0(\omega) \to \bar{A}_0(\omega), \quad \bar{\mathcal{A}}(\omega) \to \bar{A}(\omega), \quad \mathcal{F} \to F, \quad S_{\mathcal{V}_0}(\omega) \to S_{V_0}(\omega),$$

we get the modified dRPA eqs. (with taking the spreading effect into account) which are valid at an arbitrary (but high enough) excitation energy.

- Two-level model

$$\varepsilon_1 > \varepsilon_2, \quad R_{1,2}(r), \quad j_1 \simeq j_2 = \frac{1}{2}\Omega \gg 1, L \ll \Omega.$$

$$S_{V_0}(\omega) = -\frac{1}{\pi}\mathrm{Im} S_d^L \left\{ \frac{1}{\omega - \omega_d + \frac{i}{2}\Gamma_d^{\downarrow}(\omega)} - \frac{1}{\omega + \omega_d - \frac{i}{2}\Gamma_d^{\downarrow}(\omega)} \right\}$$

DWS energy, $\omega_d = \varepsilon_1 - \varepsilon_2 + F\Omega[R_1^2 R_2^2]$, strength, $S_d^L = [R_1 V_0^L R_2]^2$, spreading width: $\Gamma_d^{\downarrow}(\omega) = 2\mathcal{W}(\omega) f_1 f_2$

- From dRPA to cRPA

$$\sum_{\lambda} \frac{\phi_\lambda(x)\phi^*_\lambda(x_1)}{\varepsilon_\lambda - \varepsilon_\mu - \omega + i\mathcal{W}(\omega) f_\mu f_\lambda} \simeq \bar{g}(x, x_1; \varepsilon_\mu + \omega),$$

$$\{h(x) - (\varepsilon_\mu + \omega - i\mathcal{W}(\omega) f_\mu f_{WS}(r))\}\, \bar{g}(x, x_1; \varepsilon_\mu + \omega) = -\delta(x - x_1).$$

$$\sum_{\mu} \frac{\phi_\mu(x_1)\phi^*_\mu(x)}{\varepsilon_\lambda - \varepsilon_\mu - \omega + i\mathcal{W}(\omega) f_\lambda f_\mu} \simeq \bar{g}(x_1, x; \varepsilon_\lambda - \omega),$$

$$\{h(x_1) - (\varepsilon_\lambda - \omega + i\mathcal{W}(\omega) f_\lambda f_{WS}(r_1))\}\, \bar{g}(x_1, x; \varepsilon_\lambda - \omega) = -\delta(x_1 - x).$$

$$\bar{g} \sim \bar{\chi}^{reg} \cdot \bar{\chi}^{ir}$$

The cRPA basic quantity $\bar{A}_0(x,x_1;\omega)$ that takes the full p-h basis into account:

$$\begin{aligned}\bar{A}_0(x,x_1;\omega) &= \sum_{\mu} n_\mu \phi^*_\mu(x)\phi_\mu(x_1)\bar{g}(x,x_1;\varepsilon_\mu+\omega) + \\ &+ \sum_{\lambda} n_\lambda \phi^*_\lambda(x_1)\phi_\lambda(x)\bar{g}(x_1,x;\varepsilon_\lambda-\omega) + \\ &+ \sum_{\mu\lambda} n_\mu n_\lambda \phi^*_\mu(x)\phi_\mu(x_1)\phi^*_\lambda(x_1)\phi_\lambda(x)\cdot \\ &\cdot \frac{2i\mathcal{W}(\omega)f_\lambda f_\mu}{(\varepsilon_\lambda-\varepsilon_\mu+\omega)^2+\mathcal{W}^2(\omega)f^2_\mu f^2_\lambda}.\end{aligned}$$

Def.: $[\bar{\mathcal{A}}(\omega)\mathcal{V}_0] = [\bar{\mathcal{A}}_0(\omega)\bar{\mathcal{V}}(\omega)] \to \bar{\mathcal{V}}(\omega) = \mathcal{V}_0 + [\mathcal{F}\bar{\mathcal{A}}_0(\omega)\bar{\mathcal{V}}(\omega)]$;

$$\bar{S}_{\mathcal{V}_0}(\omega) = -\frac{1}{\pi}\mathrm{Im}[\mathcal{V}^+_0\bar{\mathcal{A}}(\omega)\mathcal{V}_0] = -\frac{1}{\pi}\mathrm{Im}[\mathcal{V}^+_0\bar{\mathcal{A}}_0(\omega)\bar{\mathcal{V}}(\omega)];$$

- Nucleon-nucleus resonance scattering and DSD-reactions

Def.:$[\mathcal{A}(\mathcal{F}+\mathcal{T})] = [\mathcal{A}_0\mathcal{G}], \mathcal{G}(\omega)$—nonlocal scattering amplitude;

$\psi^{(\pm)}_{\mu,0}(\omega) = \phi^{(\pm)}_{\varepsilon=\varepsilon_\mu+\omega}(x)\phi_\mu(x_1)$—nonlocal free decay-channel w.f.;

$\mathcal{G}_{\mu',\mu}(\omega) = [\psi^{(-)*}_{\mu',0}\mathcal{G}\psi^{(+)}_{\mu,0}]$—resonance-scattering matrix elements.

Def.:$[\mathcal{G}\psi^{(+)}_{\mu,0}] = [(\mathcal{F}+\mathcal{T})\psi^{(+)}_\mu], \quad \psi^{(+)}_\mu(\omega)$—effective d.-ch. w.f.

Basic eqs.:$\bar{\psi}^{(+)}_\mu = \bar{\psi}^{(+)}_{\mu,0} + [\bar{\mathcal{A}}_0\mathcal{F}\bar{\psi}^{(+)}_\mu] \to \bar{\psi}^{(+)} = \bar{\psi}^{(+)}_0[1-\bar{\mathcal{A}}_0\mathcal{F}]^{-1}$,

$\bar{\psi}^{(+)}_{\mu,0} = \psi^{(+)}_{\mu,0} + [\mathcal{A}_0\bar{\mathcal{T}}\bar{\psi}^{(+)}_{\mu,0}], \quad \bar{\psi}^{(+)}_{\mu,0} = \bar{\phi}^{(+)}_{\varepsilon=\varepsilon_\mu+\omega}(x)\phi_\mu(x_1)$—mean free w.f.

$$\{h(x) - (\varepsilon_\mu + \omega + i\mathcal{W}(\omega)f_\mu f_{WS}(r))\}\bar{\phi}^{(+)}_{\varepsilon=\varepsilon_\mu+\omega}(x) = 0.$$

$$\bar{M}_{\mathcal{V}_0,\mu}(\omega) = [\bar{\psi}^{(+)}_{\mu}, \mathcal{V}_0] = [\bar{\psi}^{(+)}_{\mu,0}\bar{\mathcal{V}}].$$

Local-limit basic relationships:

$$\bar{V}(\omega) = V_0 + [F\bar{A}_0(\omega)\bar{V}(\omega)],$$

$$\bar{S}_{V_0}(\omega) = -\frac{1}{\pi}\mathrm{Im}[V_0^+\bar{A}_0(\omega)\bar{V}(\omega)], \;\; \bar{M}_{V_0,\mu}(\omega) = [\bar{\psi}^{(+)}_{\mu,0}\bar{V}(\omega)].$$

- Consequences:

  (i) a semimicroscopic model for description of the main relaxation modes of high-energy (p-h)-type excitations is proposed and formulated for practical implementations;

  (ii) a confirmation is obtained for the "$\omega + \frac{i}{2}I$" method of evaluation of the GR main relaxation parameters.

2. The GR energy shift due to the spreading effect.
Tulupov, U., PAN, '09.
The analytical properties of $\mathcal{A}$ and $\mathcal{T}$ are similar and the latter can be presented in the form: $\mathcal{T}(\omega) = \mathcal{T}'(\omega) - \mathcal{T}'(0)$ with

$$\mathcal{T}'(x, x'; x_1, x_1'; \omega) = \sum_m \left\{ \frac{v_m^*(x', x) v_m(x_1, x_1')}{\omega - \omega_m + i0} - \frac{v_m^*(x_1, x_1') v_m(x, x')}{\omega + \omega_m - i0} \right\}.$$

Here $v_m(x, x')$ is the transition matrix potential for a mqps $|m\rangle$, and $\mathcal{T}(\omega = 0) = 0$.
Supposing the energy-averaged quantities $\mathrm{Im}\bar{\mathcal{T}}(\omega)$ and $\mathrm{Re}\bar{\mathcal{T}}(\omega)$ can be factorized, i.e.
$\bar{\mathcal{T}}(x, x'; x_1, x_1'; \omega) = \mathcal{W}(x, x')(-i\mathcal{W}(\omega) + \mathcal{P}(\omega))\delta(x - x_1)\delta(x' - x_1')$,
one can get the dispersive relationship for $\mathcal{P}(\omega)$:

$$\mathcal{P}(\omega) = \frac{2}{\pi} P.V. \int_0^\infty \mathcal{W}(\omega') \frac{\omega^2}{(\omega^2 - \omega'^2)\omega'} d\omega',$$

which formally takes the full basis of mpqs into account. For the saturation-like energy dependence of $\mathcal{W}(\omega)$ taken in the simplest form: $\mathcal{W}(\omega) = \frac{1}{2}\alpha\omega^2(1 + \omega^2/B^2)^{-1}$ ones get:

$$\mathcal{P}(\omega) = \frac{\alpha}{\pi} \frac{B^2\omega^2}{B^2 + \omega^2} \ln \frac{\omega}{B}.$$

The analytical expression can be also obtained for the dependence $\mathcal{W}(\omega) = \frac{1}{2} I(\omega)$ used within the "$\omega + \frac{i}{2} I(\omega)$" method (Sect. 2.4). In such a case the method is transformed in the "$\omega + \frac{i}{2} I(\omega) - \mathcal{P}(\omega)$" one. This transformation leads to the GR energy shift,which is about 1.5–2.0 MeV for high-energy GRs.

- A semimicroscopic approach to description of giant-resonance damping is presented. The basic points of the approach are the continuum-RPA and the phenomenological treatment of the spreading effect directly in the cRPA equations in terms of an effective s.p. optical-model potential. The main advantage of the approach is the possibility to describe direct-decay properties and related phenomena for various GRs. The approach is realized in many implementations with the use of the Landau-Migdal particle-hole interaction and phenomenological partially selfconsistent mean field.

- An attempt is undertaken to take phenomenologically the spreading effect into account within a RPA-based particle-hole optical model for arbitrary (but high enough) excitation energies. The model is formulated for practical implementations to describe the main relaxation parameters of high-energy particle-hole-type excitations.

Many thanks for attention!