PARTICLE-HOLE DISPERSIVE OPTICAL MODEL: UNIQUE FEATURES AND RECENT IMPLEMENTATIONS

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Dedicated to the memory of Eduard E. Saperstein

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Outline

PARTICLE-HOLE DISPERSIVE OPTICAL MODEL (PHDOM)

I. Physical content and unique features
II. Lines of formulation
III. Recent implementations
IV. Conclusive remarks

I. Physical content

1.1 Aims and terminology

- The PHDOM was initially formulated to describe in a semi-microscopic way together the structure and damping of a great variety of high-energy (p-h)-type excitations (including giant resonances (GRs)) in medium-heavy closed-shell nuclei.
- The term “PHDOM” appears in view of similarity of microscopically-based formulations of the PHDOM and single-quasiparticle dispersive optical model (SQDOM). Both models are formulated in terms of the energy-averaged s-q and p-h Fermi-system Green functions (GFs), which obey, respectively, to the Dyson- and Bethe-Goldstone-type equations, having the respective self-energy term (U., PRC`13, EPJ WoC`18)

1.2 Relaxation modes

Within the model the main relaxation modes of mentioned excitations are together taken into account. These modes are:

i. distribution of the p-h strength, or Landau damping (a result of shell structure of nuclei);

ii. coupling (p-h)-type states to the single-particle (s-p) continuum (nuclei are open Fermi-systems);

iii. coupling (p-h)-type states to many-quasiparticle (chaotic) configurations, or the spreading effect (high excitation energy).

1.3 Physical content

- The PHDOM is a semi-microscopic model, in which Landau damping and coupling (p-h)-type states to the s-p continuum are described microscopically (in terms of a mean field and p-h interaction responsible for long-range correlations), while the spreading effect is treated phenomenologically and in average over the energy (in terms of the specific p-h interaction, or the respective p-h self-energy term).
- The PHDOM can be called as “the model of interacting independently damping quasiparticles”.

1.4 Unique features

The unique features of the PHDOM are concerned with its ability to describe:

i. the energy-averaged double transition density and, therefore, various strength functions at arbitrary (but high-enough) excitation energy;

ii. direct one-nucleon decays of (p-h)-type states, including the direct + semi-direct (DSD) reactions induced by a s-p external field;

iii. the spreading (dispersive) shift of the energy of resonance-like structures related to (p-h)-type states.

II. Lines of formulation (schematically)

2.1 Continuum-RPA

- The PHDOM is a microscopically-based extension of the continuum-RPA (cRPA) versions on taking into account the spreading effect. The standard cRPA version (Shlomo, Bertsch, NPA`75) is formulated in terms the p-h Green function (GF), $A^{cRPA}(x, x', \omega)$ (ω is the excitation energy), which obeys the Bethe-Goldstone-type equation and determines the strength function, $S_{V_0}^{cRPA}(\omega)$, related to a s-p external field $V_0(x)$:

$$A^{cRPA} = A_0^{cRPA} + A_0^{cRPA} F A^{cRPA}; S_{V_0}^{cRPA}(\omega) = -\frac{1}{\pi} \mathrm{Im}\, V_0^{+} A^{cRPA} V_0.$$

Here, A_0^{cRPA} is the free propagator, $F(x, x')$ is the p-h interaction responsible for long-range correlations (e.g. for formation of GRs).

- Formulation of A_0^{cRPA} in terms of GFs of the s-p Schrodinger equation allows one to take exactly the s-p continuum into account. The non-standard cRPA version (U., NPA`08) is formulated in terms of the effective field $V(x,\omega)$, which is defined by the integral relationship, $A^{cRPA}V_0 = A_0^{cRPA}V$, and obeys the well-known integral equation:

$$V = V_0 + FA_0^{cRPA}V.$$

- In the continuum region, the strength function can be expressed in terms of the squared DSD-reaction amplitudes, or partial one-nucleon-escape strength functions:

$$S_{V_0}^{cRPA} = -\frac{1}{\pi}\mathrm{Im}\, V^{+} A^{cRPA}\, V = \sum_c \left| M_{V_0,c}^{DSD,cRPA} \right|^2 \equiv \sum_c S_{V_0,c}^{cRPA,\uparrow}.$$

The amplitudes are proportional to the effective-field matrix elements taken between the bound and continuum s-p states (c is the set of decay-channel quantum numbers).

2.2 Discrete PHDOM version

- Similarly to the ordinary (single-quasiparticle) optical model (formulated by energy averaging the Dyson equation for the single-quasiparticle GF), the PHDOM is formulated by energy averaging the Bethe-Goldstone-type equation for the (generally, non-local) p-h GF $A(x, x_1, x', x'_1, \omega)$. Along with the interaction $F(x, x')$, the equation for A contains a specific p-h interaction (the energy-averaged p-h self-energy term $\Pi(x, x_1, x', x'_1, \omega)$ responsible for the spreading effect):

$$A = A_0 + A_0 F A; \quad A_0 = A_0^{RPA} + A_0^{RPA} \Pi A_0.$$

Here, the auxiliary quantity A_0 is the “free” p-h propagator.

The phenomenological quantity Π is properly parameterized to satisfy the statistical assumption: after energy averaging different p-h configurations (with the same quantum numbers) are "decaying" into chaotic states independently of one another. In such a case, the equation for the propagator A_0 (which corresponds to the model non-interacting independently damping quasiparticles) can be approximately solved. Using a mean-field discrete basis (s-p energies ϵ_λ, wave functions ϕ_λ) one gets the expression for the A_0 expansion elements in a closed form:

$$A_{0,\lambda\mu}(\omega) = \frac{n_\lambda - n_\mu}{\epsilon_\lambda - \epsilon_\mu - \omega + \left(n_\lambda - n_\mu\right)[iW(\omega) - P(\omega)] f_\lambda f_\mu}.$$

Here, $n_{\lambda,\mu}$ are the occupation numbers, $W(\omega)$ and $P(\omega)$ are respectively imaginary and real parts of the strength of the energy-averaged p-h self-energy term, f_λ is the diagonal matrix element of the Woods-Saxon function $f(x)$.

Being taken in the local limit, i.e. $A_0(x, x', \omega) = A_0(x = x_1, x' = x'_1, \omega)$, the "free" p-h propagator

$$A_0(x, x', \omega) = \sum_{\lambda\mu} A_{0,\lambda\mu}(\omega) \phi^*_\mu(x) \phi_\lambda(x) \phi^*_\lambda(x') \phi_\mu(x')$$

is the key quantity of the discrete PHDOM version.

2.3 Continuum PHDOM version

The continuum PHDOM version (the basic one) follows from the approximate transformation of the “free” p-h propagator to the form, in which the GFs of the Schrodinger equations, having the addition to the mean field $[-iW(\omega)+P(\omega)]\,f_\nu f(x)$ $(\nu = \mu,\lambda)$, are used. (Within the cRPA, i.e. in neglecting the spreading effect, this transformation is exact). One from these equations determines also the continuum-state wave functions $\phi^{(\pm)}_{\epsilon=\epsilon_\mu+\omega>0}(x)$. In such a way, there appears an effective optical-model potential, whose imaginary part was found (e. g., from the description of the total width of various GRs) is noticeably less, than the imaginary part of the “ordinary” OM potential taken at the corresponding energy. $W(\omega)$ is a specific (phenomenological) quantity of the model

2.4 Dispersive relationship

The dispersive relationship, which determines $P(\omega)$ via $W(\omega)$, is obtained after energy averaging the spectral expansion of the p-h self-energy term. This expansion is similar to that of the 2p-2h GF. (2p-2h configurations are the doorway-states for the spreading effect).

The simplest version of the dispersive relationship

$$P(\omega) = \frac{2}{\pi} P.V. \int_0^\infty W(\omega') \left\{ \frac{\omega'}{\omega^2 - \omega'^2} + \frac{1}{\omega'} \right\} d\omega'$$

is adopted to satisfy the condition: $P(\omega \to 0) \to 0$.

In current implementations of the PHDOM, a more sophisticated version of the dispersive relationship is used.

2.5 Main PHDOM equations

Most of the main PHDOM equations, namely, the equations for the energy-averaged p-h GF $A(x, x', \omega)$, the strength function $S_{V_0}(\omega)$, the effective field $V(x, \omega)$ look similar to the respective cRPA equations (p. 2.1) after the substitution:

$$A_0^{cRPA}(x,x',\omega) \to A_0(x,x',\omega).$$

The difference is concerned with the double transition density

$$\rho(x,x',\omega) = -\frac{1}{\pi}\mathrm{Im}A(x,x',\omega).$$

Due to taking the spreading effect into account, this quantity can't be factorized in terms of one-body transition density. (The latter can't be defined).

Since existing computer codes for calculation of the inelastic hadron-nucleus scattering accompanied by excitation of a given GR exploit only one-body transition density, we suggest using for these codes the respective “projected” density:

$$\rho_g(x,\omega) = \int \rho(x,x',\omega)\, V_{0,g}(x')\, dx'\, S_{V_{0,g}}^{-1/2},\ S_{V_{0,g}} = (V_{0,g}^{+}\rho_g)^2.$$

Here, $V_{0,g}$ - specific for excitation of a given GR the external field.

The squared amplitude of the one-nucleon DSD reaction induced by a s-p external field $V_0(x)$ and accompanied by excitation of one-hole state μ^{-1} of the product nucleus is expressed in terms of the effective field (U., PRC`13; Gorelik et al., NPA`18)

$$\left|M^{DSD}_{V_0,c}(\omega)\right|^2 = n_\mu \left|\left(\phi^{(-)*}_{\epsilon=\epsilon_\mu+\omega} V(\omega)\, \phi_\mu\right)\left(\phi^*_\mu V^*(\omega)\, \phi^{(+)}_{\epsilon=\epsilon_\mu+\omega}\right)\right|^2.$$

Here, c is a set of the reaction-channel quantum numbers, which includes the quantum numbers of the one-hole state and considered (p-h)-type excitation, and $\epsilon = \epsilon_\mu + \omega > 0$.

The squared partial amplitudes, which can be called as the partial one-nucleon escape strength functions $S^{\uparrow}_{V_{0,c}}(\omega)$, determine the partial branching ratios for direct one-nucleon decay from a certain excitation-energy interval δ:

$$b^{\uparrow}_{c}(\delta) = \int_{(\delta)} S^{\uparrow}_{V_{0,c}}(\omega)\, d\omega \Big/ \int_{(\delta)} S_{V_0}(\omega)\, d\omega .$$

The total one-nucleon-decay branching ratio

$$b^{\uparrow}_{tot}(\delta) = \sum_{c} b^{\uparrow}_{c}(\delta).$$

determines the branching ratio for statistical (mainly, neutron) decay:

$$b^{\downarrow} = 1 - b^{\uparrow}_{tot}.$$

Within the cRPA (i.e. in neglecting the spreading effect), $b^{\downarrow} \to 0$.

All the main PHDOM relationships are valid at arbitrary (but high-enough) excitation energies. Only in case of using the specific for a given GR external field (probing operator) $V_{0,g}$ to define the "projected" one-body transition density, the energy interval is limited by a vicinity of this GR.

2.6 Unitarity violations

The methods used within the model for describing the spreading effect lead to weak violations of model unitarity. These violations are due to:

i. an energy dependence of the averaged p-h self-energy term (takes place for any type of p-h excitations);

ii. the use of an approximate spectral expansion for the optical-model-like GF (takes place only for isoscalar monopole (ISM) excitations).

Violation of the first type is approximately eliminated by using the modified “free” p-h propagator $A^m_{\lambda\mu}(\omega)$:

$$A^m_{0,\lambda\mu}(\omega) = A_{0,\lambda\mu}(\omega)\left(1-\left(n_\lambda - n_\mu\right)\frac{dP}{d\omega} f_\lambda f_\mu\right).$$

(the contributions proportional to $\left(\frac{dW}{d\omega}\right)^2$ might be neglected). Then the continuum PHDOM version is formulated using the properly modified optical-model-like GFs and continuum-state wave functions.

In the description of ISM excitations within the PHDOM, the respective probing operator $V_0(r)\,Y_{00}$ should be also modified to avoid spurious excitations caused by the unit external field:

$$V_0(r) \rightarrow V_0(r) - \langle V_0 \rangle$$

where averaging $\langle \ldots \rangle$ is performed over the ground-state density.

As a result, the unitary version of the PHDOM was formulated, and weak unitarity violations were found. An example is given below.

2.7 Related approaches

Many attempts have been undertaken in past to describe the spreading effect on GR properties. We mention two of them, which seem to us more advanced.

- The approaches, in which the spreading effect is described in terms of coupling (p-h)-type states to a number of 2p-2h configurations, are related to microscopic approaches (see, e.g., Kamerdzhiev et al. Phys.Rep.`04). Being only the doorway-states for the spreading effect, these configurations do not correspond to real nuclear states at high excitation energies, and their level density is much lower than the real one described by the statistical model. As a result, a rather artificial "smearing procedure" is used to get the quantities available for a comparison with exp. data

For these reasons the mentioned approaches seem not fully adequate to real physical situation. Also, the description of direct-decay properties of GRs

- In past, we actively exploited the so-called semi-microscopic approach, in which the spreading effect is phenomenologically taken into account by means the substitution

$$\omega \rightarrow \omega + [iW(\omega) - P(\omega)]f(x)$$

directly in the cRPA equations (U., NPA`08). The approach can be considered as a “pole” approximation of the PHDOM. However, it is not valid at distant “tails” of GRs. The approach looked as a reasonable prescription, but was not microscopically justified.

III. Recent implementations

3.1 Input quantities

In current implementations of the PHDOM (published in 2018), a rather simple set of input quantities is used. It includes the Landau-Migdal p-h interaction and a (realistic) partially self-consistent mean field. This field contains a phenomenological isoscalar (Woods-Saxon type) part (including the spin-orbit term), while the symmetry potential and mean Coulomb field are calculated self-consistently. It means that the isovector Landau-Migdal parameter f' belongs to the set of mean-field parameters, which are found from the description of observable single-quasiparticle spectra in doubly-closed-shell parent nuclei.

Specific for the model phenomenological quantity, the energy-dependent intensity of the imaginary part of the energy-averaged p-h self-energy term $W(\omega)$, is parameterized as follows:

$$2W(\omega > \Delta) = \alpha \frac{(\omega-\Delta)^2}{1+(\omega-\Delta)^2/B^2},\ 2W(\omega \leq \Delta) = 0.$$

Here, $\alpha \sim 0.1$ MeV^{-1} is the adjustable parameter, while the "gap" parameter $\Delta = 3$ MeV and "saturation" parameter $B = 7$ MeV are used, as the universal quantities. The real part, $P(\omega)$, is determined by the proper dispersive relationship. The parameter α is adjusted to reproduce the observed total width of the given GR in the calculated strength function. Then, the double transition density, DSD-reaction amplitudes, direct-decay branching ratios are evaluated without the use of any free parameters.

3.2 Properties of ISM excitations

Investigations of ISM excitations are popular due to the possibility of determining the nuclear matter incompressibility coefficient, which depends on the mean ISGMR energy.

Within the initial and unitary PHDOM versions, we study the ISM relative energy-weighted strength functions

$$y_g(\omega) = \omega S_{V_{0,g}}(\omega)/EWSR_{V_{0,g}}$$

related to the probing operators $V_{0,1} = r^2 Y_{00}$ and $V_{0,2} = r^2(r^2 - \eta)Y_{00}$ (η is an adjustable parameter), which lead to excitation of the ISGMR and its overtone (ISGMR2), respectively. The strength functions calculated for ^{208}Pb within the initial (solid line) and unitary (dotted line) PHDOM versions are shown in Figs.1. (Gorelik et al., NPA`18).

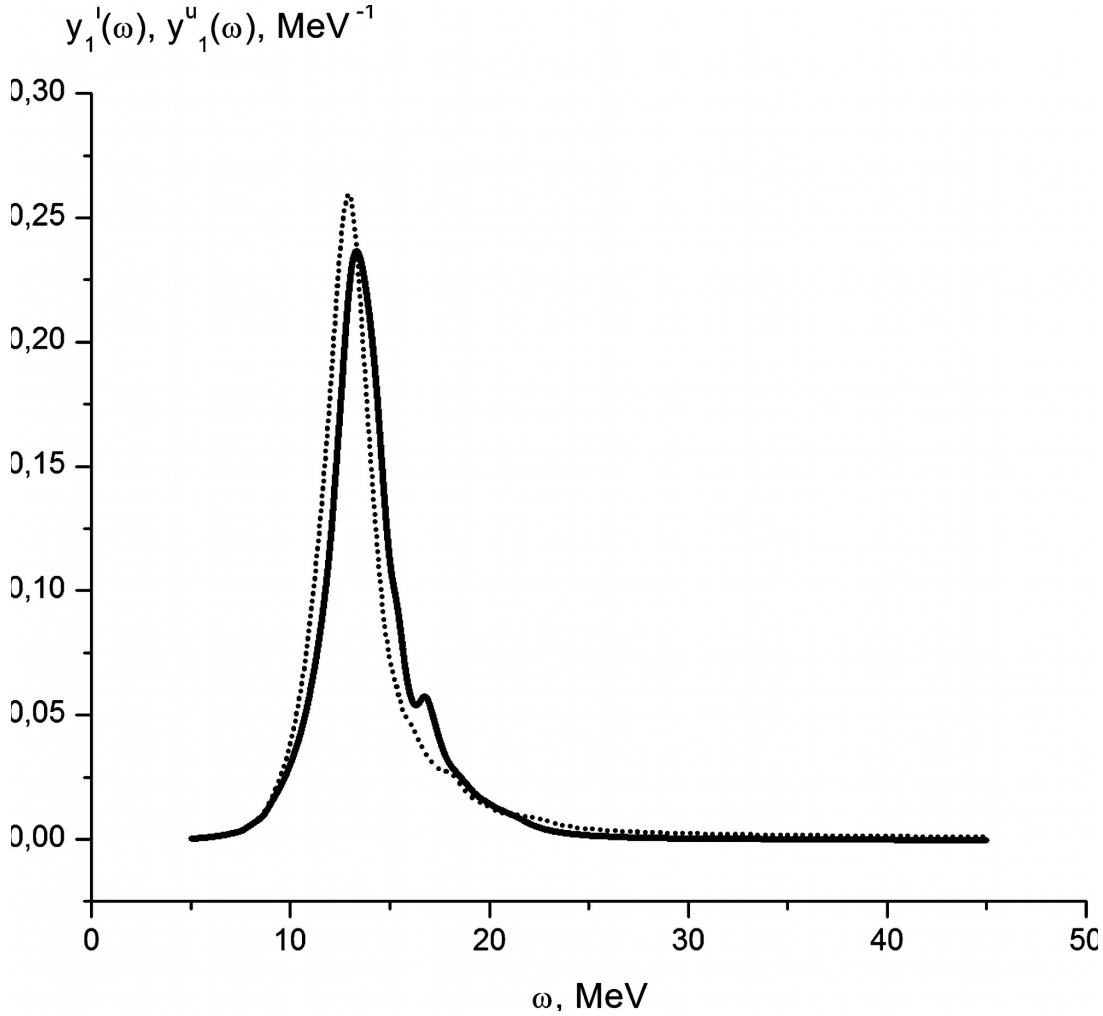
$y_1^l(\omega)$, $y_1^u(\omega)$, MeV^{-1}
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0
10
20
30
40
50
ω, MeV

Fig.1a

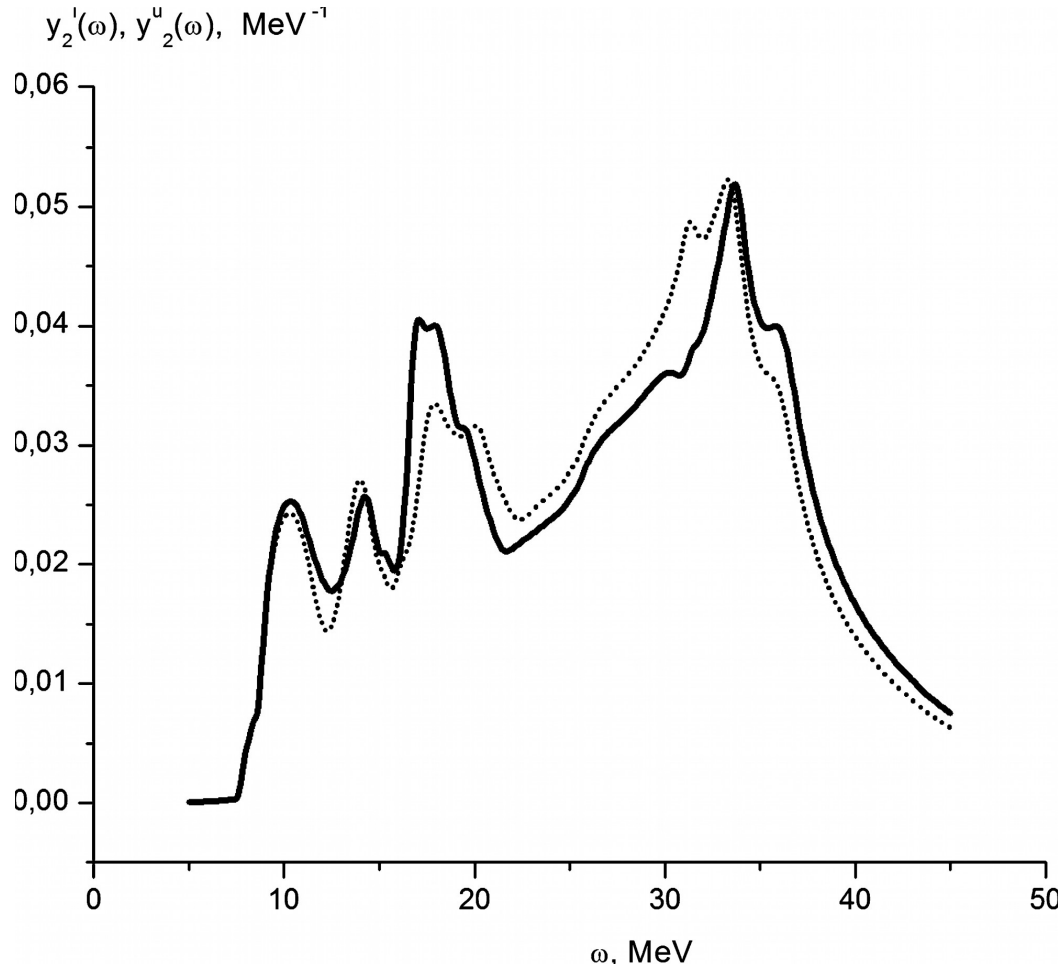
$y_2^l(\omega)$, $y_2^u(\omega)$, MeV^{-1}
0,06
0,05
0,04
0,03
0,02
0,01
0,00
0
10
20
30
40
50
ω, MeV

Fig.1b

Usually, the properly normalized (one-body, energy-independent) collective-model transition density of the ISGMR, $\rho_{c,1} \sim \left(3 + r\frac{d}{dr}\right) n(r)$ with $n(r)$ being the ground-state density, is used within the DWBA-analysis of (α,α')-scattering at small angles.

We compare the squared microscopically corrected collective (energy-dependent) radial transition density defined as follows

$$\rho_{c,1}(r,\omega) = \Lambda_1^{1/2}(\omega)\,\rho_{c,1}(r);\ \Lambda_1(\omega) = \frac{S_{V_{0,1}}(\omega)}{\left(\rho_{c,1}V_{0,1}\right)^2},$$

the squared "projected" radial transition density, $\rho_{g,1}(r,\omega)$, and the "diagonal" radial ISM double transition density, $\rho(r = r',\omega)$, in a vicinity of the ISGMR in ^{208}Pb (Fig. 2). Differences at the ISGMR "tails" are clearly seen.

ω = 10.8 MeV

ω = 13.8 MeV

ω = 16.8 MeV

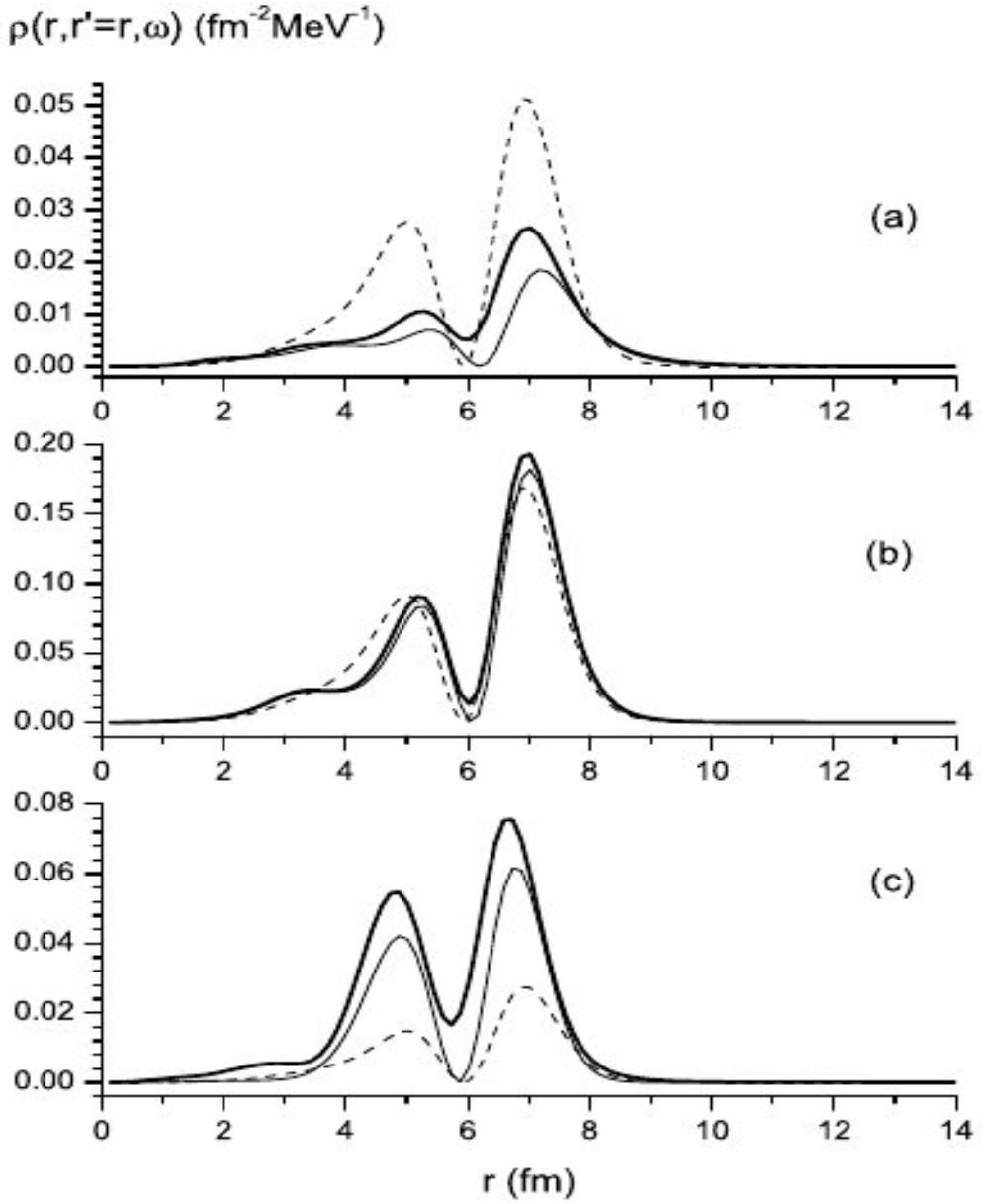

Fig.2

Within the PHDOM, the "full analysis" of properties of an arbitrary GR, having the "normal isospin", includes the description of the strength function, projected transition density, partial and total probabilities of direct one-nucleon decay. In applying to the multipole ($L = 0 - 3$) isoscalar giant resonances in ^{208}Pb, such an analysis is supposed to be presented at this Workshop by M.L. Gorelik.

3.3 Simplest photo-nuclear reactions

The first intensive implementation of the PHDOM has been concerned with photo-absorption cross section and DSD (γ, n)- and (n, γ)-reaction cross sections accompanied by excitation of the isovector dipole and quadrupole giant resonances (IVGDR and ISVGQR), respectively) (Tulupov, U., PRC`14). In this consideration, the calculation scheme was extended by inclusion of the isovector velocity-dependent forces taken in a simplest (separable) form (with the dimensionless strengths k_1' and k_2').

Here, we present new results (Tulupov, U., EPJ WoC`18) concerned with quantitative estimation of the partial and total branching ratios for direct one-neutron decay of the IVGDR in ^{48}Ca. Namely, the value $b_{tot}^{\uparrow,\,\mathrm{exp}} = 39 \pm 5\%$ for the excitation-energy interval $\delta = 11\text{–}25$ MeV is available for this nucleus. As before, we first evaluate within the model the $E1$-photo-absorption cross section, which is proportional to the energy-weighted strength function $S_1(\omega)$ related the external field

$$V_{0,1}(x) = (-1/2)\,\tau^{(3)} Y_{10},$$

$$\sigma_{a,E1}(\omega) = C\omega S_1(\omega)$$

where $C = 16\pi^3 e^2/\hbar c$, ω is the γ-quantum energy. From the comparison with the experimental data (Fig. 3), two adjustable parameters α (in MeV^{-1}) and k_1' are found.

Then, the partial cross section of the DSD (γ, n)-reaction accompanied by population of the certain one-hole state μ^{-1} in ^{47}Ca

$$\sigma_{\mu,E1}^{DSD}(\omega) = C\omega \sum_{(\lambda)} \left| M_{1,(\lambda),\mu}^{DSD}(\omega) \right|^2$$

is evaluated without the use of free parameters (Fig. 5). ($(\lambda) = j,l$ are the quantum numbers of the optical-model-like wave function of escaped neutron, having the energy $\epsilon = \epsilon_\mu + \omega$). The calculated total DSD (γ, n)-reaction cross section is shown in Fig. 4. The total branching ratio defined as the ratio

$$b_{E1}^{tot}(\delta) = \sum_\mu \int_{(\delta)} \sigma_{\mu,E1}^{DSD}(\omega)\, d\omega/\omega \Big/ \int_{(\delta)} \sigma_{a,E1}(\omega)\, d\omega/\omega$$

that then evaluated ($b_{E1}^{tot}(\delta) = 35.3\%$) and found in a reasonable agreement with the corresponding experimental value.

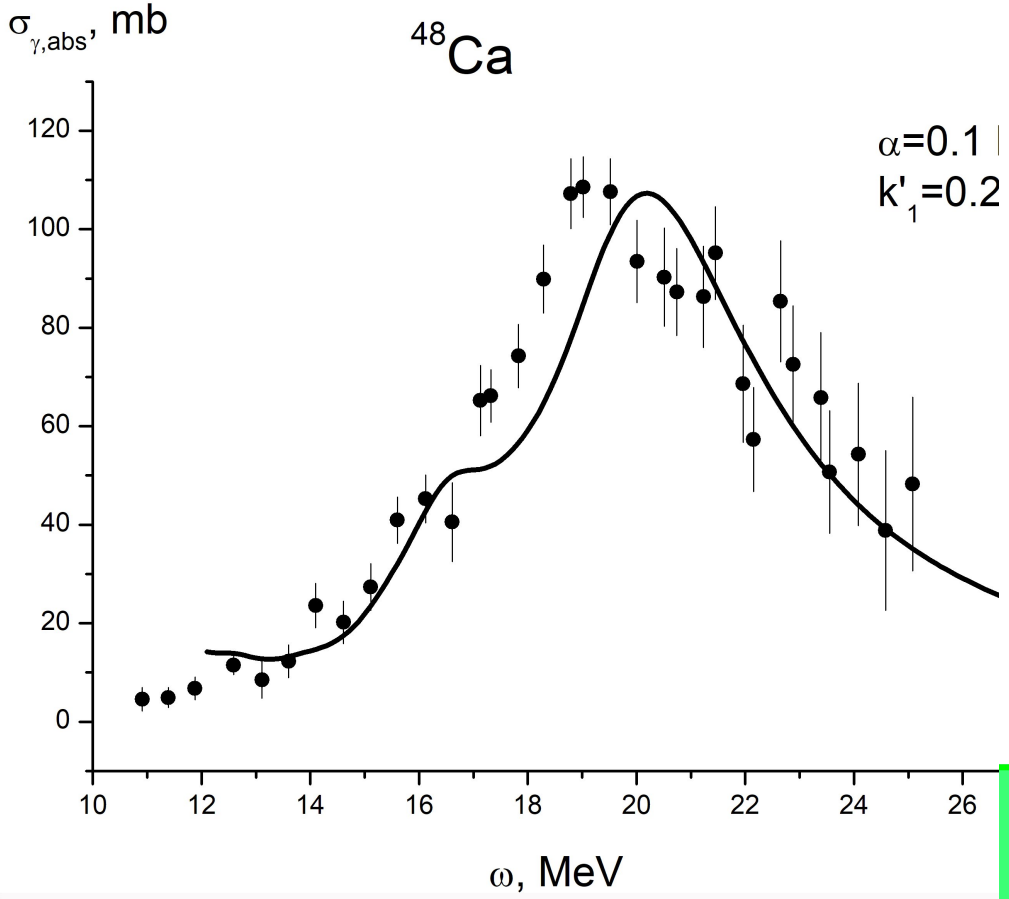
σγ,abs, mb
48Ca
α=0.1
k'1=0.2
120
100
80
60
40
20
0
10
12
14
16
18
20
22
24
26
ω, MeV

Fig. 4a

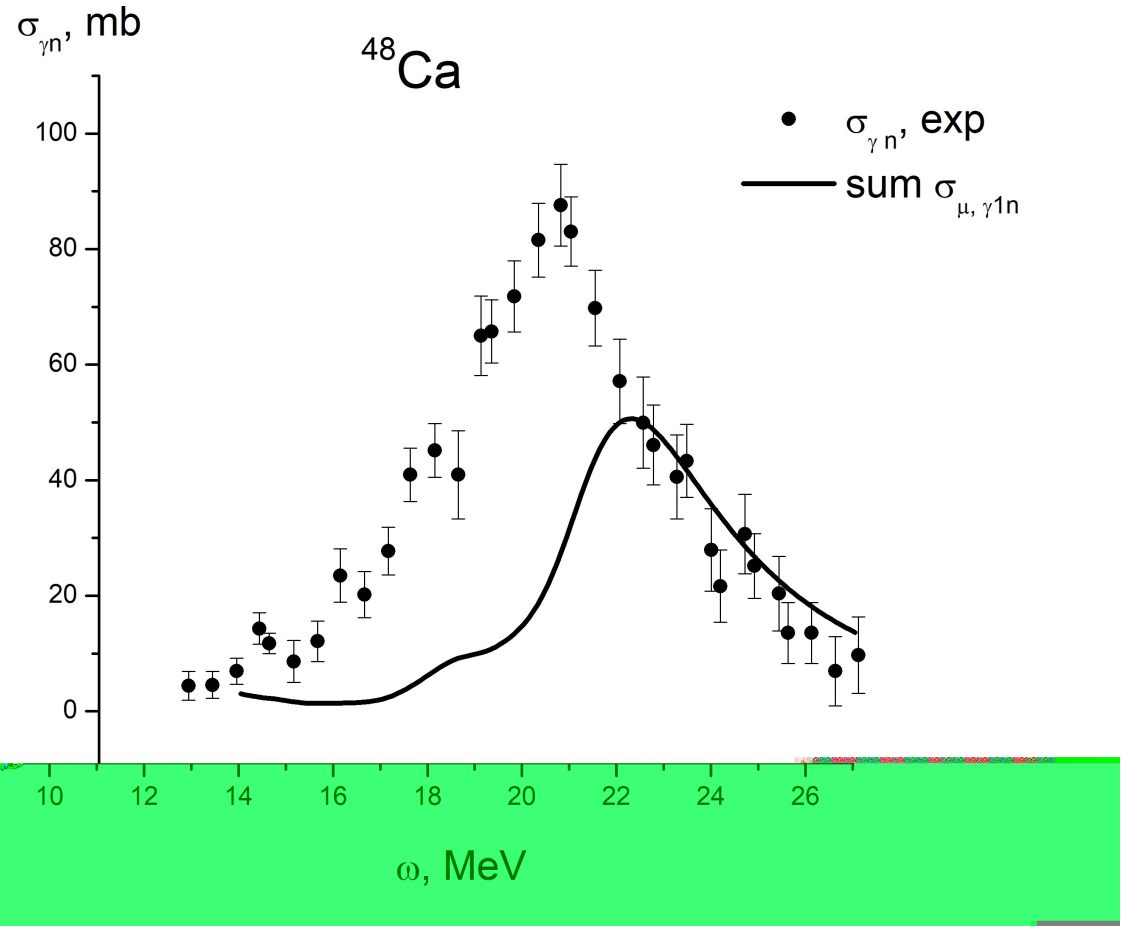
σγn, mb
48Ca
σγ n, exp
sum σμ, γ1n
100
80
60
40
20
0
10
12
14
16
18
20
22
24
26
ω, MeV

Fig. 4b

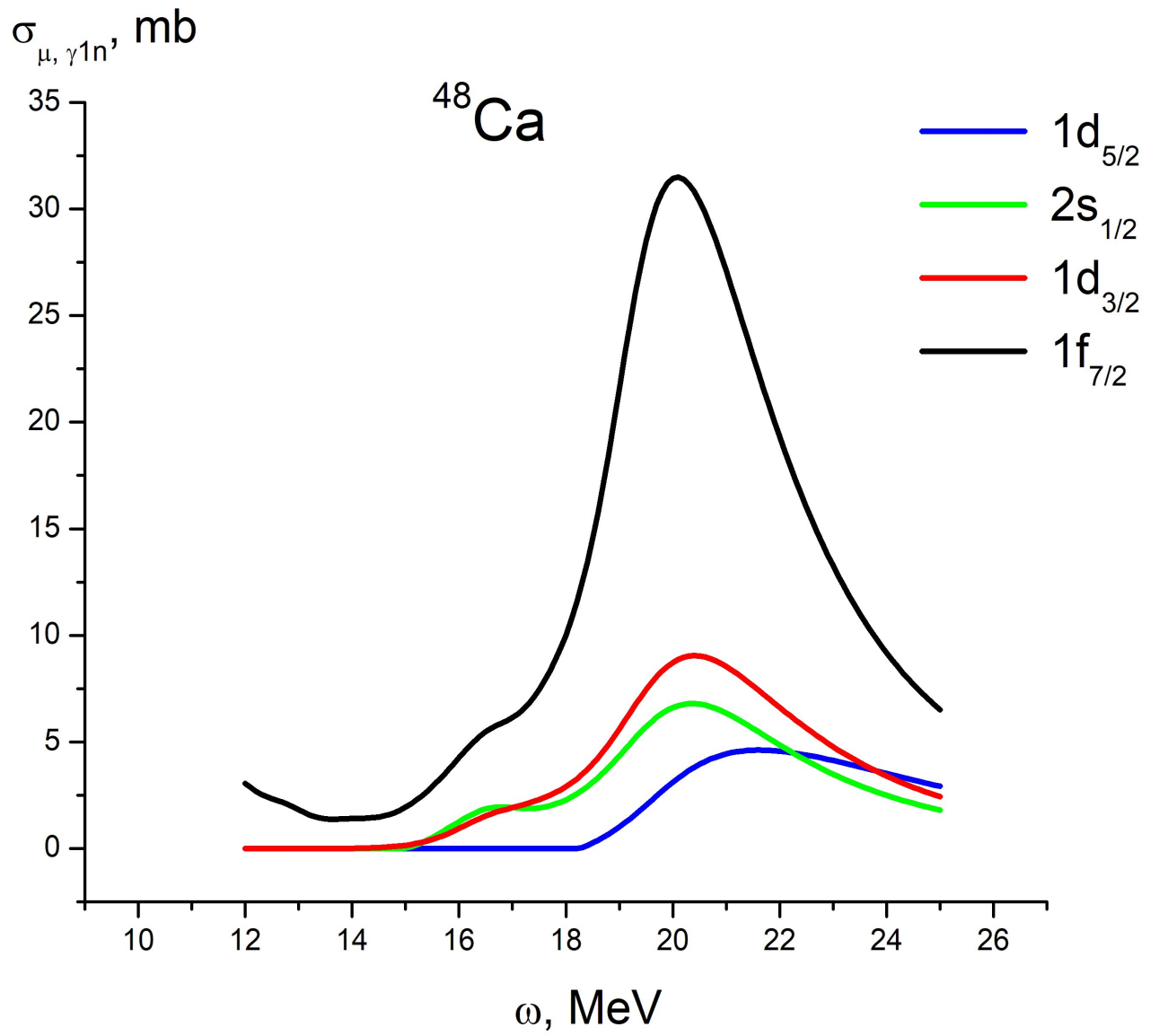
σ μ, γ1n, mb
48Ca
1d5/2
2s1/2
1d3/2
1f7/2
35
30
25
20
15
10
5
0
10
12
14
16
18
20
22
24
26
ω, MeV

Fig.5

3.4 Damping parameters of charge-exchange monopole excitations (Kolomiytsev et al., EPJ A`2018, EPJ WoC`18)

These excitations include the Isobaric Analog Resonance (IAR), its overone (the Isovector Giant Monopole Resonance in the $\beta^{(-)}$- channel (IVGMR$^{(-)}$)), the isobaric partner of IVGMR$^{(-)}$ - IVGMR$^{(+)}$. Properties of IAR are closely related to the approximate isospin-symmetry conservation in nuclei. This point allows us to reproduce a combined approach, in which the "Coulomb description" of the isospin-forbidden processes (Gorelik, U., PRC`01) is incorporated into PHDOM. Within the combined approach, the main damping parameters of the resonances are determined by the Coulomb strength functions $S_C^{(\mp)}(\omega)$, $S_{C,\nu}^{(-),\uparrow}$, $S_{C,\pi}^{(+),\uparrow}$, related to the external fields

$$V_C^{(\mp)} = \left(U_C(r) - \omega_A + \frac{i}{2}\Gamma_A \right) \tau^{(\mp)}.$$

Here, $U_C(r)$ is the mean Coulomb field, ω_A and Γ_A are, respectively, the IAR excitation energy and total width.

In particular, for the IAR total, one-proton-escape and spreading widths one gets:

$$\Gamma_A = \frac{2\pi}{S_A} S_C^{(-)}(\omega = \omega_A);\ \Gamma_{A,\nu}^{\uparrow} = \frac{2\pi}{S_A} S_{C,\nu}^{(-),\uparrow}(\omega = \omega_A);\ \Gamma_A^{\downarrow} = \Gamma_A - \sum_\nu \Gamma_{A,\nu}^{\uparrow}.$$

The IAR Fermi strength $S_A \simeq S_{A,0}$ and energy $\omega_A \simeq \omega_{A,0}$ can be found from the Fermi strength function $S_{F,0}^{(-)}(\omega)$ (related to the probing operator $V_F^{(-)} = \tau^{(-)}$) evaluated within the cRPA. One can say, that the mentioned IAR widths are determined by distant low-energy "tail" of the IVGMR(-) in Coulomb strength functions $S_C^{(-)}(\omega)$ and $S_{C,\nu}^{(-),\uparrow}(\omega)$. Being taken at the vicinity of the IVGMR(-), these strength functions determine the partial and total branching ratios for direct one-proton decay of this resonance. A similar statement is valid for direct one-neutron decay of the IVGMR(+).

Such a program is realized for the 208Pb parent nucleus (Tables 1-3). In Figs. 6 and 7 the strength functions $S_C^{(-)}(\omega)$, $S_{C,0}^{(-)}(\omega)$ and $S_C^{(+)}(\omega)$, $S_{C,0}^{(+)}(\omega)$ are shown.

Single adjustable parameter $\alpha = 0.07$ MeV^{-1} is adopted to reproduce in calculations of $S_C^{(-)}(\omega)$ the observable IVGMR$^{(-)}$ total width (Table 1). The calculated value $\Gamma_A^{\downarrow} = 60$ keV is in acceptable agreement with the corresponding experimental value $\Gamma_A^{\downarrow,exp} = 78 \pm 8$ keV. Similar statement is related to the partial one-proton-escape widths $\Gamma_{A,\nu}^{\uparrow}$ (Table 3).

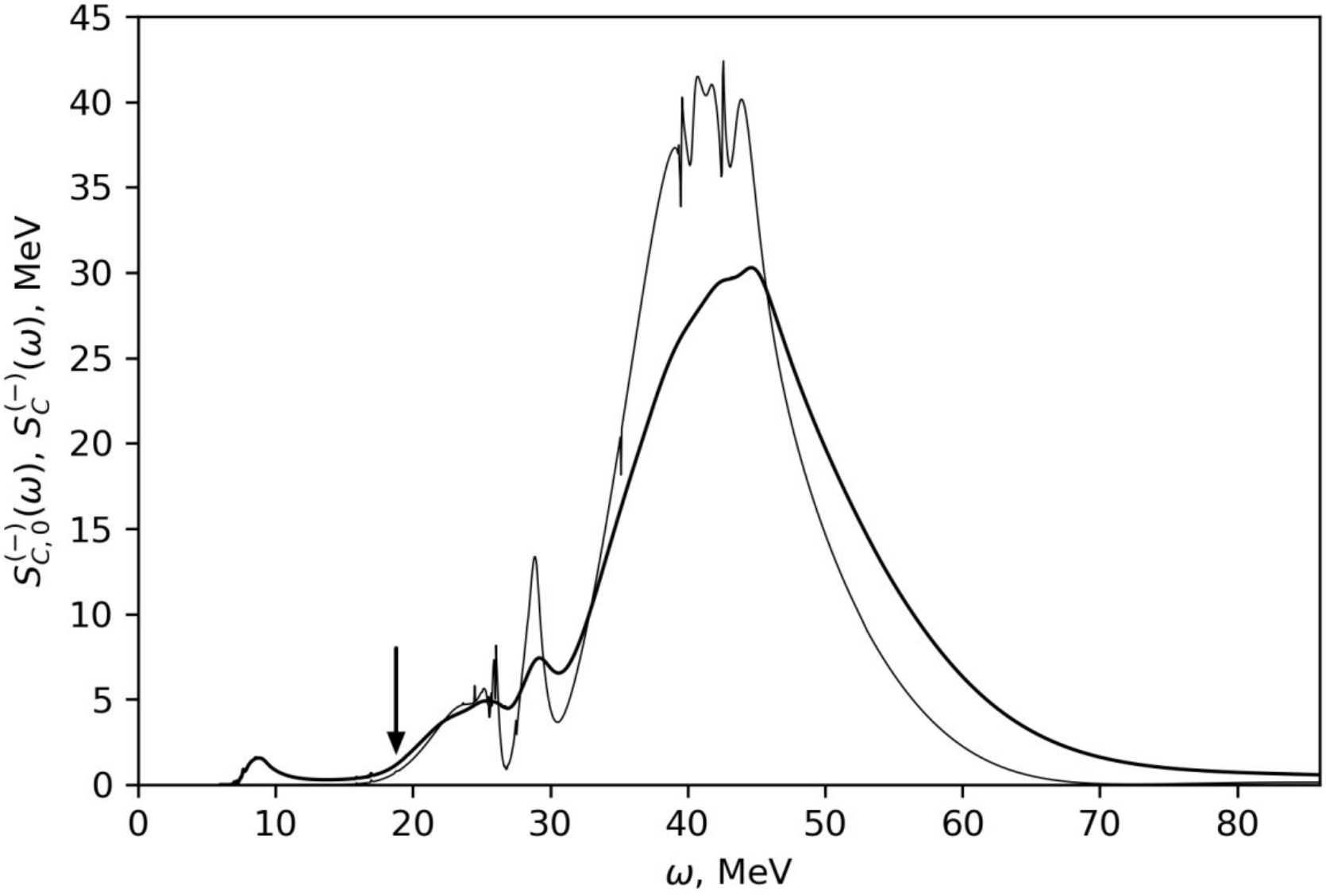
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
$S^{(-)}_{C,0}(\omega)$, $S^{(-)}_{C}(\omega)$, MeV
ω, MeV

Fig.6

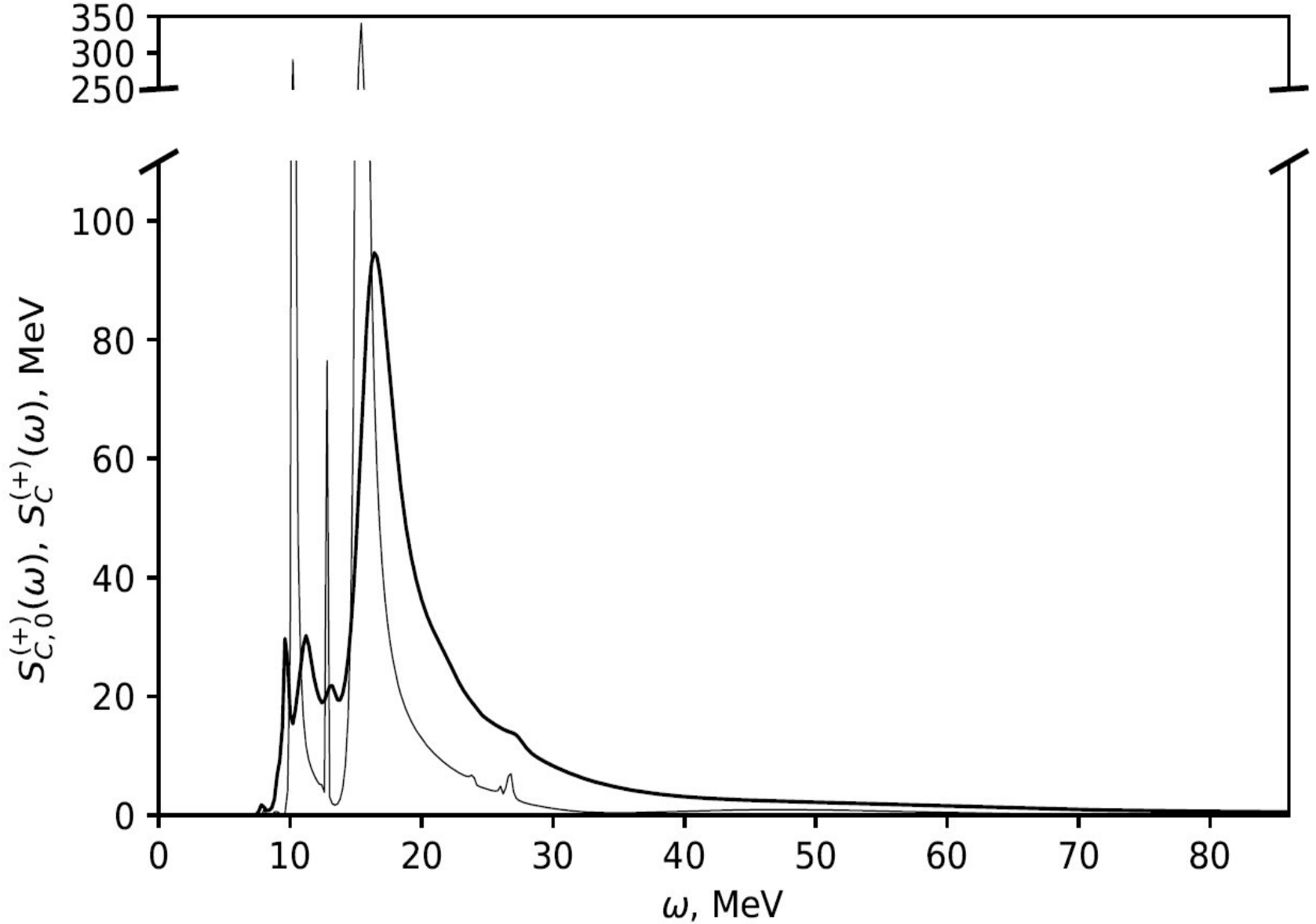
350
300
250
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
$S^{(+)}_{C,0}(\omega)$, $S^{(+)}_{C}(\omega)$, MeV
ω, MeV

Fig.6

Table 1. Energies and widths of the IVGMR$^{(\mp)}$ based on ^{208}Pb ground state in comparison with experimental data (Errel et al., PRC`86)

GR	ω_M	ω_M^{exp}	Γ_M	Γ_M^{exp}
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

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

IVGMR$^{(-)}$			IVGMR$^{(+)}$		
ν	$b_{C,\nu}^{(-),\uparrow}$ (cRPA), %	$b_{C,\nu}^{(-),\uparrow}$ (PHDOM), %	π	$b_{C,\pi}^{(+),\uparrow}$ (cRPA), %	$b_{C,\pi}^{(+),\uparrow}$ (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 and experimental data (Whitten, PRC`69; Reiter et al, Z. Phys. A`90) for the IAR based on ^{208}Pb ground state

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
$3p_{1/2}$	11,1	11,5	54,7	71,6	51.9 ± 1.6
$2f_{5/2}$	10,2	10,9	11,4	24,3	26.4 ± 2.0
$p_{3/2}$	10,1	10,6	49,5	86,4	64.7 ± 3.4
$i_{13/2}$	9,1	9,7	<0,1	0,1	–
$f_{7/2}$	7,5	9,2	0,5	7,0	4.2 ± 0.6
$h_{9/2}$	6,8	8,0	<0,1	<0,1	–

IV. Conclusive remarks

- In conclusion, the newly developed semi-microscopic model, PHDOM, is briefly presented. Within the model , the structure and main relaxation modes of high-energy (p-h)-type excitations (including GRs) in closed-shell nuclei are together described. Some recent implementations of the model are also shown.
- The lines of further development might be new implementations and the use of more advanced versions of the mean field and p-h interaction. An extension of PHDOM to open-shell spherical nuclei is also in order.

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