Properties of the isoscalar giant dipole resonance

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The main properties (strength function, energy-dependent transition density, branching ratios for direct nucleon decay) of the isoscalar giant dipole resonance in several medium-heavy mass spherical nuclei are described within a continuum random-phase approximation approach, taking into account the smearing effect. All model parameters used in the calculations are taken from independent data. The calculation results are compared with available experimental data.

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Recently, several experimental [1,2] and theoretical [3–6] works have been published describing results of studies of properties of the isoscalar giant dipole resonance (ISGDR) in several medium-heavy mass spherical nuclei. It was found in Ref. [2], from an analysis of the (α,α') reaction at small angles, that the isoscalar dipole strength distribution exhibits two main regions of strength concentration, corresponding to the lower (pygmy) and upper (main) ISGDR components. Microscopic approaches used in recent theoretical studies of the ISGDR are based on (i) continuum random-phase approximation (RPA) calculations with the use of the Landau-Migdal particle-hole interaction [3], (ii) Hartree-Fock + RPA calculations with the use of the Skyrme interactions [4,6], and (iii) relativistic RPA calculations [5]. In each of these approaches, the strength distribution of the ISGDR shows two main regions of strength concentration with corresponding centroid energies that are in qualitative agreement with those of Ref. [2]. References to previous experimental and theoretical studies of the ISGDR are given, respectively, in Refs. [1,2] and [3–6]. Here, we mention Ref. [7], where the low-energy isoscalar 1^- strength was identified from an analysis of the $(\alpha,\alpha'\gamma)$ reaction.

In connection with the above-mentioned investigations it seems reasonable to realize the next step in theoretical studies, which consists in a rather full description of ISGDR properties. Such a description includes calculations of (i) the ISGDR strength distribution in a wide excitation-energy interval, taking into account the smearing effect, (ii) the energy-dependent ISGDR transition density also in a wide energy interval, and (iii) the partial branching ratios for direct nucleon decay of the ISGDR. In each of the above-mentioned theoretical approaches, used in earlier works, this program was only partially realized. In the present work we attempt to describe ISGDR characteristics listed above in an extended version of the continuum RPA (CRPA) approach of Ref. [3]. Calculation results obtained for ^{90}Zr, ^{116}Sn, ^{144}Sm, and ^{208}Pb are compared with available experimental data.

Apart from the description of some ISGDR properties, the partially self-consistent continuum RPA approach was mainly used in Ref. [3] to describe in a quantitative way the direct neutron decay of the isoscalar giant monopole resonance (ISGMR). To realize a rather full description of ISGDR properties, we extend the approach of Ref. [3] in the following ways. (For brevity, we use below the notations of Ref. [3] and sometimes refer to equations from this reference.)

(1) We slightly change the dimensionless parameters f^{in} and f^{ex} of the radial-dependent intensity $F(r)$ of the isoscalar part of the Landau-Migdal particle-hole interaction [determined by Eq. (16) of Ref. [3]] to better describe the experimental energies of the ISGMR (taken from Ref. [8]). The new value $f^{in}=0.0875$ (as well as the value $f^{in}=-0.0875$ used in Ref. [3]) is in agreement with the systematics of the Landau-Migdal parameters of Ref. [9]. As in Ref. [3], the f^{ex} value is adjusted to make the 1^- spurious-state energy close to zero for each nucleus considered (see Table I). The relative strengths x_{SS} of the spurious state (SS), or the percentage of the respective isoscalar dipole energy-weighted sum rule (EWSR) exhausted by the SS [Eq. (18) of Ref. [3]], are also given in Table I.

(2) To calculate the energy-averaged strength functions of the ISGMR $(L=0)$ and the ISGDR $(L=1)$ $\overline{S}_L(\omega)$, accounting for the smearing effect, we solve the CRPA equations of Ref. [3] with the replacement of the excitation energy ω by $\omega+(i/2)I(\omega)$: $\overline{S}_L(\omega)=S_L(\omega+(i/2)I(\omega))$. The smearing parameter $I(\omega)$ (the mean doorway-state spreading width) is taken from Ref. [10] with the energy-dependent function having a saturationlike behavior. A reasonable description of the total width was obtained in Ref. [11] for several isovector giant resonances with the use of the $I(\omega)$ from Ref. [10]. The relative energy-weighted strength functions $y_L(\omega)=\omega\overline{S}_L(\omega)/(\mathrm{EWSR})_L$ calculated for the ISGMR and ISGDR allow us to deduce for some excitation-energy intervals $\omega_1-\omega_2$ the following parameters: centroid of the energy ω_L, root mean square (RMS) width Δ_L, and relative strength x_L. These parameters are shown in Table I for the ISGMR and in Table II for the ISGDR. The same parameters found in the CRPA $(I=0.05\ \mathrm{MeV})$ are also given in these tables. Some of the calculation results are compared with available experimental data in Table III. The calculated strength functions $y_{L=1}(\omega)$ are shown in Fig. 1.

(3) The giant-resonance transition density $\rho_L(r)$ can reasonably be defined in the CRPA in the special case when only one collective particle-hole-type state (doorway state) corresponds to the considered GR and, therefore, exhausts

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TABLE I. The relative isoscalar dipole strength of the spurious state x_{SS} calculated with the use of the value f^{ex}, which provides spurious-state energy close to zero for each nucleus ($f^{in}=0.0875$). The centroid of the energy ω_L, RMS width Δ_L, and relative strength x_L calculated for the ISGMR ($L=0$) at some excitation-energy intervals $\omega_1-\omega_2$, and the same parameters calculated in the CRPA ($I=0.05$ MeV), are shown.

A	$-f^{ex}$	x_{SS} (%)	$\omega_1-\omega_2$ (MeV)	ω_L (MeV)	Δ_L (MeV)	x_L (%)
^{208}Pb	2.897	91.9	10–20	14.29	2.05	80.2
			3–60	15.22	5.13	99.2
[a]			10–20	13.99	1.10	97.9
^{144}Sm	2.811	93.6	10–20	15.28	2.00	78.0
			3–60	16.53	5.16	98.5
[a]			10–20	15.27	0.96	98.7
^{116}Sn	2.832	93.6	10–20	15.79	2.08	74.7
			3–60	17.18	5.29	98.4
[a]			10–20	15.97	1.24	97.9
^{90}Zr	2.753	94.5	10–25	17.10	2.71	85.4
			3–60	18.05	5.30	98.2
[a]			10–25	16.89	1.35	99.8

[a] $I=0.05$ MeV.

most of the respective EWSR. Such a situation takes place in the approach of Ref. [3] for the ISGMR. In the case of the ISGDR, several doorway states have comparable strength (see, e.g., Ref. [3]) and therefore only the energy-averaged and energy-dependent transition density $\overline{\rho_L}(r,\omega)$ can be defined. In accordance with the spectral expansion for the effective particle-hole propagator (the particle-hole Green's function) one can get the expression

$$\overline{\rho_L}(r,\omega)=-\frac{1}{\pi}\frac{\mathrm{Im}\sum_{\alpha=n,p}\tilde{V}_{L,\alpha}(r,\omega+(i/2)I(\omega))}{2F(r)\overline{S}_L^{1/2}(\omega)}, \qquad (1)$$

which is equivalent to that used in Ref. [6]. In Eq. (1), $\tilde{V}_{L,\alpha}(r,\omega)$ are the effective fields [defined by Eq. (2) of Ref. [3]] corresponding to the probe operator $V_L(r)$: $V_{L=0}=r^2, V_{L=1}=r^3-\eta r$ with $\eta=\frac{5}{3}\langle r^2\rangle$ [3,4,6]. From Eq. (1) here and Eqs. (1) and (2) of Ref. [3] follows the expression $\overline{S_L}(\omega)=[\int V_L(r)\overline{\rho_L}(r,\omega)r^2dr]^2$, which is in agreement with the definitions of Ref. [6]. As applied to ^{208}Pb, the transition density $\mathcal{R}_{L=1}(r,\omega)=r^2\overline{\rho_{L=1}}(r,\omega)/\overline{S}_{L=1}^{1/2}(\omega)$, normalized by the condition $\int V_L(r)\mathcal{R}_L(r,\omega)dr=1$, is shown in Fig. 2 for some values of ω in comparison with the collective ISGDR transition density [12] normalized in the same way.

(4) To calculate the partial and total branching ratios for

TABLE II. The same parameters as shown in Table I for $L=0$, calculated for the ISGDR ($L=1$).

	Lower ISGDR				Upper ISGDR			
A	$\omega_1-\omega_2$ (MeV)	ω_L (MeV)	Δ_L (MeV)	x_L (%)	$\omega_1-\omega_2$ (MeV)	ω_L (MeV)	Δ_L (MeV)	x_L (%)
^{208}Pb	8–15	11.10	1.91	13.3	15–24	20.71	2.41	41.3
	5–15	9.87	2.52	16.7	15–30	22.57	3.36	68.6
					15–60	24.03	5.83	81.1
[a]	5–15	9.67	2.30	18.2	15–30	22.75	2.49	79.7
^{144}Sm	5–15	10.74	2.19	12.3	15–35	24.38	4.13	76.4
					15–60	25.43	6.00	84.8
[a]	5–15	10.64	1.84	13.9	15–35	24.40	3.02	84.9
^{116}Sn	11–18	14.02	2.01	10.8	18–32	25.21	3.33	65.5
	5–15	10.36	2.42	13.2	15–35	24.90	4.38	74.7
					15–60	26.10	6.28	84.3
[a]	5–15	10.31	2.25	15.0	15–35	25.09	3.42	83.3
^{90}Zr	11–18	13.89	2.08	9.9	18–32	25.64	3.52	64.5
	5–16	11.42	2.23	11.3	16–40	26.30	4.93	79.7
					16–60	27.13	6.37	85.7
[a]	5–16	11.19	1.70	12.3	16–40	26.10	3.93	87.3

[a] $I=0.05$ MeV.

TABLE III. Comparison of parameters calculated for the ISGMR and ISGDR with the corresponding experimental data (with the errors) taken from Refs. [8] and [2], respectively. All the parameters are given in MeV.

		^{208}Pb		^{116}Sn		^{90}Zr	
ISGMR	ω_L	14.17 ± 0.28	14.3	16.07 ± 0.12	15.8	17.89 ± 0.20	17.1
	Δ_L	1.93 ± 0.15	2.05	2.16 ± 0.08	2.1	3.14 ± 0.09	2.7
Lower ISGDR	ω_L	12.2 ± 0.6	11.1	14.7 ± 0.5	14.0	16.2 ± 0.8	13.9
	Δ_L	1.9 ± 0.5	1.9	1.6 ± 0.5	2.0	1.9 ± 0.7	2.1
Upper ISGDR	ω_L	19.9 ± 0.8	20.7	23.0 ± 0.6	25.2	25.7 ± 0.7	25.6
	Δ_L	2.5 ± 0.6	2.4	3.7 ± 0.5	3.3	3.5 ± 0.6	3.5

direct nucleon decay of the main ISGDR component, we follow Refs. [11] and [13], where the proton branching ratios have been estimated for the high-energy charge-exchange spin-monopole and monopole giant resonances, respectively:

$$b_{\mu,\alpha}=\frac{\sum_{(\lambda)}\int_{\omega_1}^{\omega_2}|\overline{M}_c^L(\omega)|^2 d\omega}{\int_{\omega_1}^{\omega_2}\overline{S}_L(\omega)d\omega},\qquad b_\alpha=\sum_\mu b_{\mu,\alpha}. \tag{2}$$

Here, $\overline{M}_c^L(\omega)=M_c^L(\omega+(i/2)I(\omega))$ is the energy-averaged reaction amplitude corresponding to direct nucleon decay with population of the one-hole state μ^{-1} in the product nucleus; $c=\mu,\alpha,(\lambda),\varepsilon$ is the set of decay-channel quantum numbers, which includes the energy $\varepsilon=\omega+\varepsilon_\mu$ and quantum numbers $(\lambda)=j,l$ of the escaped nucleon. The definition of the CRPA reaction amplitude $M_c^L(\omega)$ is given by Eq. (5) of Ref. [3]. Note that in the CRPA $(I=0)$ the total branching ratio $b=b_n+b_p$ is equal to unity by definition. Some partial branching ratios $b_{\mu,\alpha}$ calculated for the main ISGDR component (15–30 MeV) in ^{208}Pb are given in Table IV.

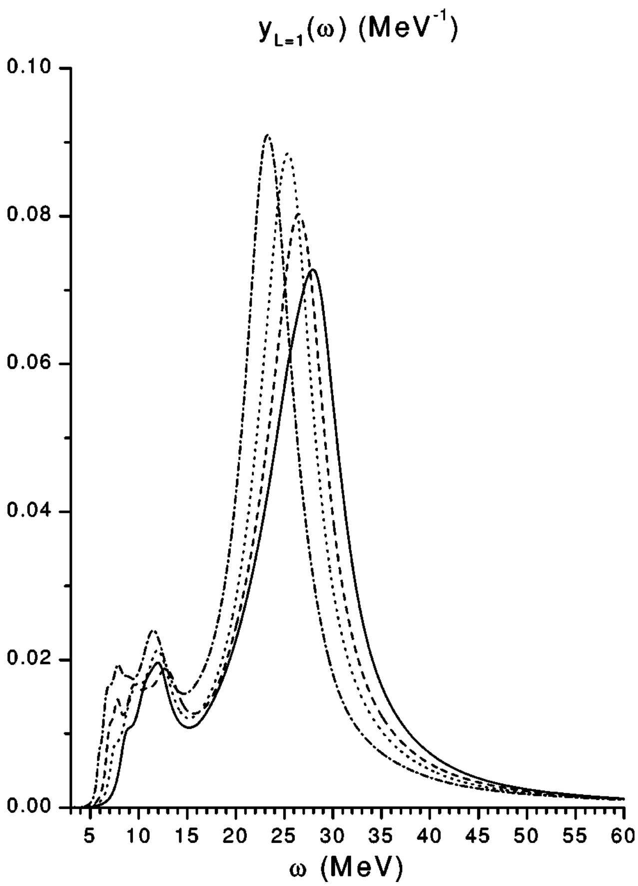

FIG. 1. The calculated relative strength function $y_{L=1}(\omega)$. The full, dashed, dotted, and dash-dotted lines are for ^{90}Zr, ^{116}Sn, ^{144}Sm, and ^{208}Pb, respectively.

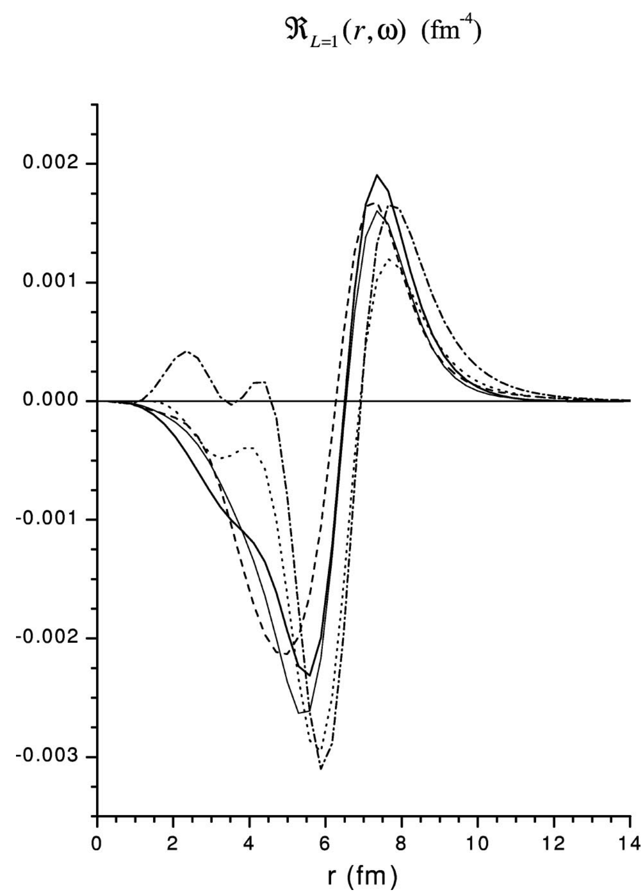

FIG. 2. The normalized ISGDR transition density $\mathcal{R}_{L=1}(r,\omega)$ calculated at several energies: $\omega=23.06$ MeV (the full line), 11.26 MeV (dashed), 7.76 MeV (dotted), and 6.81 MeV (dash-dotted). The thin line corresponds to the collective ISGDR transition density calculated in the scaling model [12] and normalized in the same way.

TABLE IV. Calculated partial branching ratios for direct nucleon decay of the ISGDR in ^{208}Pb. The results for decays with population of one-hole states from the last filled shells are shown for excitation-energy interval 15–30 MeV. Spectroscopic factors of these states $S_{\mu}=1$ are taken for all decay channels.

Neutron, μ^{-1}	$(1/2)^-$	$(5/2)^-$	$(3/2)^-$	$(13/2)^+$	$(7/2)^-$	$(9/2)^-$
b_{μ} (%)	1.4	4.8	3.4	8.0	8.5	3.9
Proton, μ^{-1}	$(1/2)^+$	$(3/2)^+$	$(11/2)^-$	$(5/2)^+$	$(7/2)^+$	
b_{μ} (%)	3.0	3.9	2.4	6.1	1.4	

We now make several comments on the results of this work. (i) With the choice of the Landau-Migdal parameters $f^{in}=0.0875$ and f^{ex} from Table I, it is possible within the present CRPA approach to describe satisfactorily the experimental centroids of the energy for the ISGMR and both ISGDR components (Tables I–III). As compared with the results of Ref. [3] the centroid values are increased by 1–2 MeV. After taking the results of Ref. [7] into account [2] (not shown in Table III) the theoretical description of the experimental centroid energies of the lower ISGDR component is improved. (ii) The use of the saturationlike dependence for $I(\omega)$ with parameters taken from independent data [10,11] allows us to describe reasonably the experimental RMS widths for the ISGMR and both ISGDR components (Table III). As is shown in Table II, the calculated ISGDR parameters discussed above are markedly dependent on the excitation-energy interval considered. Such a dependence is a result of both the Landau damping and the smearing effect. (iii) The calculated strengths of both ISGDR components (Table II) are markedly less than the corresponding values deduced from experimental data [2]. Possible reasons for the difference are the use of the specific collective ISGDR transition density for analysis of the data in Ref. [2], and (or) the neglect in our calculation of the contribution of momentum-dependent forces to the Landau-Migdal particle-hole interaction. Isovector momentum-dependent forces were taken into account in Ref. [10] to describe in the same CRPA approach the main properties of the isovector giant dipole resonance, using the relative effective nucleon mass of unity. For this reason, in the present work unit relative effective mass is also used and, therefore, the isoscalar part of the momentum-dependent forces is not considered. (iv) The radial dependence of the transition density of the main ISGDR component calculated for ^{208}Pb is rather close to that found in the scaling model [12] (Fig. 2). However, this is not true for the lower component (Fig. 2). Thus, the use of the microscopic energy-dependent transition density of Eq. (1) for analyzing experimental cross sections seems preferable. Such an attempt was recently realized in Ref. [6]. (v) The calculated branching ratios for direct nucleon decay of the upper ISGDR component are rather large due to a strong coupling of this component to the continuum. The large difference between the present calculation results for the branching ratios and the previous results is partially explained by a large contribution (due to the smearing effect) of the ''tail'' of the lower ISGDR component to the energy-averaged reaction amplitudes, and also by the poor approximation used in Ref. [3] for the parametrization of the CRPA reaction amplitudes in terms of isolated Breit-Wigner resonances.

In conclusion, we have described the main properties of the ISGDR in several medium-heavy mass spherical nuclei using a transparent and rather easy to implement approach that is based on the continuum RPA method with inclusion of the smearing effect. Except for the relative strengths, a satisfactory description of available experimental data on parameters of the ISGDR components was obtained. Following Ref. [6], we suggest using the microscopic energy-dependent transition density of the ISGDR for analysis of experimental cross sections. Such a use of the transition density allows one to clarify the problem of the underestimation of the calculated ISGDR relative strength in comparison to that deduced from experimental data.

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