Local electric dipole strength in heavy nuclei

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We show that, within a two-group schematic random phase approximation model, a concentration of local dipole strength in the lower tail region of the electric giant dipole resonance can show up. The model is tested under more realistic circumstances for the isovector 1^- states in ^{116}Sn. [S0556-2813(98)04302-7]

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In atomic nuclei, most of the electric dipole strength becomes concentrated in the giant electric dipole resonance (GDR) and has been well studied. Both the excitation energy and the total $E1$ strength are rather well understood from a collective as well as from a microscopic starting point [1].

Recent studies mainly using photon scattering off medium-heavy and heavy nuclei near closed shells have resulted in a number of conspicuous features [2]: (i) A low-energy $E1$ bound state with rather large $B(E1;0^+\rightarrow1^-)\simeq(5-10)10^{-3}\ e^2\ \mathrm{fm}^2$ is observed, at an energy near to the sum of the energy for the first 2^+ and 3^- states [2–6], and (ii) In some nuclei (^{116}Sn, ^{124}Sn, ^{140}Ce), at the tail of the GDR and near to 6–7 MeV, a local concentration of $E1$ strength is observed [7,8]. The observation of a fairly large $B(E1)$ value, at low energy, might be due to admixtures of the GDR into these low-lying 1^- states [9,10].

Some attention has been given to the latter point (ii) by, e.g., Van Isacker *et al.* [11] and Iachello [12]. Van Isacker *et al.* discuss the possibility that nuclei with a reasonable neutron skin may exhibit pygmy-$E1$ resonances below the giant electric dipole resonance. Iachello has suggested that with isospin as a local symmetry, discussing the examples of $(\alpha, \ldots)$ clustering in nuclei and of permanent octupole deformation effects, rather important concentrations of $E1$ strength might well show up at low excitation energy. He has enforced this observation recently [13] and suggested a possible explanation for the observed 1^- dipole strength in rare-earth nuclei using the above concepts of both octupole deformation and local isoscalar $E1$ modes.

Detailed quasiparticle studies, concentrating in particular on $E1$ transitions in heavy nuclei, have been carried out over the years by the Dubna group [14–16]. These calculations reproduce fairly well the experimental $E1$ strength distribution over a rather large energy range [7,8] but it is generally difficult to disentangle the different contributions to the $E1$ strength.

In the present article, we suggest that physical insight into the appearance of a local concentration of strength is provided by the general results of a two-group random phase approximation (RPA) model. This idea is tested, under more realistic circumstances and in some detail, for the concentration of local electric dipole strength (LDS) in ^{116}Sn.

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A microscopic study of the excitation energy and $E1$ strength follows in a very transparent way from schematic Tamm-Dancoff approximation (TDA) and RPA models [17], eventually taking all contributing one-particle–one-hole (1p-1h) 1^- excitations as degenerate levels. When inspecting more realistic 1p-1h 1^- unperturbed energy spectra at the $Z=50$ and $N=82$ closed shells, there is more structure to be observed, but in both the $Z=50$ and $N=82$ closed shell nuclei one observes, at the lower-energy end, particularly strong unperturbed 1p-1h 1^- configurations, i.e., $1g_{9/2}^{-1}\,1h_{11/2}$ at $Z=50$, $1h_{11/2}^{-1}1i_{13/2}$ at $N=82$. So it seems like a local concentration of unperturbed strength is always present, due in particular to the large energy gap between the aligned spin-orbit partners near those closed shells. We study the $E1$ strength and its localization within a schematic two-group RPA model [18]. In Fig. 1, we indicate a two-group RPA model (which could be extended to more groups) and call $m,i(k)$ the particle and hole indices with an extra label k $(k=1,2)$ denoting the group into which the particle-hole state belongs. It is clear that for an otherwise degenerate system in which we take all

$$\varepsilon_{m,i}(1)=\varepsilon_1 \quad \text{and} \quad \varepsilon_{m,i}(2)=\varepsilon_2$$

equal (with $\varepsilon_1\neq\varepsilon_2$) and using a separable residual interaction, one gets the RPA secular equation

$$\frac{1}{\chi}=\frac{2\varepsilon_1 S_1}{(\varepsilon_1^2-\hbar\omega^2)}+\frac{2\varepsilon_2 S_2}{(\varepsilon_2^2-\hbar\omega^2)}, \tag{1}$$

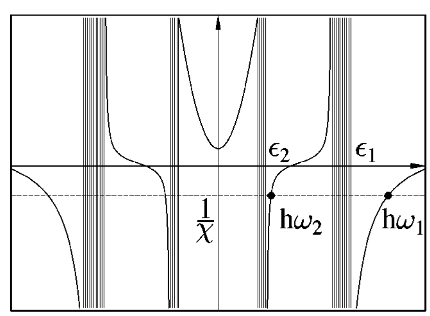

FIG. 1. Schematic two-group RPA model with the unperturbed configurations at energies ϵ_1 and ϵ_2. Besides the collective higher root corresponding to the GDR, a lower root exists ''trapped'' between the two unperturbed groups.

with $S_k=\Sigma_{m,i}|D_{mi}^{(k)}|^2$, $k=1,2$, and D_{mi} the p-h reduced matrix elements for the corresponding electric dipole $E1$ operator.

Such a two-group RPA model has been studied in detail in Ref. [18], concentrating on the isoscalar vibrational mode, with application to the octupole 3^- states in ^{146}Gd. This method can be applied by a straightforward extension to the study of isovector vibrational modes too.

Besides the strongly collective root, corresponding to the high-lying isovector giant electric dipole resonance GDR (when concentrating on 1^- excitations), which also appears in the one-group RPA, we obtain a second root at $\hbar\omega_2$ (see Fig. 1) where $E1$ strength is locally concentrated in between the energies ϵ_1 and ϵ_2 (LDS). One can easily show (see Ref. [18]) that the $E1$ transition probability from that state, at $\hbar\omega_2$, results in the expression

$$|\langle\tilde{0}|\hat{D}|\hbar\omega_2\rangle|^2 \cong \frac{\varepsilon_2 S_2}{\hbar\omega_2}\left\{1-\frac{\varepsilon_1 S_1}{\varepsilon_2 S_2}\left(\frac{\varepsilon_2^2-\hbar\omega_2^2}{\varepsilon_2^2-\hbar\omega_1^2}\right)\times\left[2+\left(\frac{\varepsilon_2^2-\hbar\omega_2^2}{\varepsilon_2^2-\varepsilon_1^2}\right)+\cdots\right]+\frac{\varepsilon_1^2 S_1^2}{\varepsilon_2^2 S_2^2}\left(\frac{\varepsilon_2^2-\hbar\omega_2^2}{\varepsilon_2^2-\varepsilon_1^2}\right)^2\times\left[1+\left(\frac{\varepsilon_2^2-\hbar\omega_2^2}{\varepsilon_2^2-\varepsilon_1^2}\right)^2+\cdots\right]\right\}, \qquad (2)$$

where now not all contributions act coherently. The second solution at $\hbar\omega_2$ is clearly less collective than the first root. The larger the gap $\varepsilon_1-\varepsilon_2$, the stronger the collectivity in the second group becomes. So this second root ''trapped'' between the ε_1 and ε_2 groups is a clear outcome of the fact that unperturbed 1p-1h states cannot be taken to form a single degenerate group in most cases.

To illustrate these general considerations, we have studied the $E1$ strength distribution in the nucleus ^{116}Sn. The unperturbed $(\mathrm{ph}^{-1})1^-$ spectrum was constructed as shown in Fig. 2, considering proton 1p-1h excitations across the gap at $Z=50$ (between the shells marked I and II in the figure) and neutron 1p-1h excitations across the gap at $N=50$ as well as the gap at $N=82$ (between shells I, II and II, III, respectively). A larger neutron configuration space was considered, since the shell between $N=50$ and $N=82$ is only half filled at $N=66$.

Realistic proton single-particle energies in ^{116}Sn, illustrated in Fig. 2, were obtained from comparison between the experimental spectra of the adjacent odd-proton nuclei ^{115}In and ^{117}Sb and calculations performed in the framework of the particle-core coupling model [19]. The neutron single-particle energies are not expected to vary much across the Sn isotopes, besides the $A^{-1/3}$ mass dependence. We have therefore used the values obtained around ^{132}Sn [20] with the same procedure as above and from the experimental data of Refs. [21] and [22], corrected for the mass scale factor. The energies of the neutron orbitals of shell I were not obtainable from experimental data in this mass region; instead, we have used the values given by the Woods-Saxon potential with the

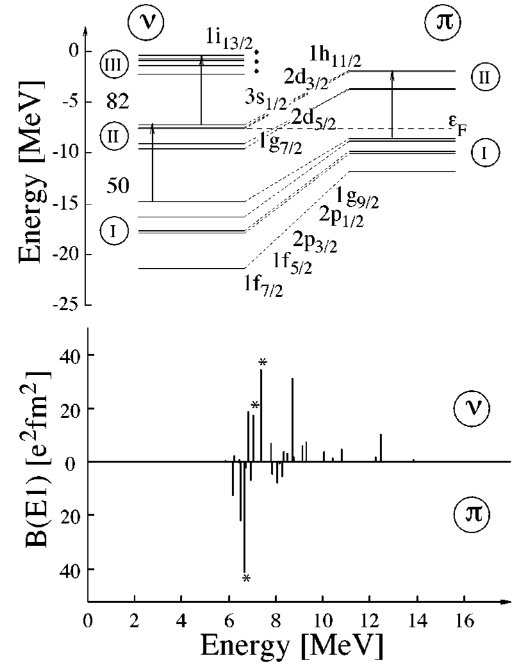

FIG. 2. Single-particle energies for ^{116}Sn (upper part) and corresponding unperturbed $(\mathrm{ph}^{-1})1^-$ spectrum and distribution of $E1$ strength (lower part). The strongest unperturbed ph^{-1} $E1$ transitions for neutron and proton configurations are marked with an arrow in the upper part and an asterisk in the lower part of the figure. The energies are given in MeV and the $B(E1;0^+\rightarrow(\mathrm{ph}^{-1})1^-)$ reduced transition probabilities in e^2 fm^2. Note the position of the Fermi level on the left side of the figure, indicating that the neutron shell $N=50-82$ is half filled at $N=66$ and the proton shell is closed at $Z=50$.

universal parameters [23]. The reduced transition probabilities $B(E1;0^+\rightarrow(\mathrm{ph}^{-1})1^-)$ were calculated using harmonic oscillator wave functions and the one-body $E1$ operator $T_\mu(E1)=e_{\mathrm{eff}}rY_{1\mu}$. The strongest unperturbed transitions corresponding to $\pi(1g_{9/2}\rightarrow 1h_{11/2})$, $\nu(1g_{9/2}\rightarrow 1h_{11/2})$, and $\nu(1h_{11/2}\rightarrow 1i_{13/2})$ are marked with an asterisk in the lower part of Fig. 2 and indicated by arrows in the upper part. The reduction of the strength of the neutron $E1$ transitions as compared to the proton ones is due to pairing effects in the half-filled shell.

A separable interaction of the form $-\chi D\cdot D$, with D the one-body $E1$ operator and $\chi<0$ (isovector channel), was considered to act between the neutron and proton $(\mathrm{ph}^{-1})1^-$ states. The strength χ was determined so as to assure the lowest (spurious) $E1$ excitation to occur at zero excitation energy with vanishing $E1$ strength, thereby removing spurious center-of-mass effects from the excited 1^- states. After diagonalization, one strongly collective state is obtained, corresponding to the GDR, but some strength indeed remains trapped between the different substructures of the unperturbed ph^{-1} spectrum, as was discussed in the schematic two-group RPA model. As shown in Fig. 3, the strength concentration (plotted with bars) displays a kind of ''periodic'' structure and the first group lies at a rather low energy ~6.5 MeV, corresponding well to the position of the local concentration of strength observed experimentally [7,8]. The effective charges $e_{\mathrm{eff}}(\nu)=-0.30$ and $e_{\mathrm{eff}}(\pi)=0.35$ were

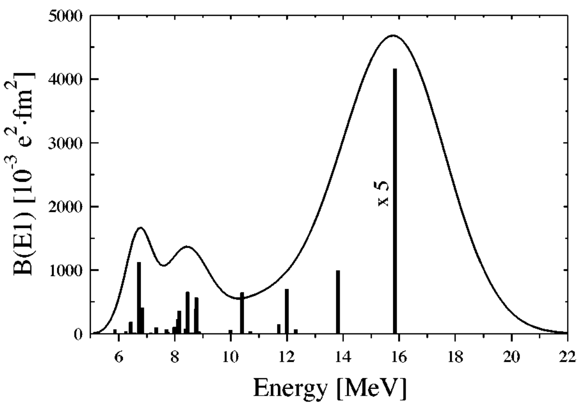

FIG. 3. Distribution of the $E1$ strength after diagonalization of a separable dipole-dipole interaction in the configuration space shown in the lower part of Fig. 2. The $B(E1)\uparrow$ values in units $10^{-3}\ e^2$ fm^2 are plotted with bars. The distribution of $E1$ strength convoluted with a Gaussian distribution of width increasing linearly with the energy is plotted as a solid line and given in units $10^{-3}\ e^2$ fm^2/MeV.

used for the calculation of the $E1$ strength, as needed to reproduce the experimentally observed strength in the region of the GDR [24] ($\sim 30\ e^2\ \mathrm{fm}^2$). The values for the effective charges thus lie in between the ones obtained from correcting only for the center-of-mass motion [$|(e_{\mathrm{eff}})| \sim 0.5$] and the ones where the polarization due to the GDR is fully taken into account [$|(e_{\mathrm{eff}})| \sim 0.1$] [10].

The calculated distribution of $E1$ strength (plotted with bars) convoluted with a Gauss distribution of width increasing linearly with the energy [12] is plotted as a solid line in Fig. 3 in order to regain the more familiar image of the GDR. The higher-lying structures are now obscured, but the local concentration of strength at the tail of the GDR remains visible. We note that the calculated strength overestimates the experimental values [8] by a factor of ~ 5, but the model used was still very schematic. We should also remark that the existence (but not the strength) of the local dipole concentration remains rather insensitive to the details of the specific residual interaction and seems to be due mainly to the structure of the unperturbed ph^{-1} spectrum, confirming the two-group RPA interpretation. Similar concentrations of local dipole strength are expected and have been observed in other Sn isotopes [8] as well as other mass regions [7] for nuclei with one closed shell.

As stated before and following from the schematic two-group RPA picture, local concentrations of strength should appear not only for the isovector dipole mode but also for other λ multipolarities, as soon as the unperturbed $(\mathrm{ph}^{-1})_\lambda$ spectrum presents significant gaps.

In conclusion, we have proposed a simple interpretation for the appearance of local concentration of dipole ($E1$) strength, within a two-group RPA model. This idea is illustrated for $E1$ strength in ^{116}Sn. For the $E1$ mode one observes that, besides the coherent mode at higher energy (the GDR), a concentration of $E1$ strength can appear locally because of irregularities in the 1p-1h unperturbed spectrum which causes smaller gaps to appear. Then it is a decoherence between various groups that may result in a spectrum of beats just like what one obtains from the addition of a number of simple, harmonic oscillating modes but with a special distribution of contributing frequencies. These local dipole (LDS) states may then, in a geometric way, correspond to local charge-mass oscillations in contrast to the full oscillating motion in the GDR collective mode. A detailed relation between a geometrical and microscopical formulation needs to be studied further, as well as the evolution of the LDS over different mass regions.

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