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Self-Consistent Calculations of the Electric Giant Dipole Resonances in Light and Heavy Nuclei

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While bulk properties of stable nuclei are successfully reproduced by mean-field theories employing effective interactions, the dependence of the centroid energy of the electric giant dipole resonance on the nucleon number *A* is not. This problem is cured by considering many-particle correlations beyond mean-field theory, which we do within the quasiparticle time blocking approximation. The electric giant dipole resonances in ^{16}O, ^{40}Ca, and ^{208}Pb are calculated using two new Skyrme interactions.

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The electric giant dipole resonance (GDR) is a well-known nuclear excitation mode which is related to bulk properties of nuclei, such as the Thomas-Reiche-Kuhn (TRK) sum rule and the nuclear symmetry energy [1]. One might assume that theories which describe both bulk properties of nuclei and shell effects rather well, such as self-consistent mean-field theories based on effective nucleon interactions [2–5], should have no problem in systematically reproducing the centroid energies of the GDR as a function of the nucleon number *A*. This is not the case, however, as has been discussed in detail in several recent reviews on mean-field theories which include strength functions obtained within the quasiparticle random-phase approximation (QRPA) [6–9]. It was impossible so far to describe ground-state properties and the centroid energy of the GDR both in light and heavy nuclei with the same effective interaction. The problem is more serious than might appear at a first glance because the physics of the GDR is intimately related to the neutron skin thickness and the pygmy dipole strength [10–12], presently investigated experimentally because of an impact on the isotope abundance produced in supernova explosions [13]. There are two hints suggesting that the mean-field approach by itself is at the origin of the problem. Complex configurations play a well-known role in the damping of nuclear excitations [14]. Even when effective interactions are fitted to the effective isoscalar mass, the symmetry energy, and the TRK sum-rule enhancement factor κ, the problem remains unsolved [9].

We employ the quasiparticle time blocking approximation (QTBA), developed and applied in [15–21], to study the GDR. The QTBA is a method to calculate nuclear response functions. It includes explicitly the coupling of one-particle one-hole($1p1h$) configuration with phonons, but omits the simultaneous excitation of two-phonon states in the presence of a $1p1h$ excitation. In the limit of vanishing phonon-nucleon coupling, the QTBA corresponds to the QRPA, a standard mean-field approach. Originally, the QTBA was used in the framework of Landau-Migdal theory, but has been generalized recently to effective interactions of the Skyrme family in order to make possible self-consistent calculations [18,19,22]. The Skyrme interactions are defined by a set of momentum- and density-dependent contact interactions; different parametrizations may be distinguished by some set of theoretical quantities, such as nuclear matter properties or the effective mass, which are not directly observable. The momentum dependence of the Skyrme interaction leads to an effective mass, with values $m^*/m < 1$ found by many investigations. Mean-field approaches which employ effective masses smaller than unity generate single-particle energies which systematically deviate from the separation energies, mainly by a too-small level density. Larger level densities can be obtained by taking into account the energy dependence of the nucleon self-energy, as is shown in Refs. [23–26]. The energy dependence of the self-energy is due to complex configurations, such as the coupling of phonons to the single-particle degrees of freedom. In this Letter we show that if these effects are considered, both centroid energies and spreading widths of the giant resonances are reproduced. As we know that Skyrme forces cannot reproduce simultaneously the GDR in ^{16}O and ^{208}Pb [8], we have adjusted new Skyrme parametrizations for the purpose of this study, concentrating on tuning the GDR in ^{16}O within the mean-field approach (RPA). Since there are only few collective nuclear vibrations in light nuclei, the inclusion of phonons within the QTBA is expected to produce results close to the ones obtained in the mean-field approach for ^{16}O. On the other hand, in heavy nuclei, the number of collective modes increases, which leads to major differences between the mean-field approach and the QTBA. We follow exactly the same fitting strategy and data as used for the systematic variation of forces in [6]. As a result, we obtain two new forces, SV-m56-O with effective mass $m^*/m = 0.56$ and SV-m64-O with $m^*/m = 0.64$. Both forces have a rather low symmetry energy $a_{\text{sym}} = 27$ MeV, and high sum-rule enhancement factor [6] $\kappa_{\text{TRK}} = 0.6$. The parameters are listed in Table I.

Of course, the new fits maintain the good ground-state properties of all the systematically varied forces in [6]. Additionally, the low effective mass and low symmetry energy $a_{\text{sym}} = 27$ MeV together with a rather high sum-rule enhancement factor κ_{TRK} of the two parametrizations delivers a high GDR energy. In the self-consistent QRPA calculation, the centroid energy of the GDR is reproduced for ^{16}O, but overestimated for ^{208}Pb. However, the inclusion of complex configurations brings the GDR in ^{208}Pb down to the correct value. Similar effects are seen for the single-particle energies. The parametrizations SV-m56-O and SV-m64-O reproduce these energies in ^{16}O reasonably well, but the single-particle spectrum in ^{208}Pb is spread out too much and deviates strongly from the experimental one. The coupling to the phonons will improve the spectrum [20]. Being built on RPA, QTBA follows basically the same trends with varying Skyrme force as RPA (see [6]), though the absolute value of the effect is different in light and heavy mass nuclei.

TABLE I. Skyrme force parameters (upper block), adjusted nuclear matter properties (middle block), and dipole polarizability α_{D} as well as neutron skin $r_{\text{rms},n} - r_{\text{rms},p}$ (lower block) for the two newly designed Skyrme forces. The standard force parameters are given, where α is the power of the density dependence. All three forces use Coulomb exchange in Slater approximation and the c.m. energy correction $\langle \hat{P}^2_{\text{cm}} \rangle/(2mA)$. For details of the functional and options, see Refs. [3,6,7].

	SV-m56-O	SV-m64-O
t_0	−1905.403	−2083.855
t_1	571.187	484.604
t_2	1594.803	1134.345
t_3	8439.036	10 720.663
t_4	133.268	113.973
x_0	0.644 020	0.619 768
x_1	−2.973 738	−2.332 678
x_2	−1.255 261	−1.305 938
x_3	1.796 626	1.210 109
b_4'	52.970 11	62.925 67
α	0.2	0.2
$\frac{\hbar^2}{2m_p}$	20.749 82	20.749 82
$\frac{\hbar^2}{2m_n}$	20.721 26	20.721 26
m^*/m	0.56	0.64
a_{sym}/MeV	27	27
κ_{TRK}	0.6	0.6
α_{D}/fm^3	20.2	19.4
n-skin [fm]	0.156	0.134

Let us outline some technical details of our numerical scheme. In our RPA and QTBA calculations of the GDR, the single-particle continuum is treated exactly according to the scheme described in Ref. [19]. The phonons were calculated within the so-called discretized RPA (DRPA). Here the results depend on the single-particle basis and on details of the discretization, e.g., the size of the box one chooses. In the present investigation, such ambiguities are small, as we control them by comparing the DRPA results with a full continuum RPA.

In self-consistent calculations, the *ph* interaction is given by the second derivative of the energy functional. In the DRPA calculations of phonons, the matrix elements of the *ph* interaction were calculated exactly except for the spin-orbit and Coulomb contributions, which were omitted. In the RPA and QTBA calculations of the GDR, we used additional (local-exchange) approximation for the velocity-dependent part of the *ph* interaction derived from Skyrme energy functional. In the case of the GDR, this approximation gives results which are close to the exact RPA results. Details will be shown in a forthcoming publication. In our investigation, we did not study spin-dependent properties of new Skyrme forces. It is well known that the spin-spin part of the residual interaction (except for $\boldsymbol{J}^2$-generating terms) does not contribute to the ground-state structure for spherical even-even nuclei. So one can omit this part in the calculations of the excited states in these nuclei without breaking self-consistency. On the other hand, inclusion of the spin-spin part of the residual *ph* interaction leads to an instability in the DRPA calculations of the phonon's characteristics with given Skyrme forces. In fact, as for most other Skyrme forces, the instability is driven by the term $\propto (\nabla\sigma)^2$ in the

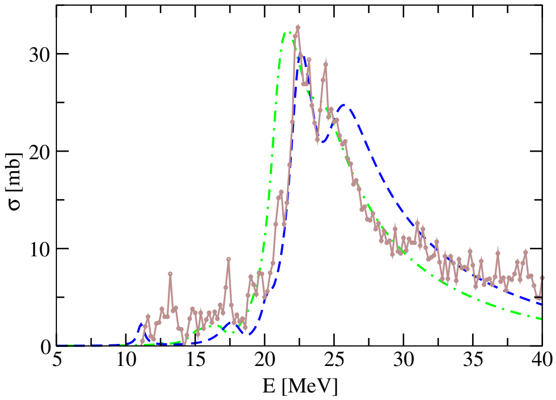

FIG. 1 (color online). Photo absorption cross section in ^{16}O calculated self-consistently in RPA, using two different Skyrme parametrizations with effective mass 0.56 (dashed [blue] line) and 0.64 (dashed-dotted [green] line). The experimental cross section is given by the (brown) dots connected by a solid line [28].

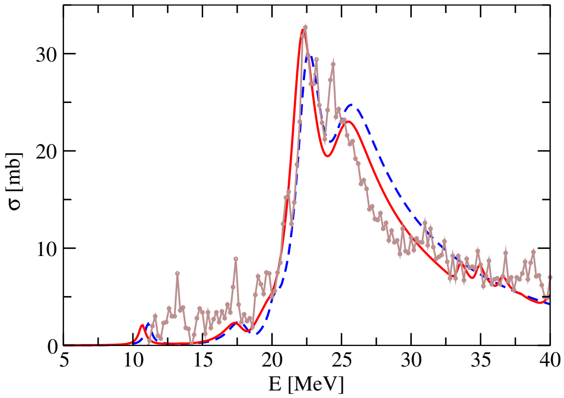

FIG. 2 (color online). Comparison of the experimental [28] photo absorption cross section in ^{16}O with theoretical ones calculated in RPA (dashed [blue] line) and QTBA (solid [red] line) using the SV-m56-O Skyrme parameters. The experimental data are given by the (brown) dots connected by a solid line [28].

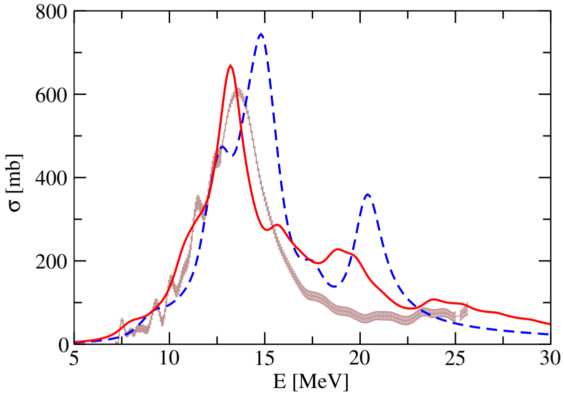

FIG. 3 (color online). Comparison of the experimental photo absorption cross section [29] in ^{208}Pb ([brown] dots with bars), with theoretical ones calculated in RPA (dashed [blue] line) and QTBA (solid [red] line). The Skyrme parametrization SV-m56-O was used.

functional. For this reason, we exclude this part of the interaction in our calculations.

The number of solutions of the RPA equations depends on the size of the configuration space. However, the majority of the RPA wave functions is dominated by a one-particle-hole configuration. In principle, one has to subtract the second-order contributions to complex (ph phonon) configurations in order to avoid double counting [27]. For simplicity, the present calculations consider only a small number of phonons, defined by having transition probabilities of at least 1/5 of the strongest state of each multipolarity. For these phonons, the second-order corrections are small and have been neglected.

In Fig. 1, we show the sensitivity of the photo absorption cross sections, obtained in the framework of RPA, on small variations of the effective mass. We used two different values $m^*/m = 0.56$ and 0.64. The higher effective mass gives lower GDR energies in all three nuclei. As we are interested in a Skyrme parametrization which reproduces the GDR in ^{16}O, we present here only results for the lower effective mass. Note that the present calculations improve the description of the GDR in ^{16}O in comparison with other self-consistent approaches. As only a few collective states exist in ^{16}O, we do not expect strong modifications of the RPA results due to the phonons. This is indeed the case and is demonstrated in Fig. 2, where we compare the RPA and QTBA results. The Lorentzian parameters of the photo absorption cross section [1] derived from the data of Refs. [28–30] are summarized in Table II for ^{208}Pb, ^{40}Ca, and ^{16}O. The data shown here and in the subsequent figures [28–30] are also available electronically [31]. In Fig. 3 we present the dipole photo absorption cross section in ^{208}Pb calculated with the Skyrme parametrization SV-m56-O and compare them with the data [29]. The result of the conventional RPA is compared with the QTBA where the phonons are included. In RPA, the mean energy of the GDR $\bar{E} = 14.30$ MeV is too high. The rather large width $\Gamma = 4.96$ MeV in the RPA is explained by a strong peak in the cross section at 20.4 MeV, i.e., in the

TABLE II. Comparison of theoretical and experimental [28–30] Lorentzian parameters. The energies considered range from 8–25 MeV for ^{208}Pb and from 10–32 MeV for ^{40}Ca and ^{16}O.

Nucleus	Force	$\bar{E}$ [MeV]	Γ [MeV]	σ_0 [mb]
^{208}Pb	SV-m56-O (RPA)	14.30	4.96	624
	SV-m56-O (QTBA)	13.37	5.99	495
	Experiment	13.43	5.08	481
^{40}Ca	SV-m56-O (RPA)	21.61	5.90	104
	SV-m56-O (QTBA)	21.14	5.92	99
	Experiment	20.00	5.00	95
^{16}O	SV-m56-O (RPA)	25.31	8.95	25.7
	SV-m56-O (QTBA)	24.49	8.85	24.8
	Experiment	23.76	7.17	24.8

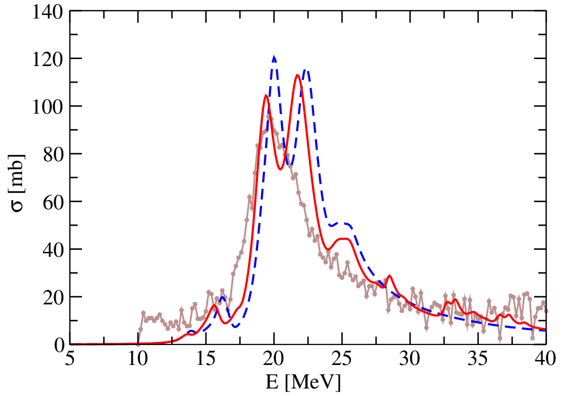

FIG. 4 (color online). The same as in Fig. 3, but for ^{40}Ca. The data are taken from Ref. [30].

high-energy tail of the GDR. The phonons shift the GDR to lower energies, where the mean energy $\bar{E} = 13.37$ MeV and the width $\Gamma = 5.99$ MeV are now in good agreement with the experimental data. We investigated the photo absorption cross section in ^{40}Ca with the same Skyrme force SV-m56-O as an example for an intermediate mass nucleus which is shown in Fig. 4. The RPA result is about 1.6 MeV higher compared to the data. The cross section calculated within the QTBA is shifted by 0.5 MeV to lower energies and agrees better with experiment.

In summary, we show that the explicit inclusion of quasiparticle-phonon coupling may solve the problem of mean-field theories in reproducing the centroid energies of the giant dipole resonance. As the phonon contribution is small in light nuclei, but large in heavy mass nuclei, phonon excitations provide a mass-dependent mechanism for damping and energy shift. Calculations employing two new Skyrme interactions show a reasonable quantitative agreement with the experimental dipole excitations in ^{16}O, ^{40}Ca, and ^{208}Pb.

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