Giant Dipole Resonance as a Fingerprint of α Clustering Configurations in ^{12}C and ^{16}O

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It is studied how the α cluster degrees of freedom, such as α clustering configurations close to the α decay threshold in ^{12}C and ^{16}O, including the linear chain, triangle, square, kite, and tetrahedron, affect nuclear collective vibrations with a microscopic dynamical approach, which can describe properties of nuclear ground states well across the nuclide chart and reproduce the standard giant dipole resonance (GDR) of ^{16}O quite nicely. It is found that the GDR spectrum is highly fragmented into several apparent peaks due to the α structure. The different α cluster configurations in ^{12}C and ^{16}O have corresponding characteristic spectra of GDR. The number and centroid energies of peaks in the GDR spectra can be reasonably explained by the geometrical and dynamical symmetries of α clustering configurations. Therefore, the GDR can be regarded as a very effective probe to diagnose the different α cluster configurations in light nuclei.

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Introduction.—Clustering is one of the most fundamental physics aspects in light nuclei. It is typically observed as excited states of those nuclei and also in the ground states for nuclei far from the β stability line, where nuclei can behave like molecules composed of nucleonic clusters. A great deal of research work has been focused on α clustering for more than four decades [1,2]. It is well established that α clustering plays a very important role in self-conjugate light nuclei near the α decay threshold due to the high stability of the α particle and the strong repulsive α-α interaction [2–4]. At low densities and temperatures, strong alpha clustering of the nuclei is also predicted [5]. An important effect on the nuclear equation of state due to the clustering effect was also reported at low densities [6–9]. The influence of clustering on nucleosynthesis is a fundamental problem to answer in nuclear astrophysics [10]. However, many problems have not yet been well understood, such as how α clustering determines the configurations and shapes of the many-body system and what are the aspects of the collective dynamics of α clustering systems and the underlying mechanism, etc. [11–15].

Isovector nuclear giant dipole resonances (GDRs), as the most pronounced feature in the excitation of nuclei throughout the whole nuclide chart, can give crucial clues to understand nuclear structure and collective dynamics. It is well established that the centroid energy of this resonance can provide direct information about nuclear sizes and the nuclear equation of state [16]. Meanwhile, the GDR width closely relates with nuclear deformation, temperature, and angular momentum [16–18]. The GDR strength has a single peak distribution for spherical nuclei with mass number > 60. The GDR in light nuclei is usually fragmented [16,19,20]. For nuclei far from the β stability line, another low-lying component appears called pygmy dipole resonance [21–24], which relates with the oscillation between the valence nucleons and the core.

It can be expected that multifragmented peaks, rather than only one broad peak in the GDR spectra, can also be obtained for self-conjugate (α) nuclei such as ^{12}C and ^{16}O with a prominently developed α cluster structure in excited states. Therefore, it is very interesting to study how an α cluster component manifests itself in GDRs. The GDR spectra should provide important and direct information to reveal the geometrical configurations and dynamical interactions among α clusters. In this work, we report on the results of GDRs of α cluster states in light excited self-conjugate nuclei within a microscopic dynamical many-body approach. Then, the way in which the different α configurations affect the GDR distributions is investigated and the underlying mechanism responsible for the collective motion is addressed.

For ^{12}C, triangularlike configuration, is predicted around the ground state by fermionic molecular dynamics [25], antisymmetrized molecular dynamics [26,27], and covariant density functional theory [28], which is supported by a new experiment [29]. A three-α linear-chain configuration was predicted as an excited state with different approaches [11,28,30]. The intrinsic density of ^{12}C and ^{16}O may display localized linear-chain density profiles as an excitation of the condensed gaslike states described with the Brink wave function and the Tohsaki-Horiuchi-Schuck-Röpke wave function [4,31,32]. For ^{16}O, the linear-chain structure with four-α clusters was supported by the alpha cluster model [33] and the cranked Skyrme Hartree-Fock method [12]. A tetrahedral structure of ^{16}O, made out of four-α clusters, is found above the ground state with the constrained Hartree-Fock-Bogoliubov approach [5]. However, recent calculations with chiral nuclear effective field theory [34], covariant density functional theory [28], and an algebraic model [35] also support the tetrahedral α

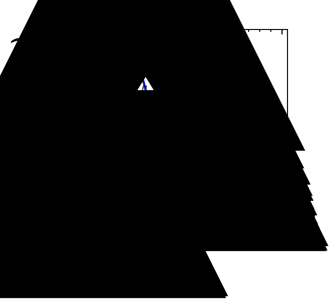
$$D''(\omega) = \int_{t_0}^{t_{\max}} D''_G(t) e^{i\omega t} dt, \tag{7}$$

the strength of the dipole resonance of the system at excited energy $E = \hbar\omega$ can be obtained, i.e.,

$$\frac{dP}{dE} = \frac{2e^2}{3\pi\hbar c^3 E} |D''(\omega)|^2, \tag{8}$$

where dP/dE can be interpreted as the nuclear photo-absorption cross section. It can be normalized as $(dP/dE)_{\rm norm} = (dP/dE)\Delta E / \int_0^\infty (dP/dE) dE$, where ΔE is the energy range of the GDR concerned. In realistic calculations, we take the integral interval from 8 to 40 MeV, which is consistent with the energy region of the GDR. The normalized dP/dE is calculated in the excitation-energy region from 8 to 35 MeV, which includes almost all the physically relevant GDR peaks. When displaying the dP/dE spectrum, a smoothing parameter $\Gamma = 2$ MeV was used (our calculation shows that the GDR width almost does not depend on Γ).

Results and discussion.—The GDR spectrum of ^{16}O obtained in the way described above is compared against the experimental data [48] and first principles calculations [49] shown in Fig. 1(a). Figure 1(b) shows the ^{16}O dipole oscillation in two decomposed directions versus time for one event. The wave function of the ^{16}O system at the ground state is obtained at a binding energy of 7.82A MeV, which is very close to the experimental binding energy: 7.98A MeV. The resulting ground state consists of four α particles with a tetrahedral configuration. The tetrahedral four-α configuration in the ^{16}O ground state is also supported by a new *ab initio* calculation of by Epelbaum *et al.* [34] using chiral nuclear effective field theory. In addition, a recent covariant density fu[redacted]tional theory calculation also shows regular tetrahedr[redacted]r-α configuration in the ground state of ^{16}O [28]. T[redacted]ashed red line represents the calculated GDR of ^{16}[redacted]ged Lorentz integral transform of a dipole resp[redacted]btained with the coupled-cluster method



from first principles. The comparison with data confirms that the tetrahedral four-α configuration in initialization is reasonable and the procedure used to calculate GDRs is reliable. Then, we apply the method to explore GDRs for excited α cluster states.

For light stable nuclei, the α cluster structure is expected around the threshold energy $E_{n\alpha}^{\rm thr} = nE_\alpha$ of the $n\alpha$ emission. The Pauli principle plays a more and more important role when the α cluster degrees of freedom become more pronounced. Therefore, to quantitatively depict the energy of α cluster states, the running parameter of c_P, which depends on the density, excitation energy, or temperature of the system, is needed. Thus, the α clustering states with different configurations around the threshold $E_{n\alpha}^{\rm thr}$ are obtained with 20 MeV Pauli potential strength, where α clusters are weakly bound, less than 1 MeV per cluster, in all systems considered.

For ^{12}C, there are linear-chain and regular triangle configurations. For ^{16}O, we consider linear-chain, kitelike [33], and square configurations. Different configurations of α clustering give different mean-field characteristics, which will essentially affect the collective motion of nucleons, e.g., in GDRs. This speculation is verified by Fig. 2.

The GDR is anisotropic for α configurations shown in Fig. 2, which originates from the fact that α clusters are in a plane or in a linear chain in ^{8}Be, ^{12}C, and ^{16}O. We decompose the collective motion into two directions. One direction is perpendicular to the plane or the line of the α configurations, called the short axis, indicated by long dashed red lines. The other direction is in the plane or chain, and we take the longest axis of configuration as this direction, called the long axis, indicated by solid blue lines in Fig. 2.

The GDR spectra along the short axis have a single peak around 30 MeV for all the cases considered in Fig. 2. It can be easily understood that the mean field along short axis is the same for different α cluster configurations. The peak at 30 MeV indicates the intrinsic collective dipole resonance of each α cluster, not affected by other degrees of freedom, which is consistent with the experimentally observed GDR of the α clusters in excited $A = 6$ and 7 nuclei with possible α cluster structure [20], where each α feels some neighboring nucleons and, thus, has a slightly increased effective mass.

Different α configurations give different GDR spectra along the long axis shown by the solid blue line. Comparing the results of ^{16}O linear-chain [Fig. 2(d)] and square [Fig. 2(f)] configurations, one sees that the main peaks are at different positions, i.e., 12 MeV for linear-chain configurations and 20 MeV for square configurations. Chain configurations with four α's in a chain have a larger size than four α's in a square configuration. The mean field with the larger scale is responsible for a lower GDR peak, which is consistent with physics that the reconstruct the GDR state. The experiment could be realized on a high intensity γ-ray source, such as the HIγS, which has gone into operation recently [51].

Conclusions.—In summary, within a microscopic dynamical framework, we revealed how α configurations affect nuclear collective motion, specifically, the GDR excitation. The dipole strengths of different α cluster configurations have different characteristic spectra. The characteristic spectra depicted by the number of main peaks and their centroid energies can be explained very well by the geometrical and dynamical symmetries and are insensitive to fine binding energy for given configurations. Therefore, the GDR spectrum is a very promising unique experimental probe to study light nuclei with possible α cluster configurations. The measurement of the GDR peak located around 30 MeV is a feasible way to confirm the existence of an α clustering state. Analysis of other low-lying peaks can be used to diagnose the different configurations formed by α clusters; for example, in the GDR spectra of chain ^{12}C and kite ^{16}O, there exist similar GDR spectra of ^{8}Be and triangle ^{12}C, respectively.

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