Pigmy and giant dipole states in oxygen isotopes

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We have studied dipole states of oxygen isotopes in large scale shell model calculations. The calculated photoreaction cross sections in ^{16}O and ^{18}O give reasonable agreement with experimental observations both in the low energy region below $\hbar\omega = 15$ MeV and in the high energy giant resonance region ($15\,\mathrm{MeV} < \hbar\omega \leq 30\,\mathrm{MeV}$). We found that the transition strength below giant dipole resonance ($\hbar\omega \leq 15$ MeV) exhausts about 10% of the classical Thomas-Reiche-Kuhn sum rule value in heavier oxygen isotopes than ^{18}O. The $T_>$ GDR (giant dipole resonance) appears in ^{18}O and ^{20}O having comparable transition strengths with the $T_<$ GDR, while $T_>$ strengths become much smaller than $T_<$ ones in ^{22}O and ^{24}O. [S0556-2813(99)02706-5]

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A study of giant resonances (GR) is one of the current issues in atomic nuclei, especially near the drip lines. GR are distinguished by different multipolarity and spin-isospin quantum numbers. Among various excitation modes, the isovector (IV) giant dipole resonances (GDR) are the most established ones throughout the mass table with large cross sections, exhausting most of the classical Thomas-Reich-Kuhn (TRK) sum rule [1,2,3]. This implies a participation of large numbers of particle-hole (p-h) excitations to create GDR as a typical collective motion. In general, the excitation energies of giant resonances are higher than the nucleon separation energy (about 8 MeV) in stable nuclei.

Recently a study of excited states in drip line nuclei have been discussed often because of the unique features relating the small separation energies and large neutron-proton mass asymmetry. One of the new observations is the soft dipole excitation in ^{11}Be and ^{11}Li [4]. Because of the large asymmetry between neutron and proton numbers, a different shell structure is expected in nuclei near drip lines. Then the structure of GDR will be also different from that of stable nuclei, especially in the low energy region below GDR [5,6]. In this paper, we will study the dipole excitations of oxygen isotopes, especially focusing on the low energy strength (so-called Pigmy resonance) below the GDR region by large scale shell model calculations. We will also discuss the isospin structure of the strength distributions.

As a microscopic model, we perform the shell model calculations in a large configuration space including $0s$-$0p$-$1s0d$-$1p0f$ shells. The effect of $3\hbar\omega$ excitations is also discussed in ^{16}O. A recently developed Warburton-Brown interaction WB10 [7] is used in this study with the model space ($0s$-$0p$-$1s0d$-$1p0f$). The center of mass spurious components in the wave functions are pushed up to higher excitation energies by adding a fictitious Hamiltonian which acts only on the center of mass excitation [8]. In a restricted model space, there still remain some spurious components in the wave functions after the diagonalization of the model Hamiltonian. In order to remove the effect of these spurious components on the transition strength, we use the effective transition operator

$$\hat{O}^{\lambda=1}_{\mu} = e\sum_i^A \left(t_{zi} - \frac{N-Z}{2A}\right) r_i Y_{1\mu}(\hat{r}_i)$$
$$= e\frac{Z}{A}\sum_i^N r_i Y_{1\mu}(\hat{r}_i) - e\frac{N}{A}\sum_i^Z r_i Y_{1\mu}(\hat{r}_i) \tag{1}$$

in which the center-of-mass correction is subtracted from the IV dipole transition operator. The transition strength $B(E1)$ is defined as

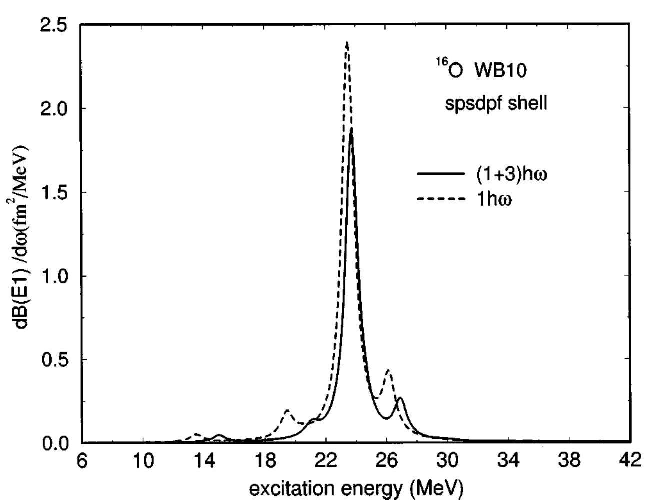

FIG. 1. $E1$ strengths of shell model calculations in ^{16}O with Warburton-Brown WB10 interaction. The solid line shows the $d\overline{B}(E1)/d\omega$ value (3) including $(1+3)\hbar\omega$ excitations in the full ($0s$-$0p$-$1s0d$-$1p1f$) shell model space, while the dashed line includes only $1\hbar\omega$ excitations.

TABLE I. Integrated photoreaction cross sections σ_{-1} (mb) and $\sigma_{\rm int}$ (MeV mb). Calculations are performed in $(0s\text{-}0p\text{-}1s0d\text{-}1p0f)$ shell model space with the Warburton-Brown WB10 interaction. The cross sections are integrated until $\hbar\omega = 40$ MeV for $T_<$ state, while the integration goes up to $\hbar\omega = 60$ MeV for $T_>$ state. For details, see the text.

	$T_<$		$T_>$		
A	σ_{-1} (mb)	$\sigma_{\rm int}$ (MeV mb)	σ_{-1} (mb)	$\sigma_{\rm int}$ (MeV mb)	$\sigma_{\rm int}$ (TRK)
^{16}O ($1\hbar\omega$)			18.56	435.2	240
^{16}O ($3\hbar\omega$)			14.52	354.7	240
^{18}O	9.36	186.4	7.72	203.6	267
^{20}O	11.56	231.3	4.12	120.7	288
^{22}O	10.88	212.4	2.32	75.7	305
^{24}O	13.88	266.4	1.24	43.6	320

$$B(E1;\omega_n) = \sum_\mu |\langle n|\hat{O}_\mu^{\lambda=1}|\text{g.s.}\rangle|^2, \tag{2}$$

where the matrix element is calculated between the ground state ($|\text{g.s.}\rangle$) and the nth excited 1^- shell model state ($|n\rangle$) with the excitation energy $\hbar\omega_n$. In order to smooth out the discrete strength, the transition strength is averaged by a weight factor $\rho(\omega)$ as

$$\frac{d\bar{B}(E1;\omega)}{d\omega} = \sum_n B(E1;\omega_n)\rho(\omega-\omega_n), \tag{3}$$

where

$$\rho(\omega-\omega_n) = \frac{1}{\pi}\frac{\Gamma/2}{(\omega-\omega_n)^2+(\Gamma/2)^2}. \tag{4}$$

The weight factor can be considered to simulate the escape and the spreading widths. The width parameter Γ is arbitrary taken as 1 MeV to draw a smooth curve of the transition strength. The oscillator length of the harmonic oscillator wave function is taken as $b = (\hbar/m\omega_0)^{1/2} = 1.8$ fm. It is known that the photoreaction cross section σ is related with the transition strength $\bar{B}(E1;\omega)$. The total photoreaction cross section $\sigma_{\rm int}$ and the first inverse energy moment σ_{-1} are written as [9]

$$\sigma_{\rm int} = \int \sigma d\omega = \frac{16\pi^3}{9\hbar c}\int_0^{E_{\rm max}} \omega \frac{d\bar{B}(E1;\omega)}{d\omega} d\omega, \tag{5}$$

$$\sigma_{-1} = \int \sigma\omega^{-1} d\omega = \frac{16\pi^3}{9\hbar c}\int_0^{E_{\rm max}} \frac{d\bar{B}(E1;\omega)}{d\omega} d\omega. \tag{6}$$

The sum rule is an useful measure of the collectivity in GR. For the IV GDR, the energy weighted sum rule value is given by

$$S(\text{TRK}) = \sum_n \hbar\omega_n |\langle n|\hat{O}_\mu^{\lambda=1}|\text{g.s.}\rangle|^2 = \frac{\hbar^2}{2m}\frac{9}{4\pi}\frac{NZ}{A}e^2$$
$$= 14.9\frac{NZ}{A}e^2 \quad (\text{MeV fm}^2) \tag{7}$$

neglecting the contributions of exchange terms. This sum rule is known as the classical Thomas-Reiche-Kuhn (TRK) sum rule. The cross section $\sigma_{\rm int}$ is then expressed as

TABLE II. Integrated photoreaction cross sections $\sigma_{\rm int}$ and the summed transition strengths $B(E1)$ in the low energy region ($\hbar\omega \le 15$ MeV) and the high energy region ($15\ \text{MeV} \le \hbar\omega \le 30$ MeV). Calculations are performed in $(0s\text{-}0p\text{-}1s0d\text{-}1p0f)$ shell model space with the Warburton-Brown WB10 interaction.

		$\hbar\omega \le 15$ MeV		$15\ \text{MeV} \le \hbar\omega \le 30$ MeV	
A	Isospin	$B(E1)$ (fm^2)	$\sigma_{\rm int}$ (MeV mb)	$B(E1)$ (fm^2)	$\sigma_{\rm int}$ (MeV mb)
^{16}O ($1\hbar\omega$)	$T_> = 1$	0.07	3.82	4.64	435.1
^{16}O ($3\hbar\omega$)	$T_> = 1$	0.06	3.53	3.84	337.0
^{18}O	$T_< = 1$	0.394	17.14	2.27	177.8
	$T_> = 2$	0.0	0.0	1.81	187.6
^{20}O	$T_< = 2$	0.686	31.26	2.62	197.8
	$T_> = 3$	0.0	0.0	0.61	65.2
^{22}O	$T_< = 3$	0.741	30.40	2.42	172.7
	$T_> = 4$	0.0	0.0	0.18	20.7
^{24}O	$T_< = 4$	0.709	27.45	3.22	232.8
	$T_> = 5$	0.0	0.0	0.0	0.0

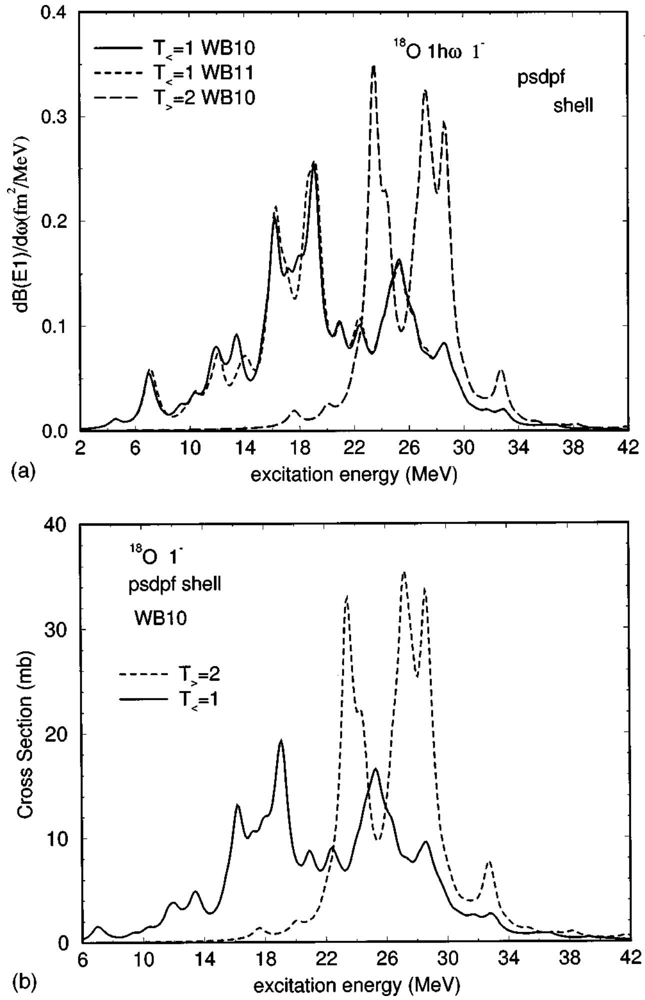

FIG. 2. (a) $E1$ strengths of shell model calculations of $1\hbar\omega$ excitations in the $(0p\text{-}1s0d\text{-}1p0f)$ shell model space in ^{18}O with WB10 and WB11 interactions. The solid (short-dashed) line shows the $d\overline{B}(E1)/d\omega$ value (3) of the $T_<$ states with WB10 (WB11) interaction, while the long-dashed line shows that of the $T_>$ states with WB10 interaction. (b) Photoreaction cross sections of ^{18}O. The solid line shows the cross section σ in Eq. (5) of the $T_<$ states, while the dashed line shows that of the $T_>$ states.

$$\sigma_{\rm int}=\frac{16\pi^3}{9\hbar c}S(\mathrm{TRK})=60\frac{NZ}{A}\ \ (\mathrm{MeV\,mb}). \tag{8}$$

The calculated results of averaged dipole strength (3) in ^{16}O are shown in Fig. 1 and the total photoreaction cross sections $\sigma_{\rm int}$, σ_{-1} and the summed transition strength are tabulated in Tables I and II. The observed photoreaction cross sections are $\sigma_{\rm int}=128.5$ MeV mb and $\sigma_{-1}=5.52$ mb in the energy region (16.5–29.0) MeV [2]. The observed $\sigma_{\rm int}$ value exhausts 61% of the TRK sum rule, while the calculated sums shows the enhancement factor κ for the sum rule, i.e., $\kappa=0.81$ (0.48) in the $1\hbar\omega(3\hbar\omega)$ calculations. The experimental mean energy of GDR is given by $\overline{E}_x=\sigma_{\rm int}/\sigma_{-1}=128.5/5.52=23.2$ MeV, while the calculated peak energies are found at $E_x=23.5$ MeV and $E_x=23.7$ MeV in the $1\hbar\omega$ and $3\hbar\omega$ calculations, respectively. One can see that the calculated values show reasonable agreement with the experimental one. It is interesting to notice that the difference between the two calculations is only 200 keV for the peak energy, although the total cross section of $3\hbar\omega$ calculation is 20% smaller than that of $1\hbar\omega$ calculation.

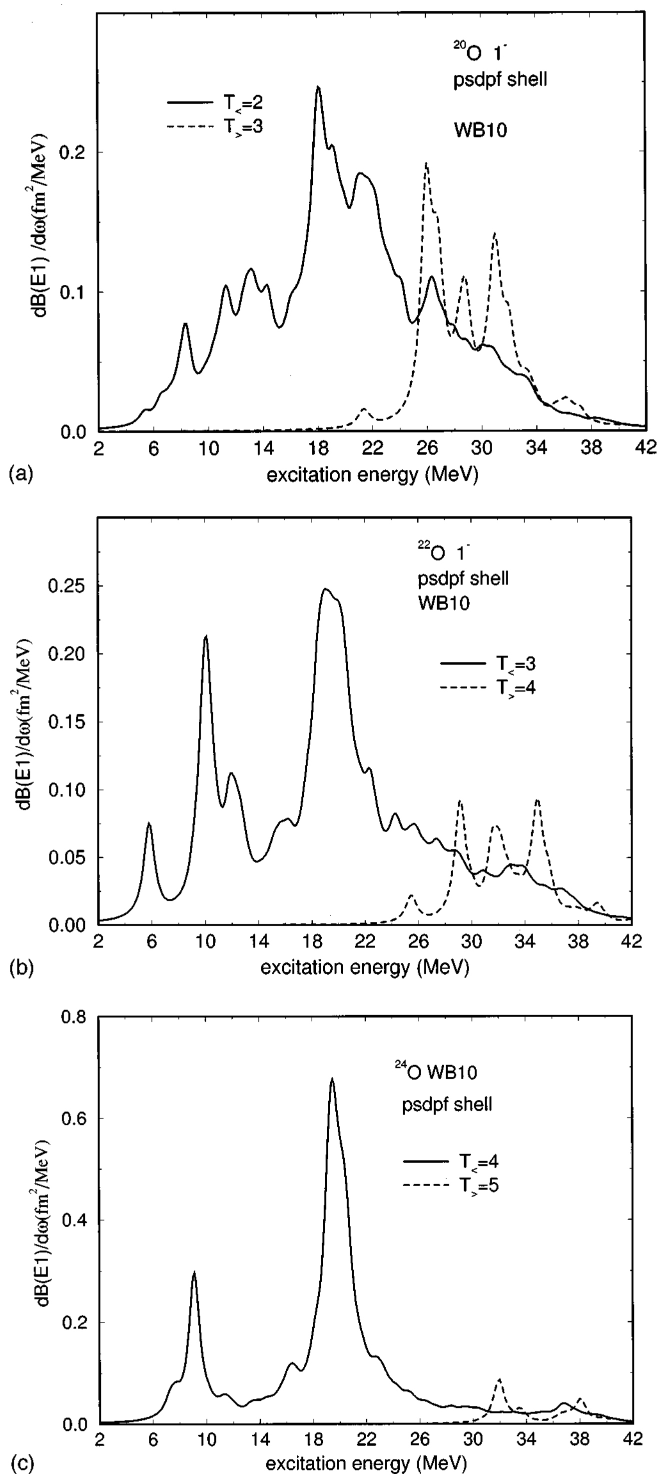

FIG. 3. $E1$ strengths $d\overline{B}(E1)/d\omega$ of shell model calculations of $1\hbar\omega$ excitations in the $(0p\text{-}1s0d\text{-}1p0f)$ shell model space with WB10 interaction. (a) ^{20}O, (b) ^{22}O, (c) ^{24}O. The solid line shows the $d\overline{B}(E1)/d\omega$ value of the $T_<$ states, while the dashed line shows that of the $T_>$ states.

The calculated transition strength $d\overline{B}(E1;\omega)/d\omega$ and the photoreaction cross section σ in ^{18}O are shown in Figs. 2(a) and 2(b), respectively. The electric dipole transition strengths for $T_<$ states are calculated by using two Warburton-Brown interactions WB10 and WB11 in Fig. 2(a). Essentially no interaction dependence is found in the strength distributions of $T_<$ states. We can see appreciable cross sections in ^{18}O below 15 MeV, while there is essentially nothing in ^{16}O in the same energy region. The calculated cross section $\sigma_{\rm int}$ below 15 MeV is $\sigma_{\rm int}=17.14$ MeV mb, while the observed one is 22.4 MeV mb ($\hbar\omega \leqslant 14$ MeV) in Ref. [2] and 15.1 MeV mb (8.5 MeV$\leqslant \hbar\omega \leqslant$13.4 MeV) in Ref. [10]. The agreement between theory and experiment is reasonable as far as the integrated cross section is concerned. The dominant peak of $T_<=1$ dipole states is found at around $E_x=18$ and 25 MeV, while there are two large peaks at around $E_x=24$ and 28 MeV for $T_>=2$ states. The experimental mean energies are $\overline{E_x}=\sigma_{\rm int}/\sigma_{-1}=122.2/6.52=18.7$ MeV and $120.4/4.20=28.7$ MeV for $T_<=1$ and $T_>=2$ states, respectively. The calculated values of the peak energies are close to the experimental resonance energies of both isospins as seen in Fig. 2.

The calculated dipole strengths of ^{20}O, ^{22}O, and ^{24}O are shown in Figs. 3(a), 3(b), and 3(c), respectively. The sum of the transition strength $B(E1)$ and the total photoreaction cross sections are listed in Tables I and II. The dipole strengths below the GDR region become substantial in these three nuclei. Namely, the cross sections $\sigma_{\rm int}$ below $\hbar\omega=15$ MeV exhaust 11%, 10%, and 8.6% of the TRK sum rule. The GDR peaks with the isospin $T_<$ are found always at around $\hbar\omega=20$ MeV in these three nuclei. On the other hand, the $T_>$ peaks appears more than 10 MeV higher in energy than the $T_<$ peaks, and smaller in peak height in heavier oxygen-isotopes. In the extreme case of ^{24}O, the cross section $\sigma_{\rm int}$ of $T_>$ states becomes only 14% of the TRK sum rule.

In summary, we have studied the Pigmy and GDR dipole strengths of oxygen isotopes by using shell model calculations in a large scale shell model ($0p$-$1s0d$-$1p0f$) space. We found that the excitation energies of GDR in ^{16}O and ^{18}O show a good agreement with the experimental data of the two isospin resonances, $T_>$ and $T_<$. Moreover the calculated Pigmy strength in ^{18}O below $\hbar\omega=15$ MeV is consistent with the experimental photoreaction cross sections. In heavier oxygen isotopes than ^{18}O, the $T_<$ GDR has always a peak at around $\hbar\omega=20$ MeV, while the $T_>$ peak is more than 10 MeV higher in energy and smaller in the cross section than the $T_<$ one. On the other hand, in these heavy isotopes, the Pigmy resonances are more pronounced than that of ^{18}O, having about 10% of the TRK sum rule transition strengths. Future experimental effort is highly desirable to observe these Pigmy resonances to clarify the structure of drip line nuclei [6].

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