Collective Correlations in the Giant Dipole Continuum of ^{12}C

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A continuum shell-model calculation based on the collective correlation model has been made for the giant resonance of ^{12}C using the eigenchannel reaction theory. The low-lying negative-parity states of ^{11}C and ^{11}B have been taken into account by core-hole coupling. Partial, total, and integrated photoabsorption cross sections are calculated for the region of the giant dipole resonance.

The gross structure in the giant dipole resonance (GDR) of light and heavy magic nuclei has been successfully explained in terms of the 1p-1h (one-particle, one-hole) shell model. Higher-resolution experimental investigations, for example, in ^{12}C and ^{16}O have, however, revealed more structure than is explicable by the simple 1p-1h model. One approach to the understanding of the extra intermediate structure in ^{12}C and several other light nuclei was suggested by Drechsel, Seaborn, and Greiner.[1] In their theory of collective correlations, they coupled the 1^- 1p-1h doorway states to the quadrupole vibrations of the nuclear surface, thereby explaining much of the observed structure.

In this work we investigate the GDR of ^{12}C following closely the treatment of Drechsel, Seaborn, and Greiner, with the difference that the effect of the one-particle continuum and the low-lying negative-parity states of ^{11}C and ^{11}B are properly taken into account. Contrary to the unrealistic bound-state calculation, the continuum calculation can make explicit predictions of the various observable quantities such as partial and total cross sections, and the angular distributions of the reaction products.

In treating the one-particle continuum we use the eigenchannel method developed by Danos and co-workers.[2,3] This method has been discussed fully in a recent review article.[4] The reliability and accuracy of the method have been investigated by Delsanto, Roetter, and Wahsweiler[5]; and it has previously been applied to the calculation of the GDR of all doubly magic nuclei in a 1p-1h continuum shell-model approximation.[4,6,7]

In the collective correlation model, the full semimicroscopic Hamiltonian of the nucleus can be written as

$$H = H_{\mathrm{ph}} + H_{\mathrm{quad}} + H_{\mathrm{ph,quad}}, \tag{1}$$

where H_{ph} stands for the p-h Hamiltonian in the 1p-1h subspace:

$$H_{\mathrm{ph}} = \sum_i \epsilon_i a_i^\dagger a_i + \tfrac{1}{2}\sum_{klmn} \langle kl|V|mn\rangle a_k^\dagger a_l^\dagger a_n a_m = H^0 + V^0. \tag{2}$$

$a_i^\dagger$ and a_i are creation and annihilation operators, respectively, for nucleons in the single-particle state i. V is the residual two-body interaction, and ϵ_i is the Hartree-Fock single particle or hole energy. The residual interaction used by us is the short-range force

$$V_{ij} = V_0(a_0 + a_\sigma \vec{\sigma}_i \cdot \vec{\sigma}_j)\delta(\vec{r}_i - \vec{r}_j), \tag{3}$$

with the exchange mixture used by Elliot and Flowers[8]:

$$a_0 = 0.9, \quad a_\sigma = 0.1.$$

V_0 is the strength of the residual interaction and has been taken to be -750 MeV fm^3 in order to obtain the position of the GDR in agreement with experiment. H_{quad} is the quadrupole Hamiltonian describing the surface vibrations. In a harmonic approximation this is

$$H_{\mathrm{quad}} = \tfrac{1}{2}\sqrt{5}\{B_2^{-1}[\pi^{[2]}\times\pi^{[2]}]^{[0]} + C_2[\alpha^{[2]}\times\alpha^{[2]}]^{[0]}\}, \tag{4}$$

where $\alpha^{[2]}$ is a tensor of rank 2 and positive parity for the surface quadrupole collective variables, and $\pi^{[2]}$ the momentum conjugate to $\alpha^{[2]}$.

The interaction representing the collective correlations between the GDR and the surface vibrations is given by

$$H_{\mathrm{ph,quad}} = \kappa_1[[D_{\mathrm{ph}}^{[1]}\times D_{\mathrm{ph}}^{[1]}]^{[2]}\times\alpha^{[2]}]^{[0]} + \sum_{L=0,2}\kappa_{2L}[[D_{\mathrm{ph}}^{[1]}\times D_{\mathrm{ph}}^{[1]}]^{[L]}\times[\alpha^{[2]}\times\alpha^{[2]}]^{[L]}]^{[0]}, \tag{5}$$

where $D_{\mathrm{ph}}^{[1]}$ is the p-h dipole operator. For ^{12}C the numerical values of the renormalized coupling constants κ_1, κ_{20}, and κ_{22} given in Ref. 1 are $\kappa_1 = -10.86$ MeV fm^{-2}, $\kappa_{20} = -18.67$ MeV fm^{-2}, and $\kappa_{22} = -23.69$ MeV fm^{-2}.

In ordinary 1p-1h shell-model calculations for ^{12}C,[9,10] one cannot describe transitions to excited states of ^{11}C or ^{11}B. These calculations take the ^{12}C ground state to be a perfect jj-coupling shell-model state with a filled $p_{3/2}$ shell, and describe the GDR essentially in terms of a single dominant $[p_{3/2}^{-1} \times d_{5/2}]$ state. Hence, they predict that the residual nucleus will be left in a $p_{3/2}^{-1}$ hole state. In this work we have taken the transitions to the low-lying excited states of ^{11}C and ^{11}B into account. In a unified-model description Clegg[11] has shown that the wave functions for the $\frac{1}{2}^-$, $\frac{5}{2}^-$, $\frac{3}{2}^-$, and $\frac{7}{2}^-$ quartet of the low-lying excited states can, to a good approximation, be described by a $p_{3/2}$ nucleon hole coupled to the 2^+ first vibrational (i.e., one-phonon) state of ^{12}C at 4.43 MeV, whereas the $\frac{3}{2}^-$ ground state was well described by a $p_{3/2}$ nucleon hole coupled to the 0^+ ground state. Thus, following Clegg, our basis wave function can be written in the form

$$|n_h n_p;(j_h\lambda)\bar{I}j_p;J\rangle^{(\nu)} = \sum_I (-)^{j_p+\lambda+I+\bar{I}}[(2I+1)(2\bar{I}+1)]^{1/2} \begin{Bmatrix} j_h & j_p & \bar{I} \\ j & \lambda & \bar{I} \end{Bmatrix} |n_h n_p;(j_h j_p)I\lambda;J\rangle^{(\nu)}, \quad (6)$$

where h and p represent holes and particles, respectively, and { } denotes a $6j$ symbol. The radial quantum numbers are given by n, and the index ν on the ket is to indicate that the particle radial wave functions in the continuum depend on the eigenchannel boundary conditions. The angular momentum λ of the phonon can take the values 0 and 2. $\bar{I}$ represents the angular momentum of the low-lying states of ^{11}B or ^{11}C, and this has been coupled with that of the particle to the total angular momentum $J^\pi = 1^-$.

The solutions of (1) were obtained by diagonalization in the basis (6), where the single-particle and hole radial wave functions have been calculated in a Woods-Saxon potential with spin-orbit and Coulomb terms parametrized to describe the single-particle level scheme of ^{12}C. The same single-particle potential parameters were used as in the 1p-1h calculation of Marangoni and Saruis.[12] The energies of $H^0 + H_{\rm quad}$ have been phenomenologically taken to be those of the low-lying states of ^{11}B and ^{11}C. In this way, the effect of anharmonicity of the quadrupole surface vibrations is partially included. The parameters $\hbar\omega_2 = \hbar(C_2/B_2)^{1/2} = 4.43$ MeV and the vibrational amplitude $\beta_0 = (5\hbar\omega_2/2C_2)^{1/2} = 0.4$ were taken from the low-lying energy spectrum of ^{12}C.[13] The calculation of the photo cross sections is performed in exactly the same way as for a normal 1p-1h eigenchannel calculation. The states consisting of a phonon coupled to the 1p-1h states are not directly excited by the incoming photons since the collective dipole operator is approximated by the p-h dipole operator. Their influence is felt only through their coupling by means of $H_{\rm dip,quad}$ to the 1p-1h states. On the whole there were 22 coupled channels. The configurations considered for both protons and neutrons are

$$[[p_{3/2}^{-1}\times 0^+]^{3/2^-}\times s_{1/2}]^{1^-},\ [[p_{3/2}^{-1}\times 0^+]^{3/2^-}\times d_{3/2}]^{1^-},\ [[p_{3/2}^{-1}\times 0^+]^{3/2^-}\times d_{5/2}]^{1^-},\ [[p_{3/2}^{-1}\times 2^+]^{1/2^-}\times s_{1/2}]^{1^-},$$

$$[[p_{3/2}^{-1}\times 2^+]^{1/2^-}\times d_{3/2}]^{1^-},\ [[p_{3/2}^{-1}\times 2^+]^{5/2^-}\times d_{3/2}]^{1^-},\ [[p_{3/2}^{-1}\times 2^+]^{5/2^-}\times d_{5/2}]^{1^-},\ [[p_{3/2}^{-1}\times 2^+]^{3/2^-}\times s_{1/2}]^{1^-},$$

$$[[p_{3/2}^{-1}\times 2^+]^{3/2^-}\times d_{3/2}]^{1^-},\ [[p_{3/2}^{-1}\times 2^+]^{3/2^-}\times d_{5/2}]^{1^-},\ [[p_{3/2}^{-1}\times 2^+]^{7/2^-}\times d_{5/2}]^{1^-}.$$

The results of the calculation are shown in Figs. 1–3. Figure 1 shows the total photoabsorption cross section. The peaks at 17.7, 19.5, and 20.9 MeV of Fig. 1(b) are in good agreement with the experimental photoabsorption cross section of Fig. 1(a), and the splitting of the strength in the giant resonance region is also reproduced by the calculation. None of the vibrational satellites is as high in energy as the experimental peak at 25.5 MeV, however, a fact which is also true of the bound-state calculation of Drechsel, Seaborn, and Greiner. The theoretical integrated photoabsorption cross section to 27.15 MeV is about twice the experimental value in both the 1p-1h model [Fig. 1(c)] and the collective correlation model [Fig. 1(b)]. This is to be expected. The extra states in the collective correlation model do not contain any dipole strength in themselves and produce their effect by modulating the strength already contained in the 1p-1h doorway states.

In Fig. 2, the (γ, n) partial cross section is compared with the experimental result of Fultz *et al.*[15] and a recent result by van de Vijver *et al.*[16] The splitting of the giant resonance observed experimentally is again reproduced. Peaks at 22, 23.4, and 24.3 MeV in the calculated cross section correspond to those observed by Fultz *et al.* at 22, 23.2, and 25.5 MeV. As mentioned earlier, the last one is too low by about 1 MeV.

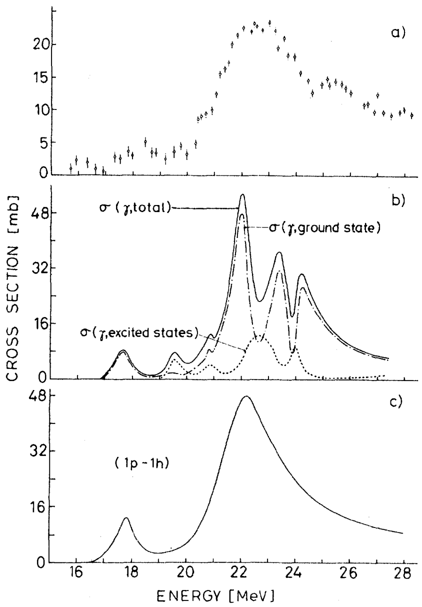

FIG. 1. Total photoabsorption cross section of ^{12}C. (a) Experimental result of Shevchenko and Yudin (Ref. 14). (b) Theoretical result with collective correlations including excited states of ^{11}C and ^{11}B. Solid curve, total cross section; dot-dashed curve, ground-state cross section; dotted curve, contribution of excited states. (c) Usual 1p-1h eigenchannel continuum calculation (without collective correlations) with residual force of $V_0 = -980$ MeV fm^3.

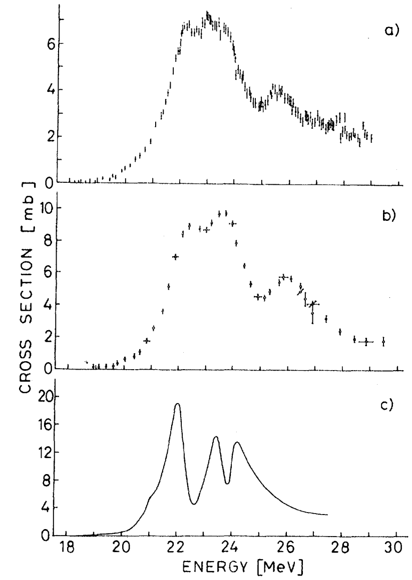

FIG. 2. Total photoneutron cross section of ^{12}C. (a),(b) Experimental data of Fultz *et al.* (Ref. 15) and van de Vijver *et al.* (Ref. 16), respectively. (c) Result with collective correlations.

83%, 6%, and 11%. For the (γ,p) process, the corresponding theoretical values are 80%, 8%, and 12% while Medicus *et al.* give 89%, 5%, and 6%. The overall agreement is thus semiquantita-

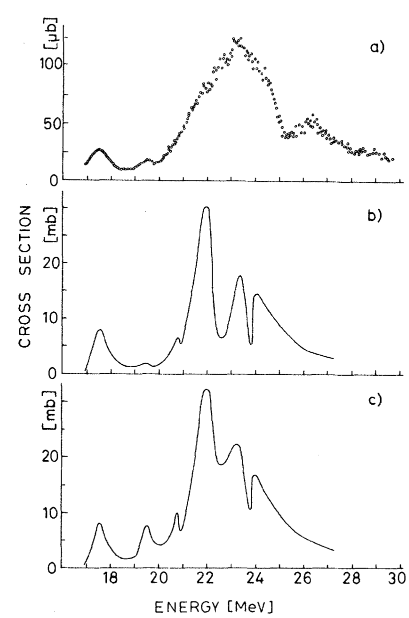

FIG. 3. Photo proton cross section of ^{12}C. (a) Experimental result of inverse photoreaction ^{11}B$(p,\gamma_0)^{12}$C according to Allas *et al.* (Ref. 17). (b),(c) Theoretical ground state (γ,p_0) and total (γ,p) cross sections, respectively.

Finally in Figs. 3(b) and 3(c) we present the results of the (γ,p_0) and (γ,p) partial cross sections, respectively. The experimental result of the inverse reaction ^{11}B$(p,\gamma_0)^{12}$C of Allas *et al.*[17] is shown in Fig. 3(a) for comparison. Besides the peaks in the giant resonance region already discussed earlier, the peaks at 17.7, 19.5, and 20.9 MeV are observed experimentally. The latter two are not present in a simple 1p-1h calculation and have been identified as one-phonon satellites of the 17.7-MeV $[p_{3/2}^{-1}\times s_{1/2}]$ peak.

The integrated differential cross sections at 90° associated with transitions to the ground and excited states have been calculated and compared with the experiments of Medicus *et al.*[18] and of Fultz *et al.*[15] The results are summarized as follows: About 91% of the integrated photoneutron cross section up to 27.15 MeV is associated with the ground-state transition, while 7% is associated with the first excited state and the remaining 2% with higher excited states. The experimental results of Medicus *et al.*, which included, apart from negative parity also positive-parity states, up to a 28-MeV limit of integration are 88%, 5%, and 7%, while those of Fultz *et al.* are tive. The inclusion of higher collective states (two and more phonons), which have been neglected here, and their coupling to the particle-hole configurations might further improve the agreement between theory and experiment.

In conclusion, the results of the eigenchannel calculation for the GDR of ^{12}C including collective correlations and the low-lying states of the mass-11 nuclei exhibit a marked improvement in the agreement with experiment over those based on a simple 1p-1h model. The intermediate structure of the GDR is better explained, and the calculations of the partial (γ,p) and (γ,n) cross sections to excited states of the residual nuclei show a semiquantitative agreement with experiment. Application of the model to other nuclei thus seems warranted.

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Two-Pomeranchukon Cuts and Vanishing of the Triple-Pomeranchukon Coupling*

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It is shown that the Gribov-Migdal lower bound on the magnitude of the two-Pomeranchukon cut is not valid unless both the triple-Pomeranchukon coupling $g_{PPP}(t, q_1^2, q_2^2)$ and its derivative $dg(t,q^2,q^2)/dq^2$ vanish when $t=q_1^2=q_2^2=0$. A numerical estimate of the cut is given. We give the connection between the behavior of g_{PPP} and the validity of the Bronzan and Jones unitarity condition on the discontinuity of the cut at $t=0$.

The importance of the triple-Pomeranchukon coupling g_{PPP} has recently become apparent both in phenomenology[1-3] and theoretical models.[4,5] It is generally believed that g_{PPP} vanishes when the masses of all three Reggeons coupled at the vertex vanish, although the mechanism for this is not yet clear.[6-9] We will assume that g_{PPP} vanishes linearly with the Pomeranchukon masses; and, *sine qua non*, the Pomeranchukon is a factorizable simple Regge pole with $\alpha(0)=1$. We will then obtain a formula connecting g_{PPP} to the discontinuity of the two-Pomeranchukon cut (Fig. 1). It follows that the Gribov-Migdal lower bound on the cut magnitude[4] is not generally valid; and, as a result, the absorption model