Particle-vibration coupling and the giant dipole resonance in 12C

Particle-Vibration Coupling and the Giant Dipole Resonance in ^{12}C

by **G. Baur**[1]) and **K. Alder**

Institute of Theoretical Physics, University of Basel, Switzerland

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Abstract. The cross sections for the reactions $^{12}C(\gamma, p)$ and $^{12}C(\gamma, n)$ in the giant resonance region have been calculated in a collective correlation model where the final nucleus may be in different excited states. The agreement with the rather incomplete experimental data is good.

I. Formulation of the Model

The main structure of the giant dipole resonance is well explained by the particle-hole interaction. In order to understand the fine structure, one also has to consider collective excitations which are coupled to the particle degrees of freedom.

In the reaction $^{11}B(p, \gamma_1)^{12}C^*$ [1] we describe the ground state of ^{11}B by a $p_{3/2}$ hole state and the first excited 2^+ level of ^{12}C by a collective vibrational state with a B (E2)-value of about 5 times the single particle strength. Further evidence for a vibrational structure may be obtained from the low lying energy spectra of ^{11}B and ^{11}C, which can be interpreted as phonon multiplets $(p_{3/2}^{-1} \otimes 2)\, j$. With this excited core model it is possible to explain $^{11}B(n, n')$ experiments [2]. A quite similar model has been used by Tamura [3] to describe elastic and inelastic scattering in the coupled channel formalism. The interaction between a hole and a collective excitation has been treated quite often theoretically, especially by Hamamoto [4]. Drechsel et al. [5] obtained an interaction between particle, hole and collective excitation, starting from a macroscopic dipole-quadrupole interaction.

In the following we consider only the interaction between particle and surface vibrations. The corresponding hole-vibration interaction is responsible for the observed energy splitting of the phonon multiplet. If we neglect the particle-vibration coupling, the following reactions and the corresponding time reversed reactions are possible:

$$\text{a)}\quad {}^{12}C + \gamma \to {}^{11}B + p_0$$
$$\to {}^{11}C + n_o\,,$$

$$\text{b)}\quad {}^{12}C^*_{4.43\,\text{MeV}} + \gamma \to {}^{11}B^* + p_i$$
$$\to {}^{11}C^* + n_i\,,$$

where the index 0 denotes the ground state, while $i = 1, 2, 3$ and 4 enumerates the different levels of the multiplet. It is, of course, not possible to measure the reactions

[1]) Present address: Max-Planck-Institut für Kernphysik, Heidelberg, Germany.

mentioned in b) and their influence can only be seen through the particle-vibration coupling which also makes the following reactions and their time reversed reaction possible:

c) $\quad {}^{12}\text{C} + \gamma \to {}^{11}\text{B}^* + p_i \qquad i = 1, 2, 3, 4$
$\qquad\qquad\to {}^{11}\text{C}^* + n_i ,$

d) $\quad {}^{12}\text{C}^*_{4.43\,\text{MeV}} + \gamma \to {}^{11}\text{B} + p_0$
$\qquad\qquad\to {}^{11}\text{C} + n_0 .$

As the reactions under d) have been considered before [6], we restrict ourselves to the treatment of the reactions c). The various reactions are illustrated in Figure 1. The

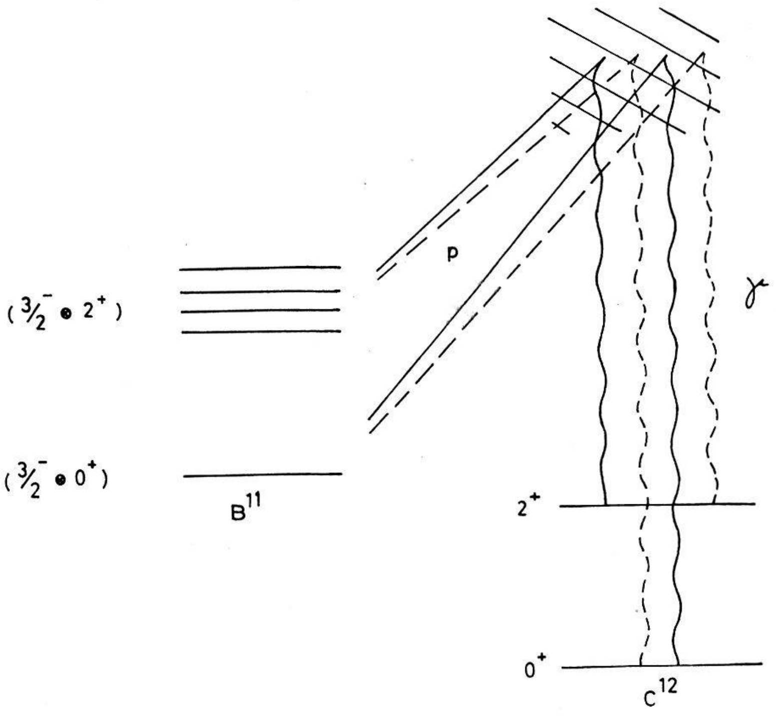

Figure 1
Schematic picture of the giant dipole resonance in ^{12}C. The reactions indicated with a continuous line are possible without a particle–vibration coupling term, those with a broken line become only possible by introducing such a coupling.

corresponding neutron channels are not shown in this figure. Because of the smallness of the particle-vibration coupling, small values for the cross sections for the reactions c) and d) compared to a) and b) are expected. This was confirmed in an experiment described in Reference [7]. It was found that only (7 ± 16) % of the final states of the reaction ${}^{12}\text{C} + \gamma$ belong to the phonon multiplet. Using the dipole sum rule, the following estimate for the cross sections integrated up to 30 MeV is obtained

$$\int^{30\,\text{MeV}} dE\, \sigma({}^{12}\text{C}^*(\gamma, p_0)) \cong \frac{1}{5} \int^{30\,\text{MeV}} dE\, \sigma({}^{12}\text{C}^*(\gamma, p_1 + p_2 + p_3 + p_4)) . \tag{1}$$

The total wave functions of our system consists of particle-hole and collective excitations. Using the notation of Reference [6] we make the following ansatz

$$\left.\begin{aligned}\psi_{1\text{-}M} &= \sum_{\alpha\beta} C_{\alpha\beta} \langle j_\alpha\, m_\alpha\, j_\beta\, m_\beta \mid 1\, M\rangle\, (-)^{j_\alpha - m_\alpha}\, a^+_\beta\, a_\alpha \mid 0\rangle \mid 0) \\ &+ \sum_{\alpha\beta M'\mu} D_{\alpha\beta} \langle j_\alpha\, m_\alpha\, j_\beta\, m_\beta \mid 1\, M'\rangle \langle 1\, M'\, 2\,\mu \mid 1\, M\rangle\, (-)^{j_\alpha - m_\alpha}\, a^+_\beta\, a_\alpha \mid 0\rangle\, b^+_\mu \mid 0) ,\end{aligned}\right\} \tag{2}$$

where the p-h excitations are always coupled to total spin 1^- (dipole vibrations). The final state is considered to result from the coupling of the hole with the surface vibration, the second term in equation (2) must therefore be recoupled in order to exhibit explicitly the coupling of the particle to the residual state. This leads to

$$\left.\begin{aligned}\psi_{1-M} &= \sum_{\alpha\beta} C_{\alpha\beta} \langle j_\alpha m_\alpha j_\beta m_\beta \mid 1 M\rangle (-)^{j_\alpha - m_\alpha} a_\beta^+ a_\alpha |0\rangle |0) \\ &+ \sum_{\alpha\beta M' \mu j} (-)^{j_\alpha - m_\alpha} D_{\alpha\beta} \sqrt{3(2j+1)} \begin{Bmatrix} j_\beta & j_\alpha & 1 \\ 2 & J & j \end{Bmatrix} \langle j_\alpha m_\alpha 2 \mu \mid j m\rangle \\ &\times \langle j_\beta m_\beta j m \mid 1 M\rangle a_\beta^+ a_\alpha |0\rangle b_\mu^+ |0) .\end{aligned}\right\} \qquad (3)$$

Assuming the same Hamiltonian as in Reference [6] the coupled channel equations given there are obtained. From these we can calculate the electric dipole matrix element $\langle \psi_{1-M} | D | C^{12}\rangle$ which describes the reactions ^{11}B*$(p, \gamma_0)^{12}$C and ^{11}C*$(n, \gamma_0)^{12}$C. The cross sections for ^{12}C$(\gamma, p_i)^{11}$B* and ^{12}C$(\gamma, n_i)^{11}$C* can then be calculated with the theorem of detailed balance. The cross section for the reaction $^{12}\mathrm{C} + \gamma \to N + A_j$ is given by

$$\sigma(\gamma, N_j) = \frac{8\pi e^2}{k_\gamma^2} \left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{(2j+1)^2}{\hbar v} \sum_{j_\beta l_\beta} \begin{Bmatrix} j_\beta & j_\alpha & 3 \\ 2 & J & j \end{Bmatrix}^2 |E_1(l_\alpha j_\alpha l_\beta j_\beta \tau)|^2 \qquad (4)$$

where N represents either a proton or a neutron and A_j stands for the corresponding final state of the phonon multiplet with spin j.

II. Results and Discussion

The cross sections for the reactions ^{12}C$(\gamma, p_i)^{11}$B* $(i = 1, 2, 3, 4)$ have not been measured directly. But there is evidence that they are small. The limit $(7 \pm 16)\%$ has been found (Ref. [7]) for transitions to the excited states compared to ground state transitions. However, for γ-energies above 30 MeV, these cross sections become comparable. In [8] the cross sections for (γ, p) and (p, γ_0) reactions have been compared. It is concluded that mainly ground state proton transitions occur. This has been confirmed in [9]. Absolute values of the cross sections to the first and higher excited states in ^{11}C are given in Reference [10]. It is of interest to have theoretical values for the branching ratios because certain experimental analyses (as e.g. in Ref. [11]) depend on the nonground state transitions.

The effect of the energy splitting of the phonon multiplet is reflected in the kinematical factors of the cross section. Apart from the effects near threshold, these factors do not differ greatly (less than 10%) if a degenerate phonon multiplet has been assumed. This has been done for the final results giving the following threshold energies for reactions leading to the phonon multiplets

$$E_{thr,p} = 20.39 \text{ MeV} \quad \text{and} \quad E_{thr,n} = 23.15 \text{ MeV} .$$

The results of these calculations are shown in Figures 2 and 3. The following parameter values have been assumed for the optical potential: $R = 2.67$ fm, $a = 0.425$ fm, $V_0 =$ 55.0 MeV, $V_{ls} = 7.5$ MeV and $W = 0.1\, E_p$. For the residual two particle interactions,

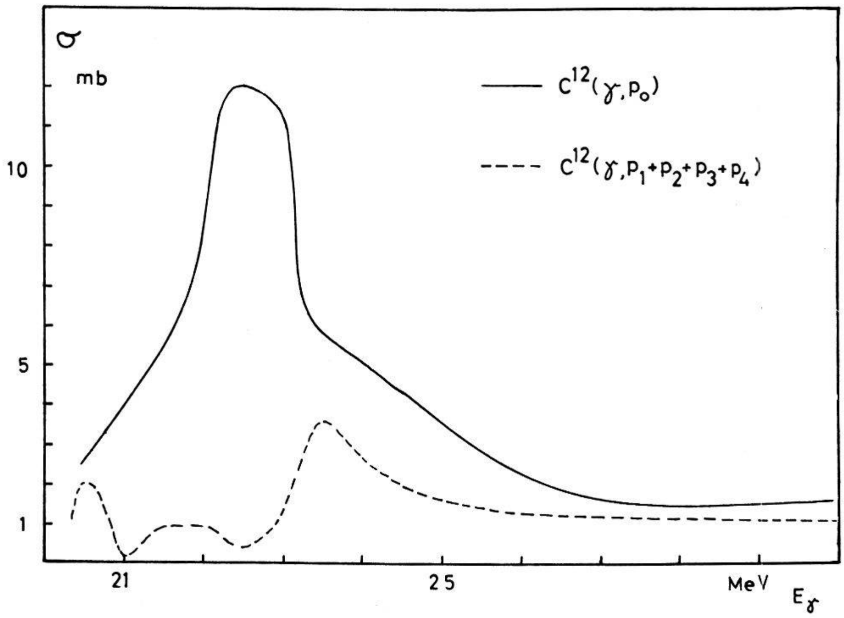

Figure 2
Total cross sections for the reactions ^{12}C (γ, $p_1+p_2+p_3+p_4$) and ^{12}C (γ, p_0).

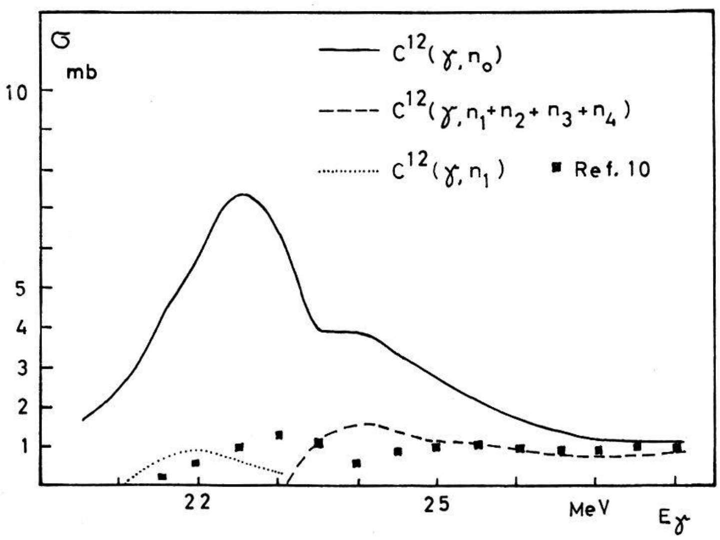

Figure 3
Total cross sections for the reactions ^{12}C (γ, n_0) and ^{12}C (γ, $n_1+n_2+n_3+n_4$). For E_γ between 20.70 MeV and 23 MeV, the cross section for ^{12}C (γ, n_1) is also shown. The calculated values are compared with experimental results given by Fultz et al. [10].

the following δ-force dependence with a spin exchange term has been assumed

$$V_p = -650 \text{ MeV } fm^3 \, \delta\,(\vec{r_1} - \vec{r_2}) \left(0.7 + 0.3\,\frac{1}{2}\,(1 + \vec{\sigma_1}\cdot\vec{\sigma_2})\right). \tag{5}$$

For the particle vibration coupling parameter, the value $\beta_2 = 0.60$ has been adopted.

The ratio of the ground state to the nonground state transitions integrated up to an energy of 30 MeV was calculated to be 25% which has to be compared with the experimental result (7 $\pm$ 16) %. The calculated cross sections for ground state and nonground state transitions become comparable in the energy region of $E_\gamma = 30$ MeV. This was found experimentally in [7]. In Figure 3 the total cross sections for the reactions $^{12}C(\gamma, n_0)$ and $^{12}C(\gamma, n_1 + n_2 + n_3 + n_4)$ are shown. The calculated cross sections are compared with the experimental results of Fultz et al. [10]. The ratio of the integrated cross sections was calculated to be 16.8%. The experimental result is 20.5%. For energies less than 23.15 MeV, the cross section for $^{12}C(\gamma, n_1)$ is shown with a dashed line. In our degenerate multiplet model this energy is below threshold. In this case the cross section is calculated using the experimental threshold energy of $E_{thr, n_1} = 20.70$ MeV.

Furthermore, the branching ratio to the various members of the phonon multiplets is of interest for the determination of the angular momenta involved. These ratios are shown in Table 1 for pure $s_{1/2}$, $d_{3/2}$ and $d_{5/2}$ emissions. For the energy region

Table 1

Branching ratios for the final states in the ^{11}B and ^{11}C phonon multiplets for various excitation energies E_γ

	$^{12}C(\gamma, p_i)\,^{11}B$ $^1/_2:{}^3/_2:{}^5/_2:{}^7/_2$	$^{12}C(\gamma, n_i)\,^{11}C$ $^1/_2:{}^3/_2:{}^5/_2:{}^7/_2$
theoretical value for pure		
$s_{1/2}$ emission	.33:.67:.00:.00	.33:.67:.00:.00
for pure $d_{3/2}$ emission	.02:.25:.73:.00	.02:.25:.73:.00
for pure $d_{5/2}$ emission	.00:.02:.25:.73	.00:.02:.25:.73
calculation for various energies E_γ		
21.0 MeV	.02:.24:.73:.01	
23.0 MeV	.04:.27:.68:.01	
25.0 MeV	.09:.34:.55:.02	.04:.27:.68:.01
27.0 MeV	.21:.48:.25:.06	.18:.43:.35:.04

21 MeV $< E <$ 24 MeV we have a ratio typical of $d_{3/2}$ emission, at higher energies some $d_{5/2}$ and $s_{1/2}$ are added. This can also be seen in Table 1.

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