Cross section for $^{12}C + {}^{12}C \rightarrow {}^{12}C(0_2^+) + {}^{12}C(g.s.)$ using breathing mode doorways

M. U. Ahmed and William P. Beres
Wayne State University, Detroit, Michigan 48202
(Received 29 June 1981)

A previously derived projection operator method is applied to the calculation of the cross section for $^{12}C + {}^{12}C \rightarrow {}^{12}C(0_2^+) + {}^{12}C(g.s.)$ with a breathing mode model being used to describe the 0_2^+ (7.68 MeV) state of ^{12}C. The relationship to processes leading to alpha particle channels is discussed. The cross section for $^{12}C + {}^{12}C \rightarrow {}^{12}C\,(3^-) + {}^{12}C(g.s.)$ is also calculated and possible correlations with inelastic scattering to the 0_2^+ and 2^+ states of ^{12}C are discussed. The results for both 0_2^+ and 3^- inelastic scattering are in reasonable agreement with experiment.

NUCLEAR REACTIONS $^{12}C + {}^{12}C \rightarrow {}^{12}C(0_2^+) + {}^{12}C(g.s.)$ and $^{12}C + {}^{12}C \rightarrow {}^{12}C(3^-) + {}^{12}C(g.s.)$, $E = 10-30$ MeV c.m., projection operator intermediate theory, calculated σ (angle integrated $\theta_{lab} = 15°$ to $25°$).

While $^{12}C + {}^{12}C$ inelastic scattering to the 0_2^+ (7.68 MeV) excited state of ^{12}C has a much smaller cross section[1] than does inelastic scattering to the 2^+ (4.43 MeV) state, the former is quite important as an exit doorway for channels involving alpha particles.[2] In addition, it is indicated in Ref. 1 that the band crossing model[3] is inconsistent with the observed 0_2^+ channel results. We have previously presented[4] a projection operator method for the calculation of low energy heavy ion inelastic scattering cross sections and applied it successfully to $^{12}C + {}^{12}C \rightarrow {}^{12}C(2^+) + {}^{12}C(g.s.)$ using a particle-vibration model for the doorway contributions. In this scheme the nucleus can perform small oscillations about an equilibrium shape, and these vibrations are described as a set of normal modes to which the relative motion of the reduced mass particle may couple. An asset of this approach is the relative simplicity of the pertinent wave functions and the resulting calculations. In light of the above, it is of interest to determine the inelastic scattering to 0_2^+ by describing this excitation as a breathing mode vibration based on the 0_1^+ ground state. Kamimura[5] indicates that while the 0_1^+ and 0_2^+ nuclear densities are quite different and that the distorting potential for the 0_2^+ state is much more shallow and longer range than for 0_1^+, the $0_2^+ \rightarrow 0_1^+$ transition density based on a breathing mode model is rather close to that found by using three alpha particle resonating group wave functions. In fact, Ref. 5 emphasizes that this transition density is the only situation in which the simple breathing mode model is a good approximation.

The 0_2^+ state has been found to decay to the other 0_1^+ ground state via internal pair production.[6,7] It follows that the particle-vibration coupling strength in this case will be much less than for levels (e.g., 2^+ and 3^-) that can be electromagnetically excited. The inelastic theory is described in Ref. 4 and the same well parameters are used in the present calculations. Angular momentum coupling restricts the number of contributing doorways in the region of a gross resonance in that

$$0_2^+ + l = J_R \ , \tag{1}$$

where l is the single particle angular momentum that is coupled to 0_2^+, and J_R is the total angular momentum of the gross resonance. The possible doorways of 0_2^+ origin are listed in Table I. The $0_2^+ \rightarrow 0_1^+$ coupling strength for a breathing mode excitation will be an important ingredient to our future calculations of $^{12}C + {}^{12}C$ reactions leading to alpha particle channels. The experimental cross section[8] for $^{12}C(^{12}C,\alpha)^{20}Ne$ has resonances in the energy region of 24–25 MeV which corresponds to the $J_R = 14^+$ calculated cross section peak in the present $^{12}C + {}^{12}C \rightarrow {}^{12}C(0_2^+) + {}^{12}C(g.s.)$ study. Based on this, we have determined the strength by normalizing the theoretical $J = 14^+$ peak to the value of the cross section observed experimentally at the same energy in Ref. 1. The angle integrated

TABLE I. Calculated $^{12}C + {}^{12}C$ gross resonances and doorways based on the 0_2^+ (7.68 MeV) state of ^{12}C. The energy of the gross resonances is E_R and the total angular momentum is J_R. The doorway energy and continuum width are E_d and $\Gamma_d^{\uparrow}$, respectively.

Gross resonances			Doorway states		
E_R (MeV)	J_R	Continuum width $\Gamma_R^{\uparrow}$ (MeV)	E_d (MeV)	Wave function $(0_2^+, l)$	Continuum width $\Gamma_d^{\uparrow}$ (MeV)
10.5	8^+	0.60	12.99	$(0_2^+, 8)$	0.001
15.0	10^+	2.60	16.32	$(0_2^+, 10)$	0.005
19.5	12^+	4.53	20.14	$(0_2^+, 12)$	0.565
26.0	14^+	6.75	24.43	$(0_2^+, 14)$	0.700
31.0	16^+	9.00	28.84	$(0_2^+, 16)$	0.610

cross section ($\theta_{lab} = 15° - 25°$) for the 0_2^+ level is presented in Fig. 1 and compared to the experimental results of Ref. 1.

Both 0_2^+ and 3^- inelastic scattering have experimental cross sections[1] that are much smaller than for 2^+. In addition, Ref. 1 discusses and interprets possible correlations between these processes. For comparison, it is thus informative to also calculate the process $^{12}C + {}^{12}C \rightarrow {}^{12}C(3^-) + {}^{12}C(g.s.)$ in the particle-vibration model. The angle integrated cross section ($\theta_{lab} = 15° - 25°$) for the 3^- level is given in Fig. 2 and compared to the experimental measurements of Ref. 1.

We note the reasonable agreement in Fig. 1 for the 0_2^+ results as compared to experiment. Having normalized the 14^+ resonance at about 24.5 MeV to experiment, the 16^+ peak in the cross section at about 29.0 MeV is reasonably comparable to the experimental value and can be associated with the observed cross section peak at essentially the same energy. We also predict smaller peaks at about 16.5 and 20.3 MeV for 10^+ and 12^+, respectively. The energy ranges of these resonances are also important in the alpha particle measurements of Ref. 8. We emphasize that the calculated cross section is based on both gross and intermediate doorway contributions. The small number of available doorways of 0_2^+ origin limits the amount of predicted structure, and in addition the detailed fine structure is not an ingredient of our theory.

In Fig. 2 the 3^- calculated results also compare

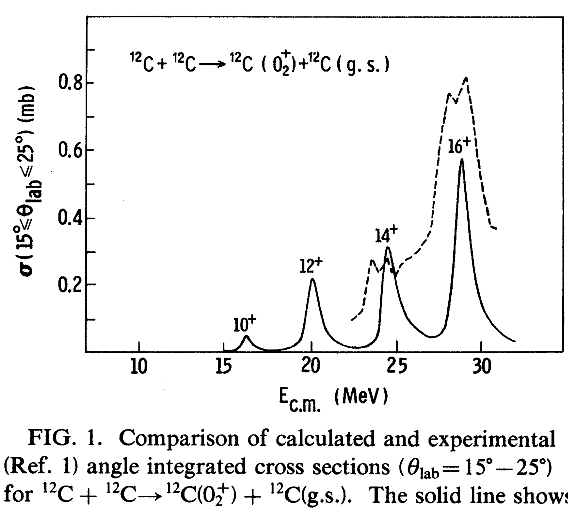

FIG. 1. Comparison of calculated and experimental (Ref. 1) angle integrated cross sections ($\theta_{lab} = 15° - 25°$) for $^{12}C + {}^{12}C \rightarrow {}^{12}C(0_2^+) + {}^{12}C(g.s.)$. The solid line shows the calculated results and the dashed line the experimental. The theoretical angular momentum assignments are indicated.

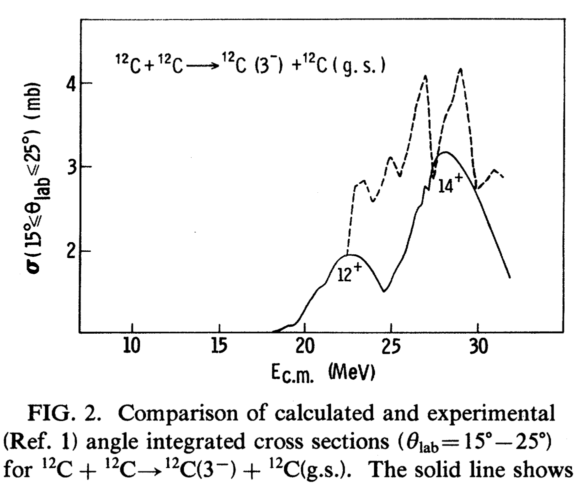

FIG. 2. Comparison of calculated and experimental (Ref. 1) angle integrated cross sections ($\theta_{lab} = 15° - 25°$) for $^{12}C + {}^{12}C \rightarrow {}^{12}C(3^-) + {}^{12}C(g.s.)$. The solid line shows the calculated results and the dashed line the experimental. The theoretical angular momentum assignments are indicated.

reasonably to the measured cross section, especially in terms of the intermediate structure at about 23 and 28 MeV. The height of the calculated cross section comes about from a 3^- coupling strength based simply on the observed $B(E3)$ value[9] and a uniform distribution of charge.[10] Conceivably one could somewhat increase the height of the calculated cross section by assuming a more realistic charge distribution.

The 0_2^+ cross section is greatly diminished relative to 2^+ because it lacks the enhanced collectivity of the latter. The ground state coupling strength for 0_2^+ in the present case is about 20% of that for the 2^+ excitation. However, despite this and the angular momentum limitations of available doorways, the 0_2^+ state still has a discernible cross section. This is due in part to the fact that the single particle portion of each doorway of 0_2^+ origin is correlated to a corresponding single particle component of a doorway based on 2^+. For example, for 14^+ the $(0_2^+, 14)$ doorway includes a quasibound resonance for $l=14$ which is also a constituent of the doorway $(2^+, 14)$. On the other hand, the 3^- inelastic cross section is reduced for different reasons. While the ground state coupling of the 2^+ and 3^- vibrations are comparable in magnitude, the inelastic scattering in the latter case is diminished to some extent because it involves only quasibound single particle resonances of odd parity, e.g. $(3^-, 13)$ and $(3^-, 15)$ in forming doorways of total even parity.

Reference 1 has correlated the observed 0_2^+ peak at about 28.5 MeV with a resonance observed at 28.75 MeV in the 3^- channel and indicates no obvious correlation with 2^+. However, based on similarities of quasibound single particle constituents of the doorway states, it is clear that the 0_2^+ doorways have a correlation with those of 2^+ origin. An analysis of the correlations must be based on more than just an observation of peaks at the same energy. The difference in energy between the 0_2^+ and 2^+ vibrations will in general displace the corresponding J_R resonances in the 0_2^+ cross section relative to the energies of the observed peaks of the same J_R in the 2^+ channel. In fact, the prominent 3^- resonance at 28.75 MeV can be associated with $J_R=14^+$, and is due to a 14^+ doorway at 28.7 MeV of structure $(3^-, 15)$ as modulated by a 14^+ gross resonance at 26.0 MeV.[11] On the other hand, the calculated 0_2^+ peak in Fig. 1 at about 29.0 MeV has angular momentum 16^+ and is due to a $(0_2^+, 16)$ doorway at 28.84 (Table I). Other than the closeness in energy this peak has little to do with the 28.75 MeV 3^- resonance in Fig. 2. We emphasize the importance of a detailed treatment of the doorways involved in the reaction processes. Reference 1 points out that the band crossing model of Kondo *et al.*[3] does not even predict this prominent 3^- peak.

In summary, while the strong resonances in the 0_2^+ channel violate the band crossing hypothesis,[1] our model has sucessfully predicted inelastic scattering to the 0_2^+ state. Consequently, this excitation is available as a possible entrance into alpha particle degrees of freedom.

This work was supported in part by the National Science Foundation via Grant No. Phy. 80-08010.

[1] B. R. Fulton, T. M. Cormier, and B.J. Herman, Phys. Rev. C 21, 198 (1980).

[2] H. Feshbach, *Clustering Aspects of Nuclear Structure and Nuclear Reactions (Winnipeg, 1978)*, Proceedings of the Third International Conference on Clustering Aspects of Nuclear Structure and Nuclear Reactions, edited by W. T. H. Van Oers and J. P. Svenne (AIP, New York, 1978), p. 766.

[3] Y. Kondo, Y. Abe, and T. Matsuse, Phys. Rev. C 19, 1356 (1979).

[4] M. U. Ahmed, W. P. Beres, and T. L. Larry, Phys. Rev. C 25, 833 (1982).

[5] M. Kamimura, Nucl. Phys. A351, 456 (1981).

[6] D. E. Alburger, Phys. Rev. C 16, 2394 (1977).

[7] R. G. H. Robertson, R. A. Warner, and S. M. Austin, Phys. Rev. C 15, 1072 (1977).

[8] R. L. Greenwood, R. E. Segal, K. Raghunathan, M. A. Lee, H. T. Fortune, and J. R. Erskine, Phys. Rev. C 12, 156 (1975).

[9] S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data Sect. A2, 347 (1966).

[10] A. Bohr and B. R. Mottelson, K. Dan. Vidensk. Selsk., Mat. Fys. Medd. 27, No. 16 (1953).

[11] T. L. Larry and W. P. Beres, Phys. Rev. C 22, 1145 (1980).