tron-scattering experiments with $Q^2$ *and* $\nu$ larger than in the experiment of Ref. 1 but still $x > \frac{1}{3}$ can help to map out this new structure of the $^3$He nucleus.

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# Exit Doorway State in $^{12}C(^{16}O,^{8}Be)^{20}Ne$

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We remark that resonances in the $^{12}C(^{16}O,^{8}Be)^{20}Ne$ reaction are due to the "exit doorway state," that is ready for decay to the exit channel. We find a parameter-free formula that relates the resonance energy and angular momentum of the $^{12}C + ^{16}O$ system to those of the $^{12}C + ^{12}C$ system. If we use the experimental resonance energies of $^{12}C + ^{12}C$, this formula yields more than a dozen one-to-one correspondences to the resonance energies of $^{12}C(^{16}O,^{8}Be)^{20}Ne$. We also find a parameter-free formula for $^{12}C(^{16}O,^{4}He)^{24}Mg$.

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The $^{12}C + ^{16}O$ reaction has been studied extensively by various workers in recent years.[1] In the energy region of $E_{c.m.} = 10$–$25$ MeV, this system is very rich in resonances. Although these resonances are strongly clustered in groups of the same angular momentum, experiments show that the intermediate structures in the $^{12}C + ^{16}O$ system are not consistent with each other for various exit channels.

For instance, Malmin *et al.*[2] report a sharp $J^\pi = 14^+$ resonance at $E_{c.m.} = 19.7$ MeV in the elastic scattering and later confirmed a rotational-band-like structure together with resonances of $J^\pi = 9^-$ and $15^-$ $(16^+)$ at $E_{c.m.} = 13.6$ MeV and $E_{c.m.} = 22.0$ MeV.[3] Later on, Eberhard *et al.*[4] observed a $J^\pi = 10^+$ resonance at $E_{c.m.} = 18.8$ MeV in the reaction $^{12}C(^{16}O, ^{8}Be_{g.s.})^{20}Ne$. The spin value $J = 10$ is four units of angular momentum below the grazing value $J = 14$ obtained from the elastic scattering by Malmin *et al.*, who did not observe this reso-

nance at $E_{c.m.}=18.8$ MeV. Almost at the same time, James and Fletcher[5] made a detailed study of the reaction $^{12}C(^{16}O, ^{8}Be_{g.s.})^{20}Ne$ and reported a group of resonances in the energy region $E_{c.m.}=18.5-22.7$ MeV, all of which turned out to be as anomalous (angular momentum mismatch) as those found by Eberhard *et al.* Moreover, the strong $14^+$ resonance at $E_{c.m.}=19.7$ MeV observed by Malmin *et al.*[2] and confirmed by many other workers was not detected by James and Fletcher.[5] There are two other $8^+$ resonances at $E_{c.m.}=13.15$ and 13.77 MeV observed in the reaction $^{12}C(^{16}O, ^{8}Be_{g.s.})^{20}Ne$ by Viggars *et al.*[6] These resonances appear to belong to the same group as those found by James and Fletcher.[5] The extension to lower energies was done by Hurd *et al.*,[5] $E_{c.m.}=11.5$ to 18.6 MeV.

The intermediate structure in the elastic or inelastic scattering was accounted for by the model of doorway state. Since a simple optical model[3,7] or a rotational model[8] yields substantially larger width ($\Gamma=2-4$ MeV) than the observed width ($\Gamma=100-800$ keV), a dynamically reasonable account was given by Feshbach.[9] He suggested that once the doorway state is formed as a consequence of the excitation of one or both of the colliding nuclei, it then subsequently fragments into individual states by weak coupling. In all theories presented so far, such as the coupled-channels model,[10] the double-resonance model,[11] the $\alpha$-transfer model,[12] and a microscopic model,[13] the gross structure of the reaction is determined by the initial stage, as in the doorway-state model by Feshbach.

In the elastic or inelastic scatterings, the system emerges from the collision complex again through the "entrance doorway state." The remainder of the system that proceeds to the compound state will forget the intermediate resonance structure of the entrance doorway state, as the compound elastic scattering does not manifest the resonance structure. Now, if we think of a reaction in the time-reversed way, we realize the importance of a resonant state at the final stage. By studying the reaction $^{12}C(^{16}O, ^{8}Be)^{20}Ne$, we found that this is the case. Let us call the final resonant state the "exit doorway state." This state is, by definition, *ready* to decay to the exit channel. Feshbach's doorway state depends on the initial channel, and analogously the exit doorway state depends on the final channel.

More specifically, in the reaction $^{12}C(^{16}O, ^{8}Be)^{20}Ne$, the exit doorway state is assumed to consist of $^{8}Be$ and $^{16}O$ in resonance and $^{4}He$ forming almost $^{20}Ne$ with $^{16}O$. Thus $^{4}He$ is an $S$ state with a *negative* energy, which is equal to the negative of binding energy of $^{20}Ne$ with respect to $^{4}He$ and $^{16}O$. At the same time, the system of $^{8}Be$ and $^{16}O$ has the resonance energy and angular momentum observed in the $^{12}C+^{12}C$ scattering. Under this situation, all the resonance energy and angular momentum of the $^{8}Be$ and $^{16}O$ in the exit doorway state are transferred to the resonance energy and angular momentum of the relative motion of $^{8}Be$ and $^{20}Ne$ in the final channel. In equation, this condition is represented as

$$E_{c.m.}^{res,J\pi}(^{8}Be+^{16}O)=E_{c.m.}^{res,J\pi}(^{8}Be+^{20}Ne) \tag{1}$$

with obvious notations.

Once we assume Eq. (1), and make use of the experimental fact that there is no angular momentum mismatch in $^{12}C+^{12}C$ reactions,[14] we can express $E_{c.m.}^{res,J\pi}(^{12}C+^{16}O)$ in terms of $E_{c.m.}^{res,J\pi}(^{12}C+^{12}C)$ as

$$E_{c.m.}^{res,J\pi}(^{12}C+^{12}C)=E_{c.m.}^{res,J\pi}(^{12}C+^{16}O)-B(^{16}O)-B(^{12}C)+B(^{20}Ne)+B(^{8}Be)+B(^{12}C)+B(^{12}C)-B(^{8}Be)-B(^{16}O), \tag{2}$$

where $B$ denotes the binding energy. With use of the experimental binding energies,[15] we get

$$E_{c.m.}^{res,J\pi}(^{12}C+^{12}C)=E_{c.m.}^{res,J\pi}(^{12}C+^{16}O)-2.43\ \text{MeV}. \tag{3}$$

Equation (3) is a parameter-free formula which relates the resonance energies and $J\pi$ values of $^{12}C+^{12}C$ and $^{12}C+^{16}O$ systems.

When $^{20}Ne$ gets excited in the final state, we assume again that the $^{4}He$ is still in an $S$ state, but now the angular momentum $J$ and energy $E^{res}$ of $^{8}Be+^{16}O$ are divided between the momentum $J_1$ and energy of the relative motion of $^{8}Be+^{20}Ne^*$ and the angular momentum $J_2$ and the excitation energy $E_x$ of $^{20}Ne^*$. Then Eq. (1) is written as

$$E_{c.m.}^{res,J\pi}(^{8}Be+^{16}O)=E_{c.m.}^{res,J_1\pi_1}[^{8}Be+^{20}Ne^*(J_2,\pi_2)]+E_x[^{20}Ne^*(J_2,\pi_2)]. \tag{4}$$

TABLE I. In the first column, we show resonances in the $^{12}C+^{12}C$ scattering by James and Fletcher (Ref. 14). These values are put into Eq. (3) to predict resonances in $^{12}C(^{16}O, ^{8}Be)^{20}Ne$. The predictions are given in the second column, which are to be compared with the third column giving the experimental results. Here H and JF, and V denote Refs. 5 and 6, respectively. The experimental results in the third column are put into Eq. (6) to predict the excited states of $^{24}Mg$. These predictions are to be compared with the fifth column taken from Ref. 18. The lowest three lines list the result for $^{12}C(^{16}O, ^{4}He)^{24}Mg$. Here Eq. (8) is employed. Below 12.9 MeV of $E_{c.m.}$ ($^{12}C+^{16}O$), the experimental assignments are not certain. Therefore, we do not list this part.

| $E_{c.m.}$ ($^{12}C+^{12}C$) | $E_{c.m.}$ ($^{12}C+^{16}O$) | | | Ex($^{24}Mg^{*}$) | |
|---|---|---|---|---|---|
| | Prediction | Experiment | Ref. | Prediction | Experiment |
| $\{^{10.62,\ 8^+}_{10.68,\ 8^+,W}$ | $\{^{13.05,\ 8^+}_{13.11,\ 8^+}$ | $\{^{(13.1),\ 7^-,}_{13.15,\ 8^+,}$ | H<br>V | 24.7, $8^+$ | 24.7, $8^+$ |
| $\{^{10.96,\ 8^+}_{10.98,\ 8^+,W}$ | $\{^{13.39,\ 8^+}_{13.41,\ 8^+}$ | 13.3 , $8^+$, | H | 24.8, $8^+$ | 24.9, $6^+$ |
| 11.20,($6^+$) | 13.63,($6^+$) | | | | |
| 11.38, $8^+$ | 13.81, $8^+$ | 13.77, $8^+$,<br>13.80, $8^+$,<br>(14.0), $8^+$, | V<br>H<br>H | 25.3, $8^+$<br>(25.5),$8^+$ | 25.5, $8^+$ |
| 11.90, $8^+$ | 14.33, $8^+$ | 14.25, $9^-$, | H | 25.8, $9^-$ | 26.0, $8^+$ |
| 12.36, $8^+$ | 14.79, $8^+$ | 14.7, ...,<br>14.9,($8^+$), | H<br>H | 26.2<br>26.4, $8^+$ | 26.3, $8^+$ |
| 12.98, $8^+$ | 15.41, $8^+$ | 15.2, ..., | H | 26.7 | 26.7, $8^+$ |
| 13.37,$10^+$ | 15.80,$10^+$ | 15.62,($10^+$), | H | 27.1,($10^+$) | 27.4,$10^+$ |
| 13.87,$10^+$ | 16.30,$10^+$ | 16.20,$9^-$, | H | 27.5, $9^-$ | 28.0,$10^+$ |
| (14.15),$8^+$ | (16.58),$8^+$ | | | | |
| 14.36,$10^+$ | 16.79,$10^+$ | 16.70,$10^+$,<br>(17.0),$11^-$,<br>17.30,$12^+$, | H<br>H<br>H | 28.2,$10^+$<br>(28.5),$11^-$<br>28.8,$12^+$ | 28.5,$10^+$ |
| 15.35,$10^+$ | 17.78,$10^+$ | 17.7,(>12),<br>17.98,$11^-$, | H<br>H | 29.2,(>12)<br>29.5,$11^-$ | 29.3,$10^+$<br>29.7 |
| 16.13,$10^+$ | 18.56,$10^+$ | 18.55,$10^+$, | H | 30.1,$10^+$ | 30.1,$10^+$ |
| 16.45,$10^+$ | 18.88,$10^+$ | 18.87,$10^+$, | JF | 30.4,$10^+$ | |
| 17.19,$10^+$ | 19.62,$10^+$ | (~19.65),-, | JF | (~31.2),- | 31.2,$10^+$ |
| 17.78,$12^+$ | 20.21,$12^+$ | 19.91,$12^+$, | JF | 31.4,$12^+$ | 31.8,$12^+$ |
| (18.6),$10^+$ | | | | | |
| 18.8 ,$12^+$ | 21.23,$12^+$ | 21.14,$12^+$, | JF | 32.6,$12^+$ | 32.6,$12^+$ |
| 19.46,$12^+$ | 21.89,$12^+$ | 21,8, - , | JF | 33.3, - | 33.1,12+ |
| 16.13,$10^+$ | 14.0,$10^+$ | 13.7,$10^+$( $9^-$), | B | 29.8,$10^+$($9^-$) | 29.7 |
| 17.19,$10^+$ | 15.0,$10^+$ | 14.7,$10^+$($11^-$), | B | 30.8,$10^+$($11^-$) | 31.2,$10^+$ |
| 17.78,$12^+$ | 15.6,$12^+$ | 16.0,$12^+$($11^-$), | B | 32.1,$12^+$($11^-$) | 31.8,$12^+$ |

Of course, $\pi=\pi_1\pi_2$ and $\vec{J}=\vec{J}_1+\vec{J}_2$. Our assumption is that even in this case the exit doorway state is the same and this exit doorway state determines the properties of the reaction. In equation, the right-hand side of Eq. (1) is equal to that of Eq. (4). As a result, Eq. (2) is recovered and Eq. (3) remains valid.

Here we mention the gross aspect of the ex-

change mechanism of the model. Some time before the exit doorway state is formed, $^{8}$Be is transferred from $^{12}$C to $^{16}$O. After the exit doorway state exists for some period, $^{8}$Be is exchanged by $^{4}$He, which makes $^{20}$Ne with $^{16}$O. Such an exchange process is typical of the Lovelace amplitude.[16] In fact, the above process is the second-order Lovelace amplitude. The first-order term does not involve the exit-doorway–type resonance. We note, however, that from calculations of the second-order Lovelace amplitude, we will not be able to obtain the correct angular distribution. In such a calculation as a direct mechanism, the resonance aspect of the entrance doorway state is still in memory. To reproduce the correct angular distribution, we should perform the calculation in such a way that the memory of the entrance state is smeared out at a compound stage.

To see how our simple formula (3) works quantitatively, we have calculated $E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{12}\mathrm{C}+^{16}\mathrm{O})$, using Eq. (3) and the experimental values of $E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{12}\mathrm{C}+^{12}\mathrm{C})$ due to James and Fletcher[14] and Wada *et al.*,[14] which are listed in the first column of Table I. The calculated values of resonances for $^{12}$C($^{16}$O, $^{8}$Be)$^{20}$Ne are written in the second column. These values should be compared with experimental values for $^{12}$C($^{16}$O, $^{8}$Be)$^{20}$Ne, which are exhibited in the third column. From this table, we see that our formula works surprisingly well.

Further check of the validity of our prediction is made from the experimental data of $^{24}$Mg*. The center-of-mass energy of the $^{12}$C + $^{12}$C system is related to the energy of excited $^{24}$Mg* by[17]

$$E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{12}\mathrm{C}+^{12}\mathrm{C})+13.93\ \mathrm{MeV}=E_x(^{24}\mathrm{Mg}^*). \quad (5)$$

Eliminating $E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{12}\mathrm{C}+^{12}\mathrm{C})$ from Eqs. (3) and (5), we express the energy of the excited state of $^{24}$Mg in terms of the resonance energy of the reaction $^{12}$C($^{16}$O, $^{8}$Be)$^{20}$Ne as

$$E_x(^{24}\mathrm{Mg}^*)=E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{12}\mathrm{C}+^{16}\mathrm{O})+11.50\ \mathrm{MeV}. \quad (6)$$

Making use of experimental values in the third column, we predict the excited states of $^{24}$Mg, which are listed in the fourth column of Table I. These predictions are compared with experimental values (written in the fifth column) by Lazzarini *et al.*,[18] who, however, did not measure the angular momentum of resonances. In the fifth column, the angular momentum is taken from Fig. 3 (Refs. 1 and 2) of Ref. 18.

A similar model may be used also for $^{12}$C($^{16}$O, $^{4}$He)$^{24}$Mg. Corresponding to Eq. (1), if we assume

$$E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{20}\mathrm{Ne}+^{4}\mathrm{He})=E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{24}\mathrm{Mg}+^{4}\mathrm{He}), \quad (7)$$

we obtain a formula

$$E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{12}\mathrm{C}+^{12}\mathrm{C}) = E_{\mathrm{c.m.}}^{\mathrm{res},J\pi}(^{12}\mathrm{C}+^{16}\mathrm{O})+2.15\ \mathrm{MeV}. \quad (8)$$

This formula should be used for the reaction $^{12}$C($^{16}$O, $^{4}$He)$^{24}$Mg. We list the predictions and experimental results[19] in the lowest three lines of Table I. (The spin "assignments" of Ref. 19 are speculations.)

In conclusion, we should remark that some physicists noticed the effect of the final state,[20] or have tried to understand the $^{12}$C + $^{16}$O resonances in terms of the $^{12}$C + $^{12}$C structure[21] or classified resonances of $^{12}$C + $^{16}$O into two quasimolecular bands.[22] However, the present paper is the first to relate quantitatively the resonances of the $^{12}$C + $^{12}$C system to those in the $^{12}$C + $^{16}$O system. We hope that the present paper stimulates and aids experimental physicists to plan further precise experiments and systematize their findings.

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# Observation of Giant Dipole Resonances Built on States of High Energy and Spin

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Spectra of $\gamma$ rays in the 2–30-MeV range have been observed following $^{40}Ar$-induced reactions leading to the $^{122}Te$, $^{150}Gd$, and $^{164}Er$ systems. Shoulders in the spectra for $E_\gamma > 10$ MeV are interpreted as arising from the giant dipole resonance and are consistent with statistical-model calculations that use the giant-dipole-resonance strength function. Their observation offers the possibility of studying nuclear shapes and dynamics as functions of temperature and spin.

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Studies of the giant dipole resonance (GDR) have been mostly restricted to coherent excitation from nuclear ground states which excites only the giant resonances built on them.[1] Brink,[2] however, has proposed that every state in a nucleus has a GDR associated with it. Such giant resonances have been observed in capture reactions to low-lying states.[3] A consequence is that the strength functions for electric dipole transitions from every state would have a Lorentzian-like shape as a function of $\gamma$-ray energy $E_\gamma$, with a magnitude determined from the $E1$ sum rule.[4] Such a variation of strength with $E_\gamma$ would affect the shape of the spectrum of $\gamma$ rays emitted from a highly excited nucleus, particularly in the vicinity of $E_\gamma = E_G$, the energy of the GDR. Some evidence in favor of this hypothesis is given by the shape of the $\gamma$-ray spectrum for $8 < E_\gamma < 20$ MeV following spontaneous fission[5] of $^{252}Cf$. We have observed this effect in the statistical $\gamma$ rays following heavy-ion fusion reactions.

The present measurements open the possibility of measuring the energy, yield, width, and general structure of the GDR component of the statistical $\gamma$-ray spectrum as functions of excitation energy $E_x$ above the yrast line (temperature $T$) and spin $I\hbar$. The first three of these can be related through nuclear models to the nuclear size, collectivity, and other more detailed features of the nuclear dynamics. The gross structure of the GDR is simply related to the nuclear shape; in deformed nuclei with two (or three) distinct principal radii, the GDR is split into two (or three) components. Thus the observation of only the general structure of the resonance peak should provide information on the nuclear shape as a

 