level of a β-vibration band, is readily excited by inelastic electron scattering and has an $E0$ matrix element (6.3 fm^4) which is comparable to the matrix element estimated from the present data (Ref. 13).

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Structure in the Radiative Capture of ^{12}C by ^{12}C near the Coulomb Barrier

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The yield curves of high-energy capture γ rays from $^{12}C(^{12}C,\gamma_0)$ and $^{12}C(^{12}C,\gamma_1)$ were measured at $\theta_{lab} = 45°$ from $E_{c.m.} = 5.0$ to 11.0 MeV. A $J^\pi = 2^+$ resonance, with a width (full width at half-maximum) of 261 ± 74 keV and a peak cross section at 45° of 44.3 ± 4.5 nb/sr, was observed in $^{12}C(^{12}C,\gamma_0)$ at (21.98 ± 0.03) MeV excitation in ^{24}Mg. Several other resonant features were also observed in the γ-ray yields.

Ever since the initial experiment of Almqvist *et al.*,[1] there has been continued interest in the resonant structures of the $^{12}C + ^{12}C$ system that are observed near the Coulomb barrier.[2-4] Theoretical efforts to account for these structures assume the formation of a resonance in the effective interaction potential of the two ^{12}C.[5-7] This "molecular" resonance is then split into fine structure by coupling to intermediate channels, and it it mainly in the choice of this intermediate channel that the various models differ.[8] Despite their moderate success in accounting for some of the $^{12}C + ^{12}C$ features, they fall far short of providing a complete explanation. Absent from these models is any consideration of a direct connection between these resonances and the structure of ^{24}Mg. For example, a coupling to the highly collective states of ^{24}Mg associated with "giant resonances" may provide the intermediate structure necessary to account for some of the $^{12}C + ^{12}C$ "quasimolecular" features. One possible way to study such a connection is to investigate the γ-ray decay of these features to the low-lying states of ^{24}Mg.

Feldman and Heikkinen[9] have surveyed the $^{12}C(^{12}C,\gamma)$ yield to low-lying states in ^{24}Mg between 20 and 25 MeV excitation and report no resonances above the level of a few nanobarns per steradian. However, recent measurements on the time-reversed reaction via the electron-induced fission of ^{24}Mg have located a resonance-like feature between 22 and 23 MeV excitation with a total width (Γ) ≤ 1 MeV.[10] This feature was seen to decay into two ^{12}C (g.s.) nuclei with an angular distribution indicating quadrupole ($E2$) excitation.

In this Letter we report a new measurement of the $^{12}C(^{12}C,\gamma)^{24}Mg$ yield which was undertaken to further investigate the electrofission resonance as well as to search for γ decays of other $^{12}C + ^{12}C$ resonances. Beams of $^{12}C^{3+}$ were provided by the *MP* tandem Van de Graaff accelerators at Brookhaven National Laboratory. The γ rays were detected in a 24.1 cm× 26.7 cm NaI(Tl) crystal surrounded by a plastic scintillator used in anticoincidence to reduce the large cosmic-ray background and to improve resolution by detecting escape radiation.[11] The incident beam was stopped in a tantalum plate 1.3 cm behind the target, both of which were enclosed in a 2.5-cm-diam glass chamber. The γ rays from the target were collimated by 5 cm of lead with an aperture that projected onto the full back face of the NaI(Tl) crystal. With this geometry and beam currents in the range from 0.15 to 1.00 particle μA, the counting rate above 0.5 MeV in the crystal was typically 100 kHz. In the absence of a target, no significant rate was observed. Standard techniques were used to reduce pulse pileup and to stabilize the gain of the system.[11] The detector was calibrated by observing the high-energy γ_0 and γ_1 lines from $^{11}B(p,\gamma)^{12}C$. A comparison of the measured cross section with that given by Allas *et al.*[12] was used to determine the product of the detector efficiency and its geometrical solid angle ($\epsilon\Omega = 0.050$ sr). The γ_0 line was used to fix the line shape parameters. The measured full width at half-maximum (FWHM) was 7% at 22 MeV.

Figure 1 shows the highest-energy portion of

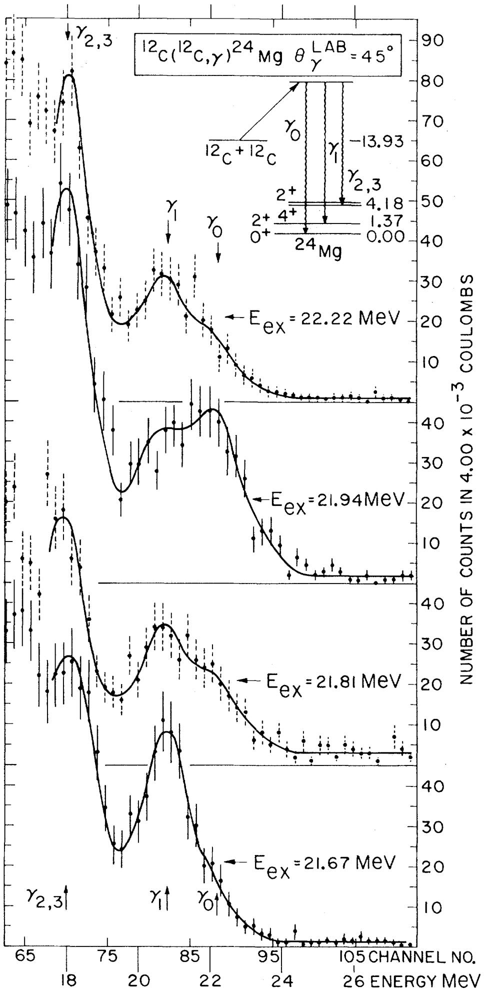

FIG. 1. The high-energy portion of the γ-ray spectra, taken at incident beam energies of 15.70, 15.98, 16.25, and 16.80 MeV with a 230-keV- (c.m.) thick target, are shown here. The spectra are labeled with the Doppler-shift–corrected excitation energies at the middle of the target and have been shifted linearly in channel number to compensate for the differences in energy. As displayed, all share a common energy scale with the data at 21.81 MeV excitation. The position of the centroids of γ_0, γ_1, and $\gamma_{2,3}$ are indicated. The variations of the Doppler shifts and of the peak widths are negligible for these spectra. The intensities of the high-energy γ-ray lines may thus be compared directly. The solid curves are three-peak fits to the data points (see text).

typical γ-ray spectra from $^{12}C(^{12}C,\gamma)$ taken with this detector system at $\theta_{lab}=45°$ where the distribution for $E2$ decay, $\sin^2 2\theta$, is a maximum. At these excitation energies the resolution of the detector prevents the decay to the ground and first excited states of ^{24}Mg, separated by only 1.37 MeV, from being clearly distinguished when both are present with comparable intensity. However, the energy separation is sufficient to allow peak fitting using the line-shape parameters measured in $^{11}B(p,\gamma)$. The γ_0 and γ_1 lines are superimposed upon a tail due to $\gamma_{2,3}$ (unresolved) and to the pilup of a very large number of low-energy events. The solid curves drawn through the data points in Fig. 1 each result from a simultaneous fit to three peaks ($\gamma_0,\gamma_1,\gamma_{2,3}$) with a constant background. Two-peak fits with the tail of $\gamma_{2,3}$ replaced by an exponential do not differ significantly in determining the areas under γ_0 and γ_1. The results from these two fitting procedures were averaged to obtain the cross sections shown in Fig. 2.

The resonance parameters of the sharp feature near 22 MeV were found by fitting the γ_0 yield to a single Breit-Wigner form assuming the background shown in Fig. 2. The fitted total width and excitation energy are 261± 74 keV and 21.98 ± 0.03 MeV, respectively; and the resonance strength,[13] assuming $J=2$,[14] is given by $(2J+1)\Gamma_\gamma\Gamma_C/\Gamma=1.37\pm 0.27$ eV, or equivalently $\Gamma_\gamma(\mathrm{eV})\Gamma_C(\mathrm{keV})=71.5\pm 20.8$. Here, Γ_γ and Γ_C are the partial widths for γ_0 and ^{12}C decay, respectively. The shape of the γ_0 yield curve is consistent with the $^{24}Mg(e,{}^{12}C)^{12}Ce'$ measurements.[15] The cross section, integrated over the γ_0 resonance from 21.1 to 22.8 MeV (including the smooth E_2 background) is 28.5± 7.8 nb MeV/sr. When converted to the equivalent photofission cross section for $^{24}Mg(\gamma,{}^{12}C)$, using detailed balancing, this becomes 2.7± 0.7 μb MeV/sr. This agrees with the cross section integrated over a 1.7-MeV interval about the $E2$ resonance observed in the electrofission of ^{24}Mg.[10]

Wada *et al.*[4] have observed a broad 4^+ resonance at $E_{c.m.}=8$ MeV in $^{12}C(^{12}C,{}^{16}O)^8Be$; however, the sharp state of Fig. 2 is absent from their excitation function. Furthermore, recent studies of the reactions[2,3] $^{12}C(^{12}C,p)^{23}Na$ and $^{12}C(^{12}C,\alpha)^{20}Ne$ fail to show any evidence for a state at 8 MeV in the $^{12}C+{}^{12}C$ system. This is consistent with the work of Kuhlmann *et al.*[16] where failure to observe the 8.05-MeV (c.m.) state of Fig. 2 as a resonance in $^{20}Ne(\alpha,\gamma_0)^{24}Mg$ implies the upper limit $\Gamma_{^{12}C}>6\Gamma_{\alpha_0}$ for this state.

The peak in the γ_0 yield at 20 MeV persists when the effects of the Coulomb barrier are removed and the cross section is converted to a nuclear structure factor [Ref. 3, Eq. (1)]. The energy of this peak, 6.07 MeV (c.m.), is very near the energies of two "quasimolecular" resonances at 5.94 MeV($J^\pi=4^+$) and 6.25 MeV ($J^\pi=2^+$)

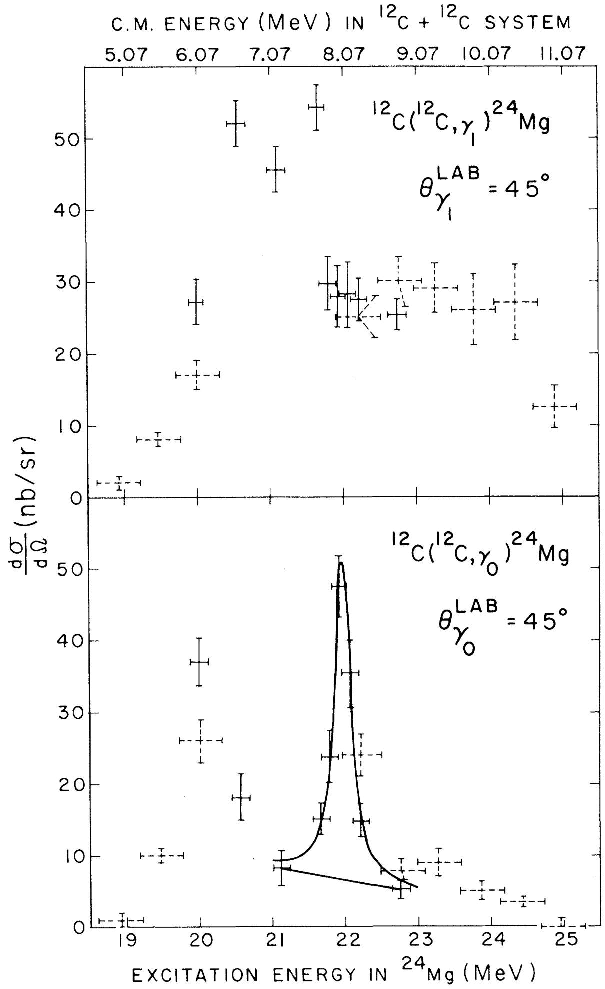

FIG. 2. The solid points on the excitation functions shown here were taken with a 74-μg/cm^2 ^{12}C(99.9%) target. The dashed data points were collected with a 280-μg/cm^2 natural carbon foil. The horizontal bars indicate the target thickness. The solid curve is a fit to the data assuming a single Breit-Wigner resonance (see text).

that have been seen in several exit channels.[1,3,4] At present our data in this region of the excitation function are insufficient to resolve these two. However, the γ_0 yields at laboratory angles of 0°, 45°, and 81° are consistent with the 2^+ assignment. In contrast to the 8.05-MeV (c.m.) state of Fig. 2, the 6.25-MeV resonance has an α_0 width [again deduced from a comparison with the data from ^{20}Ne(α,γ_0)][16] that is at least 6 times its carbon width.

Since the spin of the first excited state is nonzero, unambiguous assignments for the decaying states generally require the measurements of angular correlations between γ_1 and the subsequent decay to the ground state. Because of the very low yields in such measurements, these data are not yet available. Nonetheless, a comparison of the γ_1 excitation function with other reactions involving the ^{12}C + ^{12}C system can be informative. The peak at 6.6 MeV (c.m.) may be associated with the $J^\pi = 2^+$ doublet recently observed in ^{12}C(^{12}C,^{16}O(g.s.))^{8}Be(g.s.).[4] However, its energy is also near the 6.3-MeV $J^\pi = 0^+$ resonance originally predicted by Imanishi.[5] Interest in this intepretation has been revived by the more recent calculations of Park, Scheid, and Greiner.[6] The resonance energy is consistent with the $E0$ excitation seen in the ^{24}Mg electrofission experiments at about 21 MeV.[10] In the excitation region below this peak the γ_0 yield is still rising, indicating that the sharp drop in the γ_1 yield at lower energies is due to more than just a Coulomb-barrier effect. The energy of the peak at 7.8 MeV (c.m.) coincides with a 4^+ resonance recently seen in ^{12}C(^{12}C,α)^{20}Ne by Erb *et al.*[2] The two peaks in the γ_1 yield at 6.3 and 7.8 MeV are superimposed upon a broad structureless bump centered at about 22.5 MeV with a FWHM of about 4.5 MeV. This could form a part of the giant quadrupole resonance built on the first excited state of ^{24}Mg.

In conclusion, we have located a $J^\pi = 2^+$ capture/fission resonance in ^{24}Mg that has not been observed in any other exit channel. This state is not predicted by any of the "molecular" models presently available[5-8] and may be of quite a different origin. To the level of accuracy shown in Fig. 2, only a few of the quasimolecular resonances show detectable yield to the low-lying states of ^{24}Mg. This does not preclude the other ^{12}C + ^{12}C resonances from γ decaying to states in ^{24}Mg at higher excitation energies, or even from cascading down through a band of such "molecular" states. However, the data presented here do suggest that some of these states may have a closer connection with the structure of ^{24}Mg than had been previously considered. Such a possibility may be worth a more detailed investigation in the ^{12}C + ^{12}C capture reaction as well as in other "quasimolecular" systems such as ^{12}C + ^{16}O.

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[13]The conventions used for these parameters are defined by C. Rolfs and A. E. Litherland, in *Nuclear Spectroscopy and Reactions*, edited by J. Cerny (Academic, New York, 1974), Chap. VII.D.

[14]In the decay to the 0^+ ground state of ^{24}Mg, only EJ (J even) radiation is permitted by the symmetry of the entrance channel. Preliminary data taken at 0°, 45°, and 81° indicate that the γ_0 yield is consistent with $E2$ radiation.

[15]The sharp resonance of Fig. 2 appears 0.7 MeV higher in the electrofission work (Ref. 10), but the uncertainty in the peak position within their 1-MeV envelope, together with a systematic uncertainty in the electron beam energy, is sufficient to resolve any discrepancy with our data.

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