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# Excitation functions and Legendre analysis for the $^{12}C(^{12}C,^{8}Be)^{16}O$(g.s.) reaction

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Additional excitation functions for $^{12}C(^{12}C, ^{8}Be)^{16}O$(g.s.) have been measured. A Legendre analysis of $\sigma(\theta,E)$ confirms previous $J^\pi$ assignments of resonant structures and identifies new ones. A fragmentation of giant quasimolecular resonances provides a preferable interpretation of the resonance phenomena observed.

[NUCLEAR REACTIONS $^{12}C(^{12}C, ^{8}Be)\,^{16}O$(g.s.), measured $\sigma(\theta, E)$, $E_{c.m.} \simeq 9$ to 20 MeV, deduced $J^\pi$ of resonances.]

The $^{12}C + ^{12}C$ system has been one of the most thoroughly studied heavy-ion interactions. Much of the work is in the study of "quasimolecular" resonance phenomena and the subject has been reviewed extensively.[1] The first such resonance discovered above the Coulomb barrier was by Van Bibber *et al.*[2] at $E_{c.m.} \simeq 19.3$ MeV, by use of the $^{12}C(^{12}C,p)$ reaction going to selected final states in $^{23}Na$. Numerous resonance effects have since been reported in exit channels of $p$, $n$, $\alpha$, and $^{8}Be$ as well as inelastic scattering.

The purpose of this communication is twofold. Firstly, to report new excitation functions of the $^{12}C(^{12}C, ^{8}Be)$ reaction at angles between $\theta_{c.m.} = 70°$ and 100° which were found necessary in order to carry out a meaningful Legendre analysis of $\sigma(\theta, E)$, and secondly, to provide a summary of the results of this analysis, showing the correlation between these other resonance studies which have been reported in the literature.

The $^{8}Be$ detection is by a multiangle $\alpha-\alpha$ coincidence method which has been described in detail elsewhere.[3] Excitation functions for $^{12}C(^{12}C, ^{8}Be)^{16}O$(g.s.) were measured for $E_{c.m.} \simeq 9$ to 20 MeV in steps of $\Delta E_{c.m.} = 100$ keV at angles $\theta_{c.m.} \simeq 76°$, 84°, 92°, and 99°. These data are shown in Fig. 1. Since the cross section may be expressed as

$$\sigma(\theta,E) = \left|\sum_{l=0}^{L} A_l(E) e^{i\delta_l(E)} P_l(\cos\theta)\right|^2, \qquad (1)$$

it is expected that any resonance contribution for $l = 10$ and 12 will be suppressed at $\theta_{c.m.} \simeq 99°$, whereas the $l = 6$ contribution should be enhanced at $\theta_{c.m.} \simeq 84°$ and 99°, $l = 12$ should be enhanced at 76°, and all contributions should appear in the 92° yield. Resonating $l$ values inferred from such general observations are entirely consistent with the $J^\pi$ assignments in our earlier work.[4]

Evaluation of $A_l(E)$ and $\delta_l(E)$ at each energy does not constitute a unique description of the cross section since there exists $2^{(L/2-1)}$ sets of coefficients which yield the same value of $\sigma(E)$. These sets of coefficients have been obtained by the method of Headley, but attempts to select an appropriate energy dependence of $A_l(E)$ and $\delta_l(E)$ have not been successful.[5] The unique linear Legendre expression is alternatively chosen to express the cross section as

$$\sigma(\theta,E) = \sum_{l=0}^{L} B_{2l}(E) P_{2l}(\cos\theta). \qquad (2)$$

The coefficients $B_{2l}(E)$ are unique, but they are not as convenient for indicating resonance phenomena since a resonance appearing in $B_{2l}(E)$ will also manifest itself in all lower order coefficients. Indeed the total cross section is given by $\sigma_T(E) = 4\pi B_0(E)$, where all resonances should appear.

The present data along with that of an earlier report[4] have been used to evaluate the coefficients for $l = 6$, 8, 10, and 12 are plotted vs $E_{c.m.}$ in Fig. 2. The total cross section expressed through the coefficient $B_0(E)$ is shown in Fig. 3. The $J^\pi$ values and resonance positions indicated in Fig. 3 are from the coefficients of Fig. 2. Errors in values of $B_{2l}$ are generally less than 10% and appreciably exceed that only when the absolute values are less than 0.2 mb/sr.

Although Fig. 3 shows most of the resonance structure seen in the $B_{2l}$ values of Fig. 2, it is clear that the effects are much less pronounced in the total cross section since all $l$ contributions are summed together. For example, the two very strong $l = 10$ resonances near $E_{c.m.} = 13.37$ and 13.87 MeV show a peak to valley ratio of 5:1 in $B_{20}$ but only 2:1 in $B_0$. The $l = 10$ resonance near $E_{c.m.} = 17.2$ MeV is one of the most clearly defined structures[4] in the entire energy region, yet in the total cross section it might go unnoticed. Also, nearby is the $l = 10$ resonance at $E_{c.m.} \simeq 14.35$ MeV

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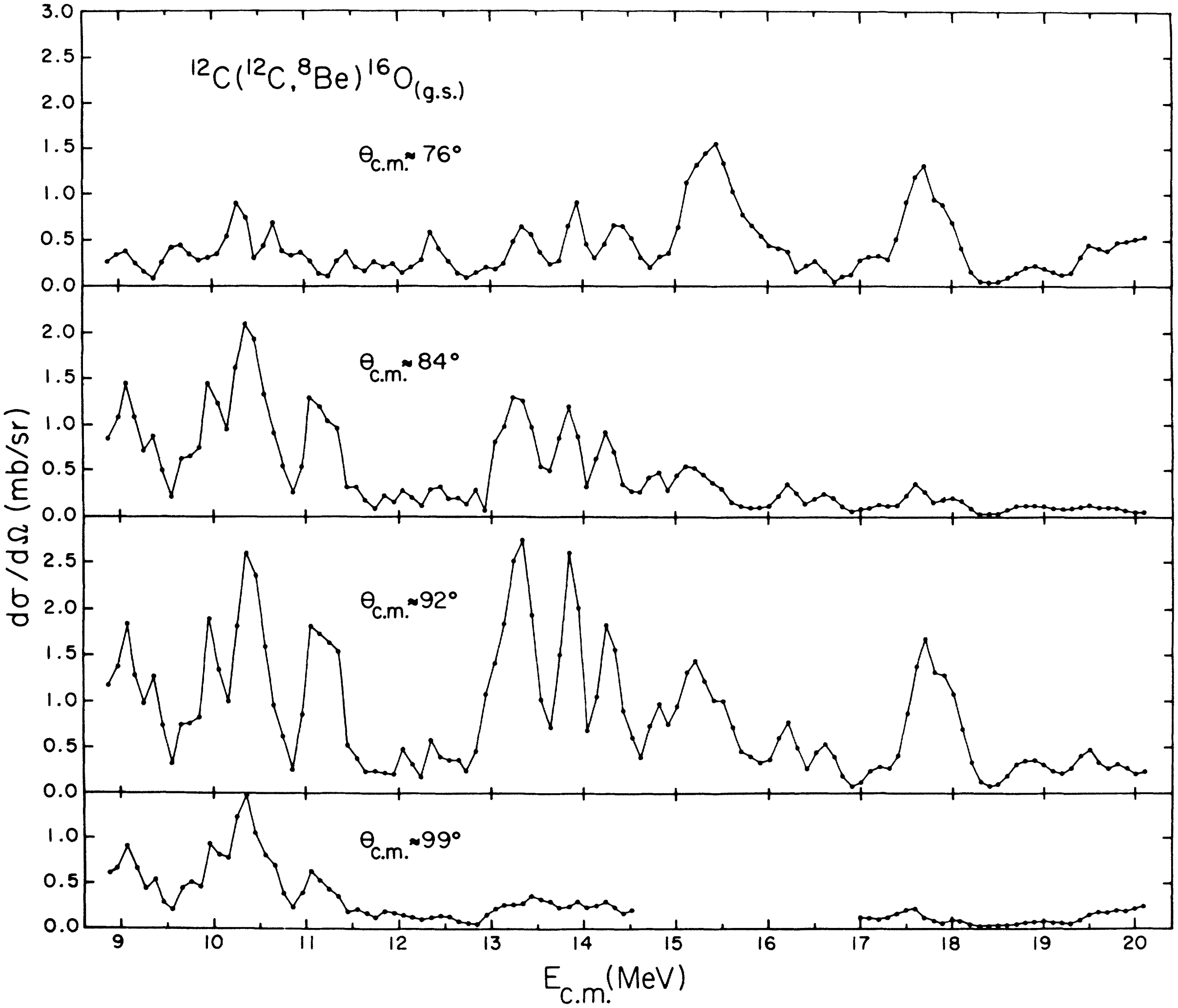

FIG. 1. Excitation functions at selected intermediate reaction angles for $^{12}C(^{12}C,^{8}Be)^{16}O$(g.s.).

which does not seem to maximize at a corresponding energy in $B_0$ because of the possible addition of $8^+$ strength as seen in the $l = 8$ coefficient in Fig. 2 at energy near 14.15 MeV. Because of such interferences, the total cross section cannot be heavily relied upon for identifying resonances and therefore our resonance energies are taken from the coefficients of Fig. 2 rather than from Fig. 3. A tabulation of these resonance energies and the corresponding $J^\pi$ values is given in Table I. This is an update to the similar table which appeared in Ref. 4, with the extension to a number of possible $J^\pi = 6^+$ resonances at lower energies and some energy adjustment.

The resonance energies and $J^\pi$ values from the present work are compared with other published results in Fig. 4. References for the work displayed in Fig. 4 are as follows: *n* channels, Ref. 6; *p* channels, Refs. 2 and 7; *d* channels, Refs. 8 and 9, respectively; *α* channels, Refs. 10 through 14, respectively; 10 through 14, respectively; the other $^8$Be work, Ref. 15; and the inverse *α* channel, Ref. 16. The values of $J^\pi$ shown in Fig. 4 are not actually determined in all of these references. The values used for the sub-Coulomb resonances are from Galster *et al.*[10] Other determinations of $J^\pi$ values are found in Refs. 11, 12, 13, 15, and 16, with valuable arguments for spin assignments presented in Refs. 7, 8, and 9. It is interesting to note that the $10^+$ resonances, observed so prominently between $E_{c.m.} = 13$ and 17 MeV in the $^8$Be channel (see also Ref. 4), are those least observed in other reaction channels. Only one of the weaker resonances (at $E_{c.m.} \simeq 14.35$

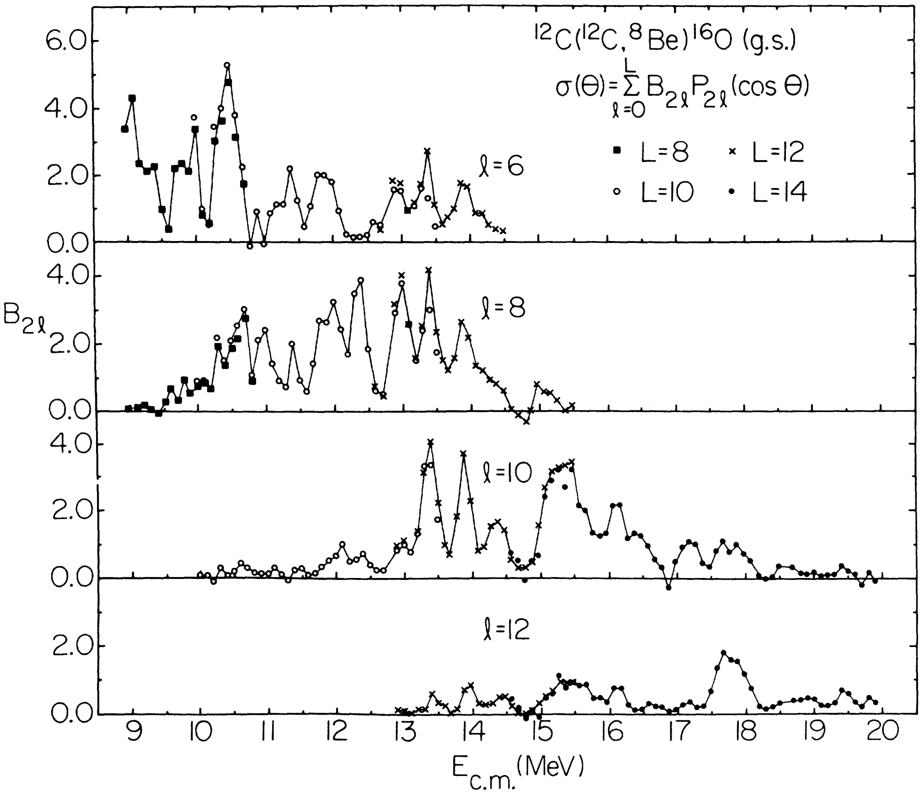

FIG. 2. Legendre coefficients $B_{2l}$ for $l$ =6,8,10, and 12, extracted from angular distributions of $^{12}C(^{12}C,^{8}Be)^{16}O$ (g.s.) measured every 100 keV from $E_{c.m.} \simeq 9$ to 20 MeV.

MeV) has been seen in other reactions. Some support for the very weak resonance with a proposed $10^+$ assignment at $E_{c.m.} \simeq 18.6$ MeV has been given by Eberhard and Bernhardt[15] who report at $E_{c.m.}$

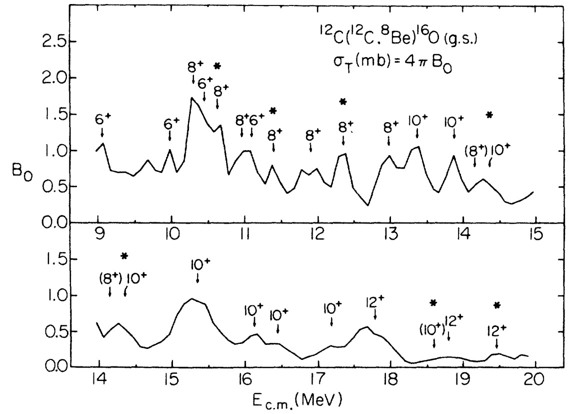

FIG. 3. Total cross section for $^{12}C(^{12}C,^{8}Be)^{16}O$(g.s.) as expressed in the zero order Legendre coefficient from $E_{c.m.} \simeq 9$ to 20 MeV. The resonance energies and $J^{\pi}$ values indicated are from Fig. 2 and Table I. The star indicates a resonance observed strongly in other channels.

TABLE I. Resonances from the $^{12}C(^{12}C,^{8}Be)^{16}O$ (g.s.) reaction.

| $E_{c.m.}$ MeV[a] | $\Gamma_{c.m.}$ (keV)[a] | $J^{\pi}$ |
|---|---|---|
| 9.05 | ... | $6^+$ |
| 9.98 | 200 | $6^+$ |
| 10.30 | (200) | $8^+$ |
| 10.45 | (400) | $6^+$ |
| 10.62 | 300 | $8^+$ |
| 10.96 | 300 | $8^+$ |
| 11.20 | < 450 | $(6^+)$ |
| 11.38 | 200 | $8^+$ |
| 11.90 | 500[b] | $8^+$ |
| 12.36 | 300 | $8^+$ |
| 12.98 | 340 | $8^+$ |
| 13.37 | 300 | $10^+$ |
| 13.87 | 240 | $10^+$ |
| (14.15) | ... | $8^+$ |
| 14.36 | 340 | $10^+$ |
| 15.35 | ~700[b] | $10^+$ |
| 16.13 | < 400 | $10^+$ |
| 16.45 | < 400 | $10^+$ |
| 17.19 | 320 | $10^+$ |
| 17.78 | 500[b] | $12^+$ |
| (18.6) | 300 | $10^+$ |
| 18.8 | ~500 | $12^+$ |
| 19.46 | 230 | $12^+$ |

[a] Error is estimated to be $\lesssim$50 keV.

[b] Some evidence for overlapping structures.

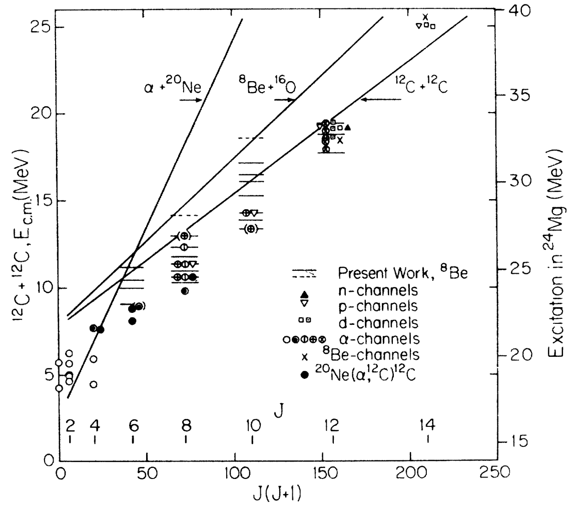

FIG. 4. Comparison of $^{12}C+^{12}C$ resonance in a variety of reaction channels. The long solid lines represent grazing angular momentum calculations.

= 18.5 MeV a dominant $l=12$ contribution in the $^{8}$Be channel and $l=10$ in the $\alpha_0$ channel. One would expect a $J^{\pi}=10^{+}$ state near this energy to show up more strongly in ($^{12}$C, α) than $J^{\pi}=12^{+}$ since the α particle carries away less angular momentum than is possible in ($^{12}$C, $^{8}$Be).

The data of Fig. 4 show quite clearly that the resonant structure appears as a fragmentation of broad enhancements with $J^{\pi}=2^{+}$ through $12^{+}$. The $6^{+}$, $8^{+}$, and $10^{+}$ regions are centered roughly at $E_{c.m.}$ 10, 12, and 15 MeV, with widths of 2, 3, and 5 MeV, respectively. The distribution of $12^{+}$ structure is incomplete above $E_{c.m.}=20$ MeV and difficult to observe in the $^{12}C(^{12}C,^{8}Be)^{16}O$(g.s.) reaction at higher energy because of increasing angular momentum mismatch. There is, however, a broad enhancement in the inelastic scattering[17] near $E_{c.m.}=19$ MeV, the region of our $12^{+}$ resonances, which could reflect an absorption of $l=12$ partial waves.

There does not appear in the summary data any recognizable support for a quasimolecular rotational band interpretation as proposed earlier[2] when only a few narrow resonant structures could be identified in the proton channel. The broad enhancements observed are more easily explained as fragmented giant resonances due to absorption of grazing partial waves. Ironically, the resonances could appear because of a weak absorption of these partial waves relative to the strong absorption from more direct nuclear collisions which can excite a high density of lower angular momentum compound states. A number of giant resonance fragmentation models have been proposed[18]. Recent calculations[19] of resonances as single-particle shape resonances in an effective $^{12}C+^{12}C$ quasimolecular potential fragmented by coupling to the first $2^{+}$ state of $^{12}$C give a semiquantitative explanation of the observations.

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[1] D. A. Bromley, Second International Conference on Clustering Phenomena in Nuclei, 1975, University of Maryland (unpublished) [ERDA Report No. ORO-4856-26 (unpublished), p. 465].

[2] K. Van Bibber, E. R. Cosman, A. Sperduto, T. M. Cormier, and T. N. Chin, Phys. Rev. Lett. 32, 687 (1974).

[3] G. R. Morgan and N. R. Fletcher, Phys. Rev. C 16, 167 (1977).

[4] N. R. Fletcher, J. D. Fox, G. J. Kekelis, G. R. Morgan, and G. A. Norton, Phys. Rev. C 13, 1173 (1976).

[5] D. R. James, Ph.D. dissertation, Florida State Univ., 1977 (unpublished).

[6] P. Sperr, D. Evers, K. Rudolph, W. Assman, E. Spindler, P. Konrad, and G. Denhofer, Phys. Lett. 49B, 345 (1974).

[7] E. R. Cosman, T. M. Cormier, K. Van Bibber, A. Sperduto, G. Young, J. Erksine, L. R. Greenwood, and Ole Hansen, Phys. Rev. Lett. 35, 265 (1975).

[8] M. Conjeaud, S. Harar, S. M. Lee, E. F. da Silveira, and C. Volant, Compte rendu d'activite', Department de Physique Nucleaire, Saclay, p. 12 (1975) (unpublished).

[9] G. Kekelis and J. D. Fox, Phys. Rev. C 10, 2613 (1974); A. Lumpkin (private communication).

[10] W. Galster, W. Treu, P. Duck, H. Frolich, and H. Voit, Phys. Rev. C 15, 950 (1977); E. Almqvist, D. A. Bromley, and J. A. Kuehner, Phys. Rev. Lett. 4, 515 (1960); E. Almqvist, D. A. Bromely, J. A. Kuehner and B. Whalen, Phys. Rev. 130, 1140 (1963).

[11] K. A. Erb, R. R. Betts, D. L. Hanson, M. W. Sachs, R. L. White, P. P. Tung, and D. A. Bromley, Phys. Rev. Lett. 37, 670 (1976).

[12] E. Almqvist, J. A. Kuehner, D. McPherson, and E. W. Vogt, Phys. Rev. 136, B84 (1964).

[13] J. Borggreen, B. Elbek, and R. B. Leachman, K. Dan. Viden. Selsk, Mat.-Fys. Medd. 34, No. 9 (1964).

[14] H. T. Fortune, L. R. Greenwood, R. E. Segel, and J. R. Erksine, Phys. Rev. C 15, 439 (1977).

[15] K. A. Eberhard, E. Mathiak, J. Stettmeier, W. Trombik, A. Weidinger, L. N. Wustefeld, and K. G. Bernhardt, Phys. Lett. 56B, 445 (1975); K. A. Eberhard and K. G. Bernhardt, Phys. Rev. C 13, 440 (1976).

[16] N. O. Lassen and J. S. Olesen, K. Dan. Viden. Selsk.,

Mat.-Fys. Medd. 33, No. 13 (1963).

[17] T. M. Cormier *et al.*, report, 1977 (unpublished).

[18] B. Imanishi, Nucl. Phys. A125, 33 (1969); H. J. Fink, W. Scheid, and W. Greiner, *ibid.* A188, 259 (1972); N. Cindro *et al.*, Phys. Rev. Lett. 39, 1135 (1977); H. Feshbach (unpublished).

[19] J. E. Park, W. Greiner, and W. Sheid, Phys. Rev. C 16, 2276 (1977).