transfer, E_0 the incident energy, and R_u the equivalent uniform radius: $R_u^2 = \frac{5}{3}\langle r^2\rangle$.

[13]E. Moya deGuerra and S. Kowalski, to be published, and private communication.
[14]D. McLaughlin *et al.*, Phys. Rev. C 13, 1644 (1976).
[15]R. J. Powers *et al.*, Nucl. Phys. A278, 477 (1977).

Possible Mechanism for the Resonances in the $^{12}C + ^{16}O$ System

D. Shapira
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627, and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

and

R. M. DeVries, M. R. Clover, and R. N. Boyd
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627

and

R. N. Cherry, Jr.
Hamilton College, Clinton, New York 13323
(Received 18 October 1977)

New data on resonances in the $^{12}C + ^{16}O$ system are presented. A systematic pattern is observed suggesting that theoretical models which have recently been formulated for the mechanism of resonances appearing in the $^{12}C + ^{12}C$ system also apply to this system. Furthermore, energies, spins, and widths for entrance-channel resonances predicted by a recent microscopic calculation of $^{12}C + ^{16}O$ scattering agree very well with the data presented here.

Significant progress has been made recently in understanding the mechanism responsible for the appearance of correlated resonant structure in several heavy-ion–induced reactions.[1-4] Most of the theoretical descriptions have several common features. A mechanism is postulated wherein the contribution of a single partial wave in the entrance channel is enhanced over a broad energy range (e.g., shape elastic resonances). These broad entrance-channel resonances then couple to other degrees of freedom of the system which have special states with longer lifetimes. The various models differ in their description of the broad entrance-channel resonances and the intermediate degrees of freedom involved. Such coupling to intermediate states fragments the broad entrance-channel resonances into the intermediate structure which is observed. So far the most extensive body of data on such resonances has been available for the $^{12}C + ^{12}C$ system (see Refs. 1 and 2 and references therein). Resonances of the same spin in that system are grouped in clusters that form broad enhancement regions. This systematic pattern is cited as evidence that coupling of the entrance-channel resonances to the intermediate degrees of freedom is weak.[5]

The $^{12}C + ^{16}O$ and $^{12}C + ^{12}C$ systems are similar in many respects. Description of the elastic scattering can be obtained by using similar optical potentials.[6] Hence, formation of molecular resonances in the entrance channel is equally likely in both systems and their coupling to other degrees of freedom should occur with similar strength. Also, the level densities in the compound nuclei formed and the number of channels open for their decay are very close for both systems (at comparable energies).[7] Therefore, intermediate states, once formed, are expected to have comparable spreading widths in both systems. Many resonances were observed for $^{12}C + ^{16}O$ reactions,[8-13] but a pattern similar to that in $^{12}C + ^{12}C$ has not been reported yet. In the following we present new data on $^{12}C + ^{16}O$ inelastic scattering that, together with other previously published data, demonstrate that the systematic behavior seen so far of resonances in $^{12}C + ^{12}C$ also exists in the $^{12}C + ^{16}O$ system.

We have measured excitation functions for the inelastic scattering of ^{16}O by ^{12}C at several large center-of-mass angles. Natural carbon targets were bombarded with ^{16}O ions and the recoiling ^{12}C ions were detected in the focal plane of an Enge split-pole spectrograph at six angles between 4° and 10.6° in the laboratory (a c.m. angle span of 14°). Figure 1 presents a summary of our excitation-function data. Two clusters of

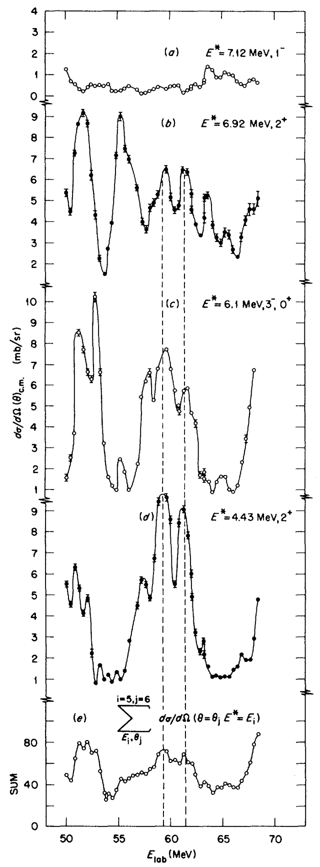

FIG. 1. $^{12}C + ^{16}O$ excitation function for inelastic scattering. (a)–(d) Measured at 4°; (e) sum of all data.

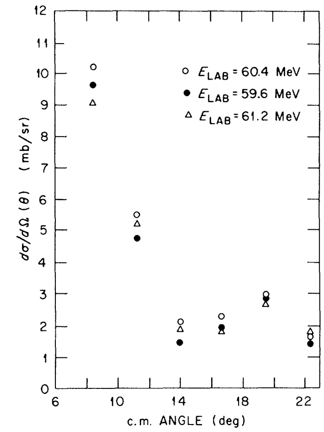

FIG. 2. Angular dependence for the 2^+ transitions for three energies where correlated peaks show up around 60 MeV.

resonances appear in the energy region shown. The doublet appearing around 52-MeV bombarding energy has been reported previously.[11,12] The group appearing around 60 MeV shows at least two correlated narrow peaks (indicated by dashed lines). The bottom part of Fig. 1 shows a summed yield curve for all five transitions at the six angles measured. This same structure is also apparent in the data taken with a thicker target[12] at a laboratory angle of ~ 2°. Fusion data for $^{12}C + ^{16}O$ display the same structure in the excitation functions.[14] Broad structure appears with peaks centered around 45, 52, and 60.5 MeV laboratory energies with widths of approximately 1.5, 3, and 5 MeV. Elastic data of Charles *et al.*[9] also have the same structure. Clearly the properties of these structures (magnitude, widths, and correlations) cannot be accounted for, within reasonable probability, by the statistical model of nuclear reactions.

We have also measured angular distributions at several energies around 52 MeV and analyzed the data of several inelastic transitions in order to determine the spins of this doublet of resonances. The details of the analysis and the data are published elsewhere.[15] We were able to assign a spin value of $J = 15$ to both resonances.

For the group around 60.5 MeV we have data at six angles where we took the excitation function. Application of the same analysis indicates that $J \geq 16^+$. As can be seen from Fig. 2, the angular distributions in that region look almost identical.

The emerging pattern is analogous to that observed of resonances in the $^{12}C + ^{12}C$ system. The resonances appear clustered in groups which form broad enhancement regions, and the resonances within such a cluster have the same spin. This behavior suggests that broad resonances, formed in the entrance channel, couple to more tightly bound (intermediate) states in which one of the colliding nuclei undergoes inelastic excitation. The fragmentation observed, however, is not complete, preserving some of the characteristics of the entrance-channel resonances, thus indicating that the coupling of the entrance channel to these intermediate states is weak. Such a mechanism and its consequences are described in more detail in Ref. 2 and by Abe.[16]

In a phenomenological approach the broad structure can be described in terms of single-particle resonances in the $^{12}C + ^{16}O$ potential, that are generated by the grazing partial waves of a surface transparent potential.[17,4] Column 2 of Table I shows the energies and spins of entrance-channel resonances calculated with an optical potential which was obtained by fitting elastic data. A different approach is that of Baye and Heenen.[18]

TABLE I. Resonance data represented as ($E_{c.m.}$, $\Gamma_{c.m.}$, J^{π}) where $E_{c.m.}$ is the energy and $\Gamma_{c.m.}$ is the width of the resonance in the center-of-mass system.

Experiment	Potential scattering[a-c]	Microscopic calculations
$(19.7, 0.4, 14^+)$	$(19.5, \cdots, 14^+)$	$(19.7, 1.0, 14^+)$
$(22.0, 1.0, 15^-)$[d]	$(21.5, \cdots, 15^-)$	$(22.2, 0.7, 15^-)$
$(25.2, 2.5, \geq 16^+)$[d]	$(23.6, \cdots, 16^+)$	$(25.1, 3.3, 16^+)$
?	$(26.2, \cdots, 17^-)$	$(28.3, 5.0, 17^-)$

[a]The potential used to get the resonance energies and spins is $V_R = 17.0$, $r_R^0 = 1.35$, $a_R = 0.49$, $V_I = 0.4 + 0.1E + 0.006E^2$, $r_I^0 = 1.27$, and $a_I = 0.15$. The $J = l$ resonance energy was taken as the energy where $T_l = 0.5$.

[b]No width assignment was attempted. The derived width would depend on the parametrization used but they are all expected to be several MeV wide.

[c]Prominent structure can be seen in the calculated 90° c.m. excitation function where only even partial waves contribute but it is somewhat washed out at other angles.

[d]These data represent a cluster of resonances.

They performed a microscopic calculation for $^{12}C + ^{16}O$ scattering. Using a modified R-matrix theory, they antisymmetrize the wave function of the 28 nucleons and take the relative ^{12}C-to-^{16}O center-to-center distance as a generator coordinate. In this basis they calculate the phase shifts for $^{12}C + ^{16}O$ scattering and obtain several groups (bands) of resonances corresponding to different excitation levels of the relative-motion wave function. The third column in Table I lists four broad resonances that are predicted to lie above 19.5-MeV c.m. incident energy which belong to $n = 0$ bands, i.e., no excitation of the relative-motion wave function. These theoretical assignments agree well with those obtained from the experimental data which are summarized in the first column.

The results of the microscopic calculation agree with the data in several other respects. No isolated broad resonances are predicted below 19 MeV. This may be the reason why such systematics as mentioned here were not observed at lower energies. Optical-model-generated shape resonances, however, are expected to appear at lower energies. The microscopic calculation also predicts the existence of the 12^+ and 13^- resonances seen at energies between 19.7 and 22 MeV.[9,19]

In conclusion, we presented here experimental data which show that the mechanism responsible for the resonances in $^{12}C + ^{16}O$ is the same as the one in the $^{12}C + ^{12}C$ system, at least over the energy range studied here. The highest energy points in the excitation function we present here suggest the appearance of more correlated structure at the energies where a broad $J = 17^-$ resonance is predicted by Ref. 18. Extending these measurements to higher energies and obtaining spin assignments for more resonances will hopefully corroborate the picture presented here and show its persistence over a wider energy range.

The authors wish to acknowledge many useful comments and suggestions by R. G. Stokstad. This work has been supported by the National Science Foundation and the U. S. Department of Energy under contract with Union Carbide Corporation.

[1]D. A. Bromley, in *Proceedings of the Second International Conference on Clustering Phenomena in Nuclei, College Park, Maryland, 1975*, edited by D. A. Goldberg, J. B. Marion, and S. J. Wallace, ERDA Report No. ORO-4856-26 (National Technical Information Services, Springfield, Va., 1975).

[2]H. Feshbach, J. Phys. (Paris) Colloq. C5-37, 177 (1976).

[3]B. J. Cole, C. T. Toepffer, and K. Dietrich, Phys. Rev. Lett. 39, 3 (1977).

[4]P. Singh, D. Sink, P. Schwandt, R. Malmin, and R. Siemssen, Phys. Rev. Lett. 28, 1714 (1972).

[5]T. M. Cormier, J. Applegate, G. M. Berkovitz, P. Braun-Munzinger, P. M. Cormier, J. W. Harris, C. M. Jachinski, L. L. Lee, Jr., J. Barrette, and H. E. Wegner, Phys. Rev. Lett. 38, 94 (1977).

[6]R. Siemssen, Argonne National Laboratory Report No. 7837, 1972 (unpublished).

[7]D. L. Hanson, R. G. Stokstad, K. A. Erb, C. Olmer, and D. A. Bromley, Phys. Rev. C 9, 1760 (1974).

[8]M. L. Halbert, F. E. Durham, and A. Van der Woude, Phys. Rev. 162, 899, 919 (1967).

[9]P. Charles, F. Auger, I. Badawy, B. Berthier, M. Dost, J. Gastebois, B. Fernandez, S. M. Lee, and E. Plagnol, Phys. Lett. 62B, 289 (1976).
[10]R. E. Malmin, R. Siemssen, D. Sink, and P. P. Singh, Phys. Rev. Lett. 28, 1590 (1972).
[11]R. E. Malmin and P. Paul, in *Proceedings of the Second International Conference on Clustering Phenomena in Nuclei, College Park, Maryland, 1975*, edited by D. A. Goldberg, J. B. Marion, and S. J. Wallace, ERDA Report No. ORO-4856-26 (National Technical Information Services, Springfield, Va., 1975), p. 450.
[12]D. Shapira, R. G. Stokstad, M. W. Sachs, A. Gobbi, and D. A. Bromley, Phys. Rev. C 12, 1907 (1975).
[13]E. R. Cosman, A. Sperduto, T. M. Cormier, T. N. Chin, H. E. Wegner, M. J. Levine, and D. Sehwalm, Phys. Rev. Lett. 29, 1341 (1972); P. Sperr, D. Evers, A. Harassim, W. Assman, P. Konrad, K. Rudolph, G. Denhoefer, and C. Ley, Phys. Lett. 57B, 438 (1975).
[14]J. J. Kolata, R. M. Freeman, F. Haas, B. Bensch, and A. Gallman, Phys. Lett. 65B, 332 (1976). The authors wish to thank J. J. Kolata for providing the fusion measurement data in tabular form.
[15]D. Shapira, R. M. DeVries, M. R. Clover, R. N. Boyd, and R. N. Cherry, to be published.
[16]Y. Abe, in *Proceedings of the Second International Conference on Clustering Phenomena in Nuclei, College Park, Maryland, 1975*, edited by D. A. Goldberg, J. B. Marion, and S. J. Wallace, ERDA Report No. ORO-4856-26 (National Technical Information Service, Springfield, Va., 1975).
[17]A. Gobbi, R. Wieland, L. Chua, D. Shapira, and D. A. Bromley, Phys. Rev. C 7, 30 (1973); R. Siemssen, T. Fortune, R. Malmin, A. Richter, J. Tippie, and P. Singh, Phys. Rev. Lett. 25, 536 (1970).
[18]D. Baye and P. H. Heenen, Nucl. Phys. A283, 176 (1977).
[19]D. R. James, G. R. Morgan, N. R. Fletcher, and M. B. Greenfield, Nucl. Phys. A274, 177 (1976).

Can the Hadronic Mass Spectrum Be Discovered through High-Energy Nuclear Collisions?

Norman K. Glendenning and Yasha Karant
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 6 October 1977)

It is suggested that the general form of the hadronic mass spectrum can be determined by studying the decay of hot hadronic matter produced in very-high-energy nuclear collisions. In a thermodynamic model we find that at presently attainable energies the temperature and the hadron populations in the matter depend strongly on the form of the hadronic spectrum.

One of the fundamental properties of matter is the mass spectrum of the hadrons. Besides being an object of interest in particle physics, it has profound cosmological significance. The spectrum starts with the pion and rapidly becomes dense up to masses of about 2 GeV. Thereafter, according to our present knowledge, but most likely because of the difficulty of measurement, there are only a few additional known particles and resonances. The experimental spectrum is shown in Fig. 1 with the exception of isolated recent discoveries. According to the bootstrap hypothesis the spectrum continues beyond the known region and, in effect, exponentially. The hypothesis can be stated simply as follows: From the known particles or resonances select two (or more) and combine their quantum numbers. The multiplet so obtained are also particles or resonances (at something like the sum of the masses). Add these to the pool of particles and continue. The spectrum thereby generated by Hamer and Frautschi[1] is also shown in Fig. 1. The implication is astonishing. The number of particles and resonances (each charge and spin state counted individually) grows so fast that at masses of only 2.5 GeV the number in a mass interval of the pion mass, expected from the bootstrap hypothesis, is $\sim 10^4$. The number of known hadrons is $\sim 10^2$. If new particles were discovered at the rate of one a day it would require of the order of a hundred years to confirm the bootstrap prediction by a direct count, and that in only such a small mass interval and at such a low mass!

We suggest as an alternative that it may be possible to determine the general behavior of the spectrum without the necessity of discovering the individual particles and resonances. The decay of hadronic matter produced in ultrahigh-energy collisions between nuclei will depend upon the type and masses of particles that can energetically be produced; that is, on the mass spectrum of the hadrons. After that obvious statement,