Structure in the Excitation Functions of $^{12}C(^{16}O, p)^{27}Al$, $^{12}C(^{16}O, d)^{26}Al$, and $^{12}C(^{16}O, \alpha)^{24}Mg$†

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The excitation functions for the above reactions show evidence for a large statistical conpound-nucleus contribution. In addition, a broad structure (~1 to 2 MeV) is seen in $^{12}C(^{16}O,\alpha)^{24}Mg$, and narrower correlated resonances (~300 keV) appear in $^{12}C(^{16}O,p)^{27}Al$, one of them, at $E_{c.m.} = 19.71$ MeV, having the same position and width as a recently found anomaly in $^{16}O + {}^{12}C$ elastic and inelastic scattering.

The recent discovery of resonances in $^{16}O + {}^{12}C$ elastic and inelastic scattering[1,2] and of selectively enhanced transitions in the reactions[3,4] $^{12}C(^{16}O, p)^{27}Al$ and $^{12}C(^{16}O, \alpha)^{24}$ Mg has provoked speculation on possible direct reaction and intermediate structures involving nuclear clusters and quasimolecules. A crucial input in clarifying the questions raised is more complete excitation functions for the charged-particle reaction channels.

Here we have studied the reactions $^{12}C(^{16}O, p)^{27}Al$, $^{12}C(^{16}O, d)^{26}Al$, and $^{12}C(^{16}O, \alpha)^{24}Mg$ for $E_{lab} = 20$–65 MeV,[5] $E_{c.m.} = 8.5$–28 MeV, using the Brookhaven National Laboratory (BNL) double MP tandem Van de Graaff facility. Two counter telescopes at $\theta_{lab} = 15°$ to the beam were used, one to detect p's and d's, and the other to detect α's. With 10-$\mu g/cm^2$ carbon foils, an overall resolution of about 120 keV was achieved. Sample spectra are shown in Fig. 1. Marked selectivity of final states and large variations with bombarding energy in their yields are evident. The excitation functions extracted for a number of the stronger groups are shown in Fig. 2. From these data, there are indications that both statistical compound-nucleus and nonstatistical reaction mechanisms are involved. The evidence for each is elaborated below.

In a statistical compound process, the $^{16}O + {}^{12}C$ fusion into compound ^{28}Si levels and the subsequent decay modes are governed only by statistical level densities and transmission factors. The evidence that this mechanism is, with the exception of certain anomalies discussed below, dominant in giving rise to the backgrounds and narrow peaks is observed in the following: (1) A Hauser-Feshbach calculation[6-8] of the relative total yields of the p, d, and α spectra matches closely the measured values, suggesting that the net direct-reaction contributions are comparatively small; (2) a narrow rapidly varying structure of width $\Gamma_{c.m.}$ from $\simeq 100$ to 500 keV appears in the excitation functions of nearly all groups and often shows no obvious correlations in position or widths. This is particularly evident for

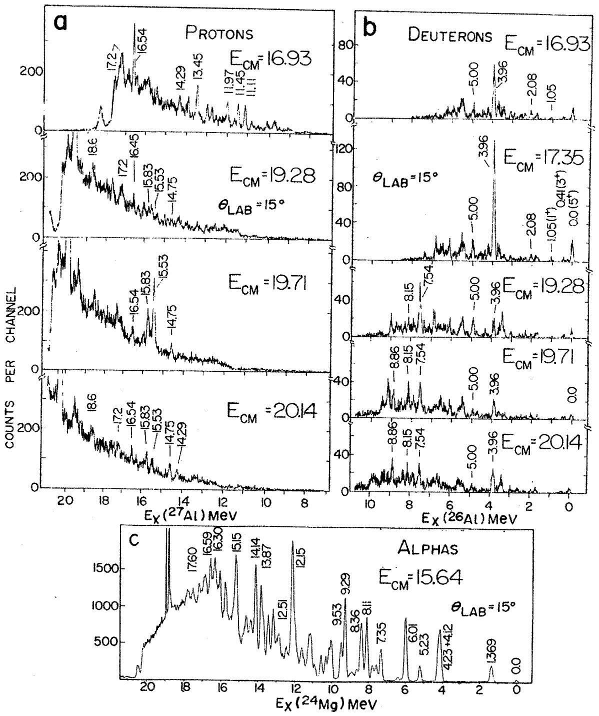

FIG. 1. Spectra of (a) $^{12}C(^{16}O,p)^{27}Al$, (b) $^{12}C(^{16}O, d)^{26}Al$, and (c) $^{12}C(^{16}O,\alpha)^{24}Mg$ at various angles of interest. The labeled excitation energies are accurate to about ±30 keV. The data were obtained with the counter-telescope arrangement.

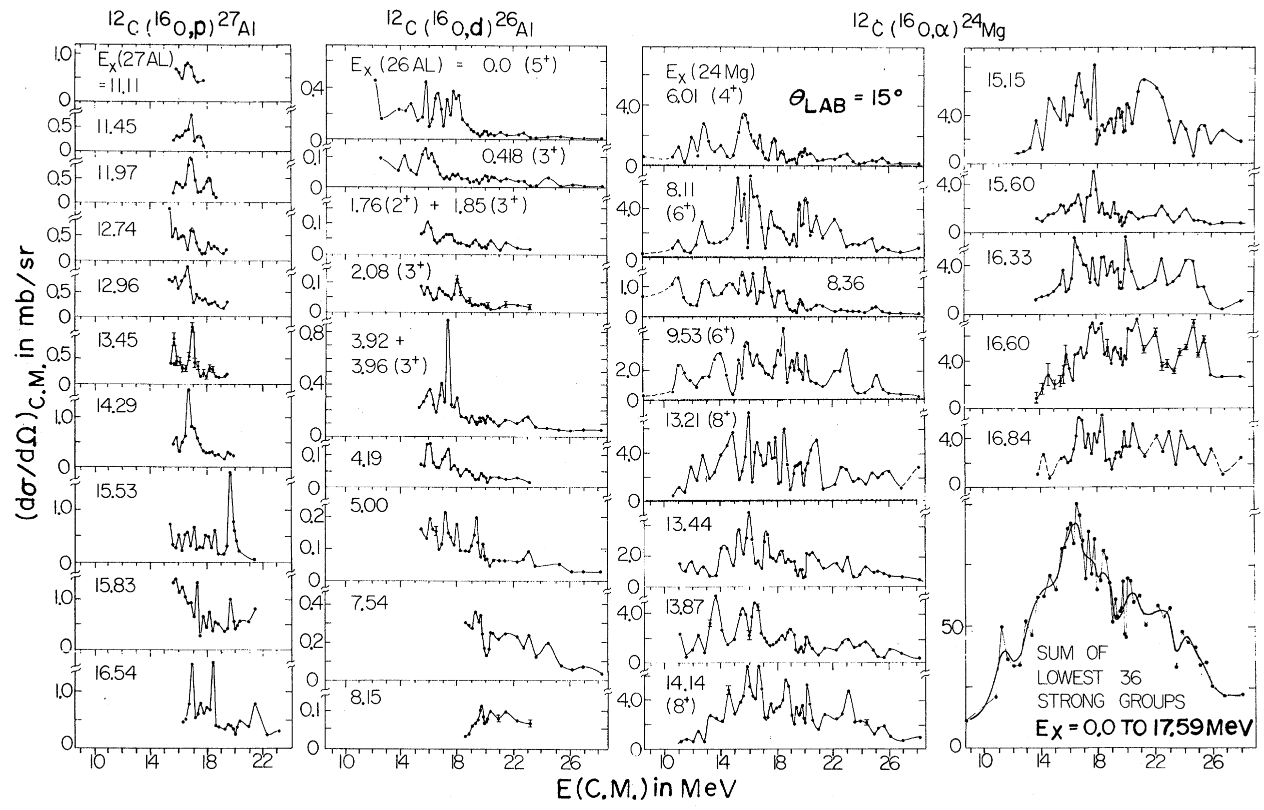

FIG. 2. Excitation functions from the counter-telescope data for a selection of the stronger transitions seen. Solid lines are merely guides to the eye and representative error bars are shown for some cases.

the ^{12}C(^{16}O, α)^{24}Mg groups. Greenwood *et al.*[9] have recently done a detailed correlation analysis for this reaction with very fine energy steps in the range $E_{\text{c.m.}} = 19.6-23$ MeV and agree with this conclusion.

Two additional remarks on the consistency of the compound-nucleus interpretation can be made. First, it predicts the enhancement of high-spin states, since the average angular momentum brought in by the heavy ions during fusion is much larger than can be carried off by the emitted light particle. Indeed, recent spin measurements[10] of the selected final states in the p and α spectra support this. Secondly, the criterion for sharp states to be strongly visible in these light-particle channels is that there exist few other channels that can carry off the high angular momentum brought into the compound system. By simple energetic arguments,[8] this occurs when the target and projectile are most tightly bound. There is a growing body of data[11] which confirm this, too, and which show that the most dramatic selectivity occurs for reactions induced by such combinations as ^{12}C + ^{12}C, ^{16}O + ^{12}C, ^{16}O + ^{16}O, ^{12}C + ^{20}Ne, and so on.

The most interesting question is to what extent intermediate structures and nonstatistical processes are involved in the heavy-ion collision. The light-particle emission spectra are in principle natural probes for this. The criterion of the last paragraph for pronounced selectivity in these spectra is equivalent, in optical-model terms, to weak absorption or transparency in the ^{16}O + ^{12}C interaction potential for surface partial waves,[12] which means that shape or quasimolecular resonances may exist or that these or other intermediate structures may not be severely damped. Since by angular-momentum matching, the selected states in the α, d, and p channels are themselves mappings of the entrance surface waves, their excitation functions might be expected to manifest such structures. Two examples from our data indicate that they do.

First, in ^{12}C(^{16}O, α)^{24}Mg, we have summed excitation functions for various groups of states, as shown in Fig. 2. In the sum over the lowest 36 prominent levels up to $E_x = 17.5$ MeV, for example, a broad structure modulating the underlying evaporation curve is evident with characteristic half-widths of order of 1 to 2 MeV. A

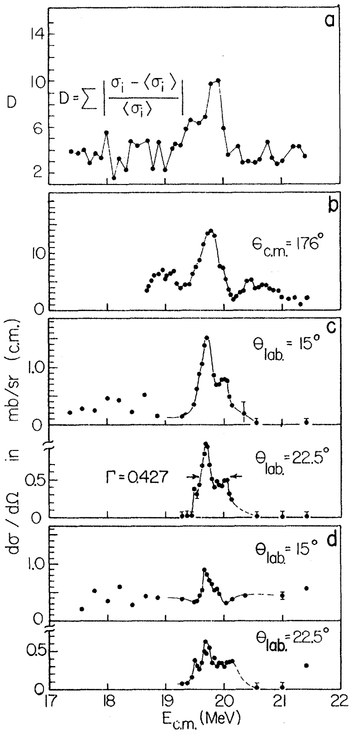

FIG. 3. Comparison of the excitation functions from (a) ^{16}O(g.s.) + ^{12}C(g.s.) elastic scattering from Ref. 1 (this is the angle-integrated correlation function D which measures the deviation from the mean elastic cross sections); (b) $^{16}O^*(6.05+6.13)$ + ^{12}C(g.s.) inelastic scattering from Ref. 2, (c), (d) $^{12}C(^{16}O,p)^{27}Al$ reaction excitation functions to the $E_x=15.53$- and 15.83-MeV states, respectively, at $\theta_{lab}=15°$ and 22.5° ($\theta_{c.m.}\simeq 19.8°$ and 29.7°) from the present work using the MIT multiple-gap spectrograph data. An anomaly at $E_{c.m.}\simeq 19.7$ MeV is evident in each case.

distinct minimum is seen at $E_{c.m.}=19.2$ MeV, which was noted previously by Stokstad *et al.*[2] These broader structures, in contradistinction to the narrower ones cited above, probably arise from shape resonances or intermediate structures in the entrance-channel surface waves.

The second example is the appearance in the reaction $^{12}C(^{16}O,p)^{27}Al$ of narrow correlated resonances in certain highly excited states of ^{27}Al. Figure 3 displays the best example, studied with finer energy steps using the Massachusetts Institute of Technology (MIT) multiple-gap spectrograph.[13] Two proton groups at $E_x=15.53$ and 15.83 MeV show anomalous enhancements at $E_{c.m.}=19.71$ MeV, just the energy where Refs. 1 and 2 have recently reported resonances in the ^{16}O(g.s.) + ^{12}C(g.s.) and unresolved $^{16}O^*(6.05, 3^-+6.13, 0^+)$ + ^{12}C(g.s.) channels. They estimate the resonance width to be between 350 and 400 keV. Our data indicate that the resonance may have a substructure, the overall width of the anomaly being about 427 keV. No evidence for similar resonances at this energy was found in the α channel or in the d channel; however, other candidates exist in $^{12}C(^{16}O,p)^{27}Al$, for example, at $E_{c.m.}=16.9$ and 18.2 MeV, where several proton groups are enhanced together (see Figs. 1 and 2).

Two explanations for correlations in the $p+{}^{27}Al$ channel at $E_{c.m.}=19.71$ MeV can be given: (1) An intermediate structure in a high partial wave ($l=14$ has been suggested in Ref. 1) associated with the $^{16}O+{}^{12}C$ and $^{16}O^*+{}^{12}C$ configuration acts as a doorway to more complex compound states in ^{28}Si, which then evaporate protons statistically to high-spin states of ^{27}Al. This might be more visible for protons because they are fed by fewer J states in ^{28}Si than heavier-particle channels. (2) There is a spectroscopic connection between the resonating ^{27}Al levels and the intermediate structure in ^{28}Si, the widths of the latter to the $^{16}O+{}^{12}C$, $^{16}O^*+{}^{12}C$, and $p+{}^{27}Al^*$ being large because of favorable configuration overlap. This is a speculative but tempting interpretation because it would imply that the resonating ^{27}Al states have an exotic structure, probably of $^{15}N+{}^{12}C$ nuclear molecular character. In this picture, quantitative knowledge of decay widths to $p+{}^{27}Al^*$ could distinguish between models already suggested for the resonances in ^{28}Si; viz., core excitation[14] and α clusters,[15] or indicate the need for other configurations perhaps involving valence proton exchange. The systematics, spins, and decay modes of such structures are needed to clarify further their origin.

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[1] R. H. Siemssen, in *Proceedings of the Symposium on Heavy-Ion Scattering, Argonne National Laboratory, 1971*, edited by R. H. Siemssen (Argonne National Laboratory, Argonne, Ill., 1971); R. E. Malmin, R. H. Siemssen, D. A. Sink, and P. P. Singh, Phys. Rev. Lett. 28, 1590 (1972).

[2] R. Stokstad, D. Shapira, L. Chua, P. Parker, M. W. Sachs, R. Wieland, and D. A. Bromley, Phys. Rev. Lett. 28, 1523 (1972).

[3] E. R. Cosman, A. Sperduto, W. H. Moore, T. N. Chin, and T. M. Cormier, Phys. Rev. Lett. 27, 1074 (1971).

[4] R. Middleton, J. D. Garrett, and H. T. Fortune, Phys. Rev. Lett. 24, 1435 (1970); E. R. Cosman, H. A. Enge, and J. C. Britt, unpublished.

[5] Preliminary results have been reported: E. R. Cosman, A. Sperduto, T. M. Cormier, T. N. Chin, H. Wegner, M. LeVine, and D. Schwalm, Bull. Amer. Phys. Soc. 17, 489 (1972).

[6] Results from Hauser-Feshbach Program SERENA; T. N. Chin, T. M. Cormier, and E. R. Cosman, to be published.

[7] R. G. Stokstad, D. Shapira, L. Chua, A. Gobbi, P. Parker, M. Sachs, R. Wieland, and D. A. Bromley, Bull. Amer. Phys. Soc. 17, 529 (1972).

[8] R. E. Malmin, K. Katori, L. R. Greenwood, T. H. Braid, and R. H. Siemssen, in Proceedings of the Symposium on Heavy-Ion Reactions and Many-Particle Excitations, Saclay, France, 1971 [J. Phys. (Paris), to be published].

[9] L. R. Greenwood, T. H. Braid, K. Katori, R. H. Siemssen, and J. C. Stoltzfus, Bull. Amer. Phys. Soc. 16, 645 (1971), and Phys. Rev. C (to be published).

[10] A. Gobbi, P. R. Maurenzig, L. Chua, H. Hadsell, P. D. Parker, M. W. Sachs, D. Shapira, R. Stokstad, R. Wieland, and D. A. Bromley, Bull. Amer. Phys. Soc. 26, 306 (1971); D. P. Balamuth, J. E. Holden, J. W. Noé, and R. W. Zurmühle, Phys. Rev. Lett. 26, 1271 (1971); M. J. LeVine and D. Schwalm, Bull. Amer. Phys. Soc. 16, 1421 (1971).

[11] E. R. Cosman, Bull. Amer. Phys. Soc. 16, 1421 (1971); R. Middleton, J. D. Garrett, H. T. Fortune, and R. R. Betts, J. Phys. (Paris), Colloq. 32, C6-39 (1971).

[12] For a thorough account of this point, see the *Proceedings of the Symposium on Heavy-Ion Scattering, Argonne National Laboratory, 1971*, edited by R. H. Siemssen (Argonne, National Laboratory, Argonne, 1., Ill., 1971.

[13] The MIT multiple-gap spectrograph now installed at BNL has a unique rotating emulsion-holder carousel, such that by masking off all but one gap, 72 broad-range spectra for that gap can be taken in sequence without breaking vacuum. This feature was used to obtain the finer stepped excitation function of $^{12}\mathrm{C}(^{16}\mathrm{O}, p)^{27}\mathrm{Al}$ shown in Fig. 3.

[14] B. Imanishi, Nucl. Phys. A125, 33 (1969); W. Schneid, W. Greiner, and R. H. Lemmer, Phys. Rev. Lett 25, 176 (1970).

[15] G. Michand and E. W. Vogt, Phys. Lett. 30B, 85 (1969), and Phys. Rev. C 5, 350 (1972).

New Exact Solution for the Gravitational Field of a Spinning Mass

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A solution for the gravitational field is presented, which reduces to one of the Weyl metrics in the limit of angular momentum $J=0$ and reduces to the Kerr metric in the limit of $J=m^2$.

The Kerr metric has been the only known example[1] of an exact exterior solution representing the gravitational field of a spinning mass. In this note we shall present a solution for the metric which does not reduce to the Schwarzschild metric in the limit of angular momentum $J=0$, unlike the case of the Kerr metric, but does reduce to one of the Weyl metrics[2] representing fields of deformed masses.

According to the formulation of Ernst,[3] stationary axisymmetric solutions in empty space can be derived from a complex function ξ which satisfies the following equation:

$$(\xi\xi^* - 1)\nabla^2\xi = 2\xi^*\nabla\xi\cdot\nabla\xi. \tag{1}$$

A solution of Eq. (1) has been obtained as $\xi = px - iqy$,[3] where x and y are the coordinate variables, and p and q are the parameters defined by J and gravitational mass m: $q = J/m^2$ and $p = (1-q^2)^{1/2}$. Besides the above Ernst solution from which the Kerr metric is derived, we found a new solution given by

$$\xi = \frac{p^2x^4 + q^2y^4 - 2ipqxy(x^2 - y^2) - 1}{2px(x^2-1) - 2iqy(1-y^2)}. \tag{2}$$