$^{18}O + ^{12}C$ System: Evidence for Nonstatistical Intermediate Structure with Enhancement of Odd Partial Waves in the Elastic Channel*

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$^{18}O + ^{12}C$ elastic-scattering excitation functions have been measured at eight angles over the energy range 12–25 MeV (c.m.). In addition, cross sections for the reaction channels $^{12}C(^{18}O, \alpha)^{26}Mg$ ($E_x = 0.0$–5.47 MeV) and $^{12}C(^{18}O, ^{16}O)^{14}C$ were measured over nearly the same energy range. The elastic scattering exhibits the novel behavior of being dominated by odd partial waves. Correlated structures were observed at 16.6, 19.0 ($J^{\pi} = 15^-$), and 21.8 ($J^{\pi} = 17^-$) MeV (c.m.).

One of the most perplexing phenomena in heavy-ion reactions has been the existence of nonstatistical intermediate-structure "resonances." At energies well in excess of the Coulomb barrier these resonances, most clearly seen in the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ systems,[1-3] are characterized by a width of approximately 0.5 MeV (c.m.) and by a cross correlation in energy among various reaction channels. The width, intermediate between that expected for compound nuclear fluctuations and that for potential scattering, has (at energies near the Coulomb barrier) given rise to various "molecular" models[4,5] in which the integrity of the target and projectile is assumed to be largely preserved in a "diatomic" or, possibly, a more complicated spatial geometry. The energy correlation observed in some reaction channels argues against these resonances having a random, statistical origin. The presence of intermediate-structure resonances in only a few systems, and their absence in some reaction channels of these systems, represents a continuing puzzle. In order to gain a further understanding of these resonances, we have undertaken a detailed study of the energy and angular dependence of the elastic scattering as well as the $\alpha + ^{26}Mg$ and the $^{14}C + ^{16}O$ reaction channels of the $^{18}O + ^{12}C$ system.

^{18}O beams from the University of Washington FN tandem Van de Graaff accelerator were used to bombard 50–100-μg/cm^2 [90–180 keV (c.m.)] ^{12}C targets. A kinematic coincidence technique which allowed the simultaneous measurement of four excitation functions was used to obtain the elastic-scattering data. In addition, the $^{14}C + ^{16}O$ channel could be measured simultaneously with the elastic scattering at a few angles. The surface-barrier detectors used to define the angle subtended a full angle of 0.40° (lab). The back-angle α data were obtained with a transmission-mounted E counter (~250 μm thick) backed by a veto counter to suppress contributions from protons and deuterons.

Elastic-scattering excitation functions were measured at 73°, 80°, 86°, 90°, 95°, 100°, 105°, and 115° (c.m.). Four of the excitation functions are shown in Fig. 1(a). Resonancelike structures at 19.0 and 21.8 MeV are observed cross correlated in angle with widths of approximately 600 keV (full width at half-maximum). The excitation functions at 105° and 115° (not shown), where the Rutherford cross section is less dominant, exhibit a similar structure at 16.6 MeV. Figure 2(a) shows the deviation function calculated for all eight excitation functions and displays

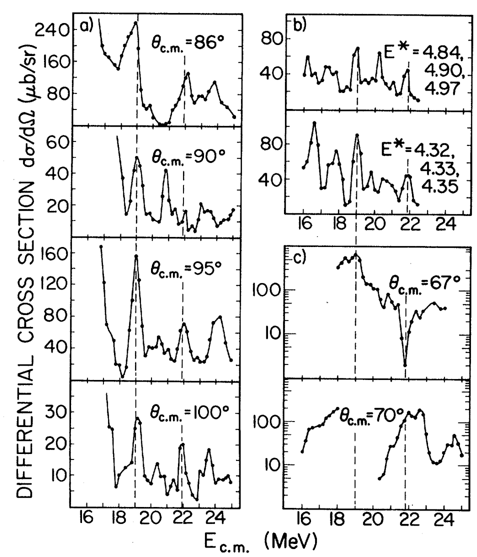

FIG. 1. Excitation functions for (a) $^{18}O + ^{12}C$ elastic scattering, (b) the reaction $^{12}C(^{18}O, \alpha)^{26}Mg$, and (c) the reaction $^{12}C(^{18}O, ^{16}O)^{14}C$. Solid lines serve only to guide the eye. The dashed lines indicate the position of the resonances.

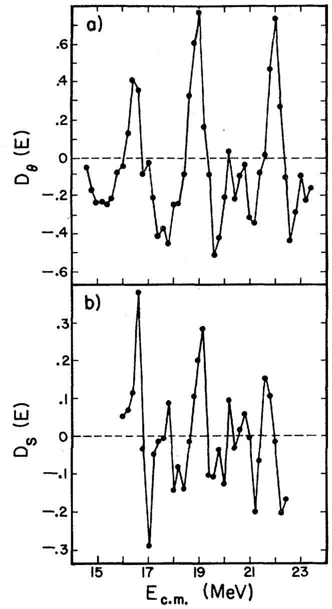

FIG. 2. The deviation function for (a) the elastic scattering at eight angles,

$$D_\theta(E)=\frac{1}{8}\sum_{i=1}^{8}[(\sigma_i-\langle\sigma_i\rangle)/\langle\sigma_i\rangle]$$

and (b) for the reaction $^{12}C(^{18}O,\alpha)^{26}Mg$ for twelve states in ^{26}Mg at $\theta_{c.m.}=169°$,

$$D_S(E)=\frac{1}{12}\sum_{i=1}^{12}[(\sigma_i-\langle\sigma_i\rangle)/\langle\sigma_i\rangle].$$

The averaging interval was 2.6 MeV (c.m.) in both cases.

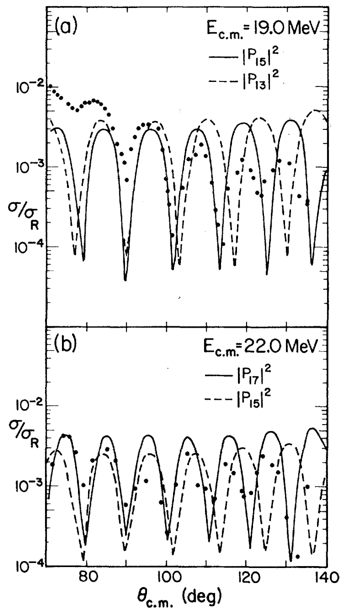

FIG. 3. $^{18}O+^{12}C$ elastic-scattering angular distributions at (a) 19.0 MeV and (b) 22.0 MeV. The curves are arbitrarily normalized $|P_l(\cos\theta)|^2$ functions.

the strong enhancements at 16.6, 19.0, and 21.8 MeV. The average elastic-scattering cross section is fairly modest, of the order of 10 to 100 μb/sr. Hauser-Feshbach calculations done with the code STATIS[6] indicate large compound nuclear contributions at these energies and angles.

Elastic-scattering angular distributions at 19.0, 22.0, and 23.0 MeV were measured over an angular range 40°–135° (c.m.). The large-angle portions of the 19.0- and 22.0-MeV angular distributions are shown in Fig. 3 along with arbitrarily normalized $|P_l(\cos\theta)|^2$ functions. The periodicity of the data at 19.0 MeV is well reproduced by the Legendre polynomial with $l=15$, with qualitatively inferior fits for $l=13$ and $l=17$ (not shown). The periodicity of the 22-MeV data is consistent with a $|P_{17}|^2$ distribution. The angular distribution at 23 MeV could not be fitted with a single $|P_l|^2$ and portions of an angular distribution at 20.6 MeV, where the $l=16$ partial wave was expected to contribute, could not be fitted with a $|P_{16}|^2$ or any other single partial wave. These results suggest that the elastic scattering at the resonance energies of 19.0 and 21.8 MeV is dominated by the behavior of a single partial wave and (since the target and projectile both have 0^+ ground states) that the spins and parities of these resonances may be assigned as 15^- and 17^-, respectively. Angular distributions around 16.6 MeV have not been measured at this time. Although the resonances observed in the present work have odd spin, they occur at energies consistent with the even-parity resonances found in the $^{12}C+^{12}C$ and $^{12}C+^{16}O$ systems.

A notable feature of the excitation functions is that the cross section at those angles where the odd partial waves exhibit maxima (85°, 95°, and 105°) is 3–5 times larger than at those angles where the even partial waves are enhanced (80°, 90°, and 100°). It appears, therefore, that the elastic scattering of the $^{18}O+^{12}C$ system is dominated by odd partial waves, a behavior unlike any other heavy-ion system studied to date.

To see whether these resonances persisted in any reaction channels, we have measured $^{12}C(^{18}O,\alpha)^{26}Mg$ excitation functions at 153° and 169° (c.m.). Reactions leading to twelve states in ^{26}Mg could be identified and all exhibited fluctuating cross sections. Figure 1(b) shows those states exhibiting the most pronounced enhancement at 19.0 and 21.8 MeV. The deviation function for $\theta_{c.m.}=169°$ is shown in Fig. 2(b). Correlations appear at 16.6, 19.0, and 21.8 MeV. An angular distribution for the ground-state transition (not shown here) was measured at 19.0 MeV and found to be consistent with $|P_{15}|^2$ (as was the elastic scattering at this energy) for angles between 50° and 110°. In addition, excitation functions were measured for the $^{14}C + ^{16}O$ reaction channel at 67° and 70° (c.m.). The data, shown in Fig. 1(c), exhibit some evidence for correlated structure, particularly at 21.8 MeV.

The intermediate structure resonances observed at 16.6, 19.0, and 21.8 MeV may have origins similar to the 19.7-MeV resonance in the $^{12}C + ^{16}O$ system. From the individual excitation functions of the $\alpha + ^{26}Mg$ channel, no systematics could be determined as to whether any states had been selectively populated. The states which showed the most striking enhancement at 19.0 and 21.8 MeV were the unresolved triplets shown in Fig. 1(b). The enhancements were evident at both angles measured. We are pursuing the measurement of additional reaction channels to determine which other channels display resonant behavior. It would appear that the suggested condition that the entrance channel must consist of α-particle nuclei, and the concomitant assumption that these resonances are due to α-particle doorway states,[7] is not necessarily the case at energies well in excess of the Coulomb barrier. In addition, the requirement that the compound-nuclear level density needs to be low for the observation of intermediate-structure resonances[7] does not hold in case of the $^{18}O + ^{12}C$ system.

The relative absence of even partial waves in the elastic scattering of ^{18}O from ^{12}C may find an explanation as an entrance-channel effect[8,9] in which the behavior of the direct reaction channels has a strong influence on the elastic-scattering cross section. The scattering amplitude for the $^{14}C + ^{16}O$ exit channel, a final state which is coherently fed by *both* $2n$ and α transfer, must be written as a sum of amplitudes which, when expanded in Legendre polynomials, appears as

$$f(\theta) = \sum_l [f_l^{2n}(\theta) + (-)^l f_l^{\alpha}(\theta)].$$

If the phases of f_l^{2n} and f_l^{α} are similar and if the magnitudes of the two scattering amplitudes are comparable, the $(-)^l$ factor leads to an l staggering of the total scattering amplitude which can produce a significant enhancement of the contribution of the even over the odd partial waves for this reaction channel. There is some evidence that the amplitudes are comparable and that the phases are the same, at least for the even partial waves, from the work of Schneider *et al.*[10] who found that the angular distributions for the reaction $^{18}O + ^{12}C \rightarrow ^{14}C + ^{16}O$ measured at four energies all exhibit a maximum at 90°. The observed maxima and minima of our $^{14}C + ^{16}O$ exit-channel excitation functions are consistent with dominant contributions from $l = 16$ at 19.0 MeV and $l = 18$ or 20 at 21.8 MeV. Thus, the even partial waves may be selectively absorbed into the $^{14}C + ^{16}O$ exit channel (which, from singles energy measurements, exhibits a qualitatively greater cross section than any other reaction in this system) resulting in the elastic scattering exhibiting a dominant contribution from odd partial waves. This selective inhibition is unique among all systems studied to date.

Another factor in the odd-even effect may be the spin dependence of the compound-nuclear level density. We have observed that the resonances occur at excitation energies rather close to the yrast levels of the compound nucleus, ^{30}Si. If the odd-spin yrast levels were displaced up in energy relative to the even-spin levels, as is observed for low-J yrast levels, there may be only a few odd-spin compound levels available whereas the level density of even-spin states would be larger. The odd-spin strength could, therefore, be more concentrated in energy than the even-spin strength resulting in the observation of structure dominated by odd partial waves only. We note, however, that this effect is not observed in the $^{12}C + ^{16}O$ system.

In summary, we have observed correlated intermediate-structure resonances in the elastic and α-decay channels of the $^{12}C + ^{18}O$ system. The observation of such structure in a system involving neither α-particle nuclei nor a low level density in the compound nucleus is contrary to previous suggestions. Two of the resonances are found to have odd spin ($l = 15$ and 17) with no evidence for an $l = 16$ resonance. Possible explanations of this surprising odd-even effect have been suggested, but further work is required to confirm their validity.

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Differential Cross Sections for Electron Capture from Argon by 6-MeV Protons*

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Differential cross sections for the capture of electrons from argon by 6-MeV protons have been measured as a function of the hydrogen-atom scattering angle between 0.02° and 0.14°. Cross sections were measured for capture from all shells and from the argon K shell alone. The differential cross section for K-shell capture does not agree with theoretical results obtained using either the Oppenheimer-Brinkman-Kramers approximation or a Born calculation which includes a contribution from the core-core interaction.

The capture of bound target electrons by fast point projectiles has been the subject of much theoretical study[1] but continues to stimulate considerable controversy. Whereas the Born approximation has been useful in describing ionization[2] and excitation[3] processes when the projectile velocity (v) is comparable to or exceeds that of the active target electron, it has not been totally successful in dealing with electron capture. For the former processes the potential between positive-charge centers does not contribute to the first Born amplitude, whereas in the case of electron capture this so-called core-core interaction may contribute importantly. Inclusion of this interaction is necessary to obtain detailed agreement between the Born theory and experiment for total electron capture by protons from hydrogen and helium.[4,5] However, if the nuclear charge of either projectile (Z_1) or target (Z_2) is large, the core term becomes the major contributor to the cross section and yields theoretical values far above experiment.[6] Indeed, for higher Z, the first Born cross sections calculated omitting the core term altogether [the Oppenheimer[7]-Brinkman-Kramers[8] (OBK) approximation] come closer to the experimental values.

Assessment of the success of the theory has been hampered by lack of data for capture from a specific target shell, and a lack of experimental differential electron-capture cross sections, $(d\sigma/d\Omega)_c$, as a function of the projectile scattering angle, θ. For example, Born calculations of $(d\sigma/d\Omega)_c$ are highly sensitive to the presence of the core term. Such experimental information is of special interest for higher-Z targets or projectiles since such cases emphasize effects of including this term in the calculation. In this paper we present results of experimental measurements of the differential cross section at small angles for the capture of argon K-shell electrons, $(d\sigma/d\Omega)_{cK}$, by protons at 6 MeV. At this energy the proton velocity is comparable to that of the target K-shell electron, and the K-capture cross section is near a maximum. Our results are in substantial disagreement with the calculations. In the experimental data there is no evidence for a zero in the differential cross section predicted by a Born calculation which includes the core term.[9] At somewhat larger angles the measured cross section decreases more slowly with angle than does the OBK calculation but follows the trend of the Born calculation.

The absence of experimental data on differential electron-capture cross sections is due largely to the extremely forward-peaked character of the angular distribution. For 6-MeV protons,