Molecular Resonances and the Production of Fast α Particles in the Reaction of ^{16}O with ^{12,13}C Nuclei

W. D. Rae, R. G. Stokstad, B. G. Harvey, A. Dacal,(a) R. Legrain,(b)
J. Mahoney, M. J. Murphy, and T. J. M. Symons
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

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A search was made for a resonant, final-state interaction between carbon ions produced in the reactions $^{12}C+{}^{16}O\rightarrow\alpha+{}^{12}C+{}^{12}C$ and $^{13}C+{}^{16}O\rightarrow\alpha+{}^{12}C+{}^{13}C$ at $E_{lab}=140$ MeV. However, the α-^{12}C coincidence spectra for both ^{12}C and ^{13}C targets were instead found to be dominated by the excitation and subsequent α decay of states in the projectile.

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Recently Nagatani *et al.*[1] presented experimental results which suggest the direct population of molecular resonance states by ^{12}C transfer in the reaction ^{12}C(^{16}O, α) at $E_{lab}(^{16}O)=145$ MeV. This has aroused considerable excitement as the ^{12}C-^{12}C system has been of interest for over two decades and the ability to study it via a direct-transfer reaction would provide a powerful new experimental tool. A large variety of other molecular systems presumably could also be studied via such massive transfer reactions.

The inclusive spectra presented by Nagatani *et al.*[1] show structure in the yield of fast α particles on top of a large underlying continuum. After subtraction of a smooth background, broad peaks are observed whose corresponding excitation energies in ^{24}Mg correlate with structures observed in $^{12}C+{}^{12}C$ elastic and inelastic scattering and fusion.[1] In contrast, these structures are not observed in the singles α spectra obtained by bombarding ^{13}C with 145-MeV ^{16}O. Since molecular resonance structure is not as prominent in $^{12}C+{}^{13}C$ reactions, it has been suggested[1] that this contrast demonstrates that the reaction ^{12}C(^{16}O, α) selectively populates residual states of ^{24}Mg.

The higher-energy resonances observed in the $^{12}C+{}^{12}C$ system are estimated to have large partial widths for decay into the ^{13}C(g.s.) + ^{12}C(g.s.) and ^{12}C(g.s.) + ^{12}C(2^+) channels,[2] and so for the $^{16}O+{}^{12}C$ system an experiment in which carbon ions are detected in coincidence with α particles could be expected to include events from the decay of a resonant $^{12}C+{}^{12}C$ final state. Such a measurement would reduce the background from other processes and allow the molecular states to be observed more clearly. To this end the following experiments were performed:

A beam of 140-MeV $^{16}O^{4+}$ from the Lawrence Berkeley Laboratory 88-in. cyclotron was used to bombard a 620-μg/cm^2 natural carbon target and a ^{13}C target of 285 μg/cm^2 thickness enriched to 99% in ^{13}C. α particles were detected in a telescope consisting of a 240-μm Si ΔE detector and a 5-mm Si(Li) E detector. A tantalum absorber foil (90 mg cm^2) was placed in front of this telescope to stop heavy ions with $Z\geqslant 3$. ^{12}C and ^{13}C ions were detected in either a second ΔE-E telescope (32.5-μm Si ΔE detector and a 400-μm Si E detector) or in the quadrupole-sextupole-dipole magnetic spectrometer. Solid angles were limited to 0.36–1.44 msr to ensure adequate resolution in the coincidence spectra.

Since we are studying a three-body final state, there are in general three possible pairs of two-body residual interactions which must be distinguished. Consider the coincident detection of α particles and ^{12}C ions produced in the reaction ^{13}C(^{16}O, ^{12}Cα)^{13}C. Examples of reaction mechanisms which can produce each of the three final-state interactions are (a) α transfer leading to unbound states in $^{17}O^*$ (the α-^{13}C residual interaction), (b) ^{12}C transfer leading to unbound states in ^{25}Mg (the ^{12}C-^{13}C interaction), and (c) excitation of the ^{16}O projectile to unbound states (the α-^{12}C interaction). The final-state interaction which is responsible for any structure in the coincidence spectra may be determined by measuring coincidences at various pairs of angles. For case (a) variation of the α-detection angle should leave the energies of the peaks in the ^{12}C energy spectrum unchanged. For case (b) variation of the ^{12}C-detection angle should not affect the energies of peaks in the α energy spectrum. In case (c) for a given excitation energy in $^{16}O^*$, the relative kinetic energy of the α particle and the ^{12}C ion should be independent of the angles of observation; specifically, the excitation energy in $^{16}O^*$ given by

$$E_x(^{16}O^*)=\tfrac{3}{2}\left[\tfrac{1}{2}E_\alpha+\tfrac{1}{6}E_C-2(E_\alpha E_C/12)^{1/2}\cos(\theta_\alpha-\theta_C)\right]+7.16\text{ MeV} \qquad (1)$$

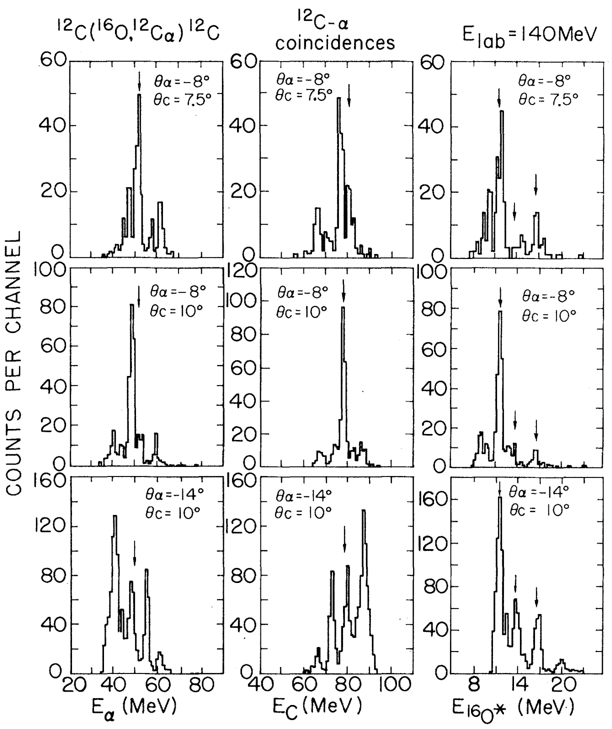

FIG. 1. Coincident counts vs E_α, $E_{\rm C}$, and $E_{^{16}\rm O^*}$ are shown in columns 1–3. Each row shows a different pair of detector angles. For E_α the arrows show the expected position of the strongest peak in the top spectrum, assuming this peak corresponds to a state in ^{24}Mg. For $E_{\rm C}$, the arrows show the expected position of the strongest peak in the middle spectrum, assuming the peak corresponds to a state in ^{16}O populated by α transfer. For $E_{^{16}\rm O^*}$ the arrows indicate states in ^{16}O at 11.6, 13.1, and 15.8 MeV.

should be independent of θ_α and $\theta_{\rm C}$. The above results depend only on kinematics and are, of course, independent of the reaction mechanism leading to the final state.

Data were taken at 22 angle pairs covering 7.5° to 30° in the laboratory for the ^{12}C telescope and −4° to −18° for the α telescope. Figure 1 shows typical spectra obtained with the two telescopes and the ^{12}C target. Only events in which all three particles emerged in their ground states ($Q = -7.16$ MeV) are shown. (The total reaction Q is easily calculated from E_α and $E_{\rm C}$.) Analysis of all the data showed that the dominant peaks are not constant in E_α or $E_{\rm C}$ as a function of either θ_α or $\theta_{\rm C}$. Also shown in Fig. 1 are ^{16}O* excitation spectra calculated with Eq. (1). The energies of the peaks in these spectra are found to be independent of both θ_α and $\theta_{\rm C}$, and the relative angle $\theta_\alpha - \theta_{\rm C}$. An analysis of the E_α spectra for those events in which one ^{12}C emerged in its first excited state resulted in identical conclusions. On the basis of these results we conclude that the coincidence data are dominated by the resonant breakup of the projectile—that is, by inelastic excitation of discrete α-unbound states of ^{16}O followed by their decay.[3] We also observed that the cross section to any particular state in ^{16}O* oscillates as a function of θ_α and $\theta_{\rm C}$. This reflects the diffractive nature of the ^{16}O* angular distribution.

For a comparison of reactions with ^{12}C and ^{13}C targets we used the magnetic spectrometer to detect the carbon ions. This had the advantage over the ΔE-E telescope of improved separation of ^{12}C and ^{13}C ions and reduced count rates at very forward angles. Because the energy bite in the spectrometer is only 24%, two field settings were generally required. The spectra at each field setting were matched after normalization by the integrated charge on the Faraday cup. Data were taken with the spectrometer as far forward as 3° in the laboratory; some measurements were also made with the α telescope on the same side of the beam as the spectrometer.

Figure 2 compares typical spectra obtained with the ^{12}C and ^{13}C targets. Note that the Q-value spectra for α-^{12}C coincidences and the energy spectra of the α particles show qualitatively similar structures. Analysis of data taken at different angles showed that the coincident yield of $\alpha + {}^{12}$C is dominated by the excitation and subsequent decay of discrete states of ^{16}O* regardless of whether the target is ^{12}C or ^{13}C.

There are several quantitative differences between the results obtained with the two targets. One prominent difference is in the coincident yield of $\alpha + {}^{13}$C observed with the ^{13}C target. This is seen in Figs. 2(c) and 2(d) where Q spectra are shown. Although our data are not conclusive in this respect we suspect that the reaction producing $\alpha + {}^{13}$C proceeds via single neutron pickup to α-decaying excited states of ^{17}O. The difference between the results for the ^{13}C target and ^{12}C target is then naturally explained by the respective Q values for neutron pickup by the projectile (−0.80 and −14.58 MeV).

A second quantitative difference is observed in the relative cross sections for the production of fast α particles in coincidence with carbon ions. The cross sections for the prominent peaks in Figs. 2(g) and 2(h) are larger for the ^{12}C target by factors of 1.4 to 1.7; however, these ratios vary with angle. The origin of this behavior is not clear at this time.

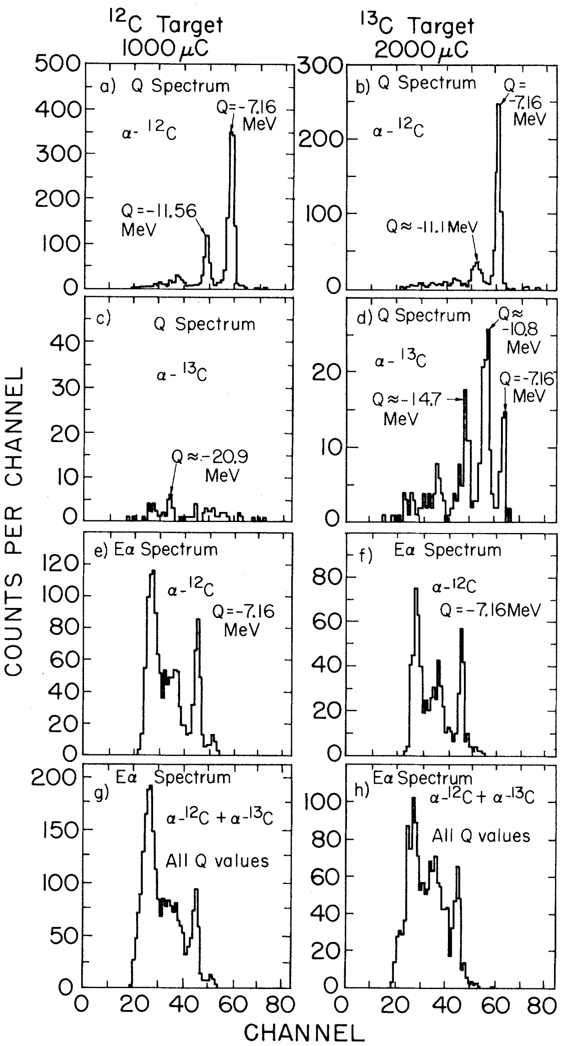

FIG. 2. A comparison of the coincidence data obtained in ^{16}O induced reactions on ^{12}C and ^{13}C at $\theta_\alpha = -14.5°$ and $\theta_C = 10°$. (a), (b) Total Q spectra for α-^{12}C events; (c), (d) Q spectra for α-^{13}C events. Channels greater than 40 in spectrum (c) contain mainly random events. (e), (f) α-^{12}C events vs E_α with $Q = -7.16$ MeV. (g), (h) All α-^{12}C and α-^{13}C events vs E_α for all Q values.

The inclusive α spectra of Ref. 1 suggest the population of highly excited states in ^{24}Mg and this has been interpreted in terms of resonances in the ^{12}C + ^{12}C system.[1] The present coincidence experiments do not reveal a ^{12}C + ^{12}C final-state interaction. There are at least three possible explanations for this.

(i) The structure seen in the α-singles experiments[1] arises from the sequential decay of ^{16}O*. The states in ^{16}O* for which we observe a decay to ^{12}C(g.s.) + α (which is the most intense mode of decay) are estimated to be at excitation energies of 10.4, 11.6, 13.1, 15.8, and 19.4 MeV (all ±0.4 MeV). If we assume that the inelastic scattering of ^{16}O is strongly forward peaked and take 0° as an average direction for ^{16}O*, we calculate α-particle energies at $\theta_{\rm lab} = 7°$ of 51.0, 54.9, 59.0, 65.2, and 72.1 MeV (all ±0.9 MeV) for a beam energy of 145 MeV. Several of these energies correlate with the energies of the structures observed in the singles data of Ref. 1. [A quantitative estimate of the intensity of these peaks in a singles spectrum would require more extensive angular correlations (for example, out of plane measurements) than were possible in the present study.] If this explanation is correct, then the absence of structure in the α-singles spectrum[1] obtained with a ^{13}C target must originate in differences in the cross section for producing ^{16}O*. The higher relative yield of $^{16}\text{O}^* \rightarrow {}^{12}\text{C} + \alpha$ observed with the ^{12}C target would be qualitatively consistent with this.

(ii) The excitation and sequential decay of ^{16}O* contributes to the smooth background under the structure in the α-singles spectra produced on both the ^{12}C and ^{13}C targets and thereby obscures any events in the coincidence data arising from molecular resonances. This explanation while also consistent with the present results, has the unfortunate consequence that verification of the reaction mechanism leading to the population of the molecular resonances with use of coincidence techniques, as well as more detailed spectroscopic studies, will be very difficult.

(iii) The levels in ^{24}Mg populated by a twelve-nucleon–transfer reaction on a ^{12}C target, contrary to the present assumption, have small partial widths for decay to a ^{12}C + ^{12}C final state and thus do not contribute to the coincidence yield.

In conclusion, the present coincidence measurements do not reveal a ^{12}C + ^{12}C final-state interaction. They do show that the excitation of the projectile to discrete excited states above the α-decay threshold is an important contribution to the yield of fast α particles produced in the reactions ^{12}C, ^{13}C(^{16}O, α).

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[a] Permanent address: Universidad Nacional Autónoma de Instituto de Física, México 20, D. F., Mexico.

[b] Permanent address: Département de Physique Nucléaire/Basses Energies, Centre d'Etudes Nuclé-

aires de Saclay, F-91190 Gif-sur-Yvette, France.

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Field-Induced Autoionization in Rare-Gas Absorption Spectra near the Ionization Threshold

B. E. Cole, J. W. Cooper, and E. B. Saloman
National Bureau of Standards, Washington, D. C. 20234

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The effect of electric fields of up to 22 kV/cm on the absorption cross sections of argon and krypton have been obtained near the ionization limit. In both gases the field-induced cross section below the limit is found to represent the predicted oscillator-strength distribution. In krypton, additional field-induced fine structure appears below the limit.

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Luc-Koenig and Bachelier have recently stressed the importance of the concept of oscillator-strength density in interpreting the Stark spectrum of atomic hydrogen near the ionization limit.[1] Since all spectral lines near the ionization limit lose their identity when an electric field is applied, it is appropriate to consider observed resonances as variations in oscillator-strength density rather than as contributions due to specific lines. Using this approach they were able to calculate the spacings of the resonant structure observed in the vicinity of the ionization limit of rubidium by Freeman *et al.*[2]

For atomic systems other than the hydrogen and alkalis, where the average oscillator strengths near this limit is frequency independent, the situation is much more complicated. Although the zero-field spectral distribution of oscillator strengths is expected to be continuous near the ionization limit,[3] it may oscillate over a broad spectral range both below and above the limit. Such behavior is typical of all of the heavier rare gases where the $^2P_{3/2}$ and $^2P_{1/2}$ ionization limits are closely spaced. Variations in oscillator-strength density are observable above the limit, where they appear as autoionization lines in absorption[4] and the same distribution of oscillator-strength density is predicted to extend below the ionization limit,[5,6] where only a small fraction of the oscillator-strength density is observable as the intensity of spectral lines.

When electric fields are applied, one would expect changes in the observed oscillator-strength distribution near the limit since the field will lower the ionization potential and thus open up new channels for autoionization in the spectral region below the limit. We find this to be true for argon, krypton, and xenon. Our major results are the following:

(a) For moderate fields (<5 kV/cm) the oscillator strength below the $^2P_{3/2}$ limit represents the continuation of the same pattern as is observed in the autoionizing region between the $^2P_{3/2}$ and $^2P_{1/2}$ limits.

(b) The oscillator-strength distribution immediately above the $^2P_{3/2}$ limit is only slightly modified except at high-field strengths (~20 kV/cm).

(c) At high-field strengths fine structure appears near the ionization limit. The spacing of the structure is irregular, field dependent, and does not appear to depend upon the polarization of the absorbed light.

The apparatus used for these measurements is essentially the same as that used for previous studies of field effects on autoionizing resonances.[7] It consists of an absorption cell of approximately one meter pathlength containing field plates spaced $\frac{1}{8}$ in. (0.3175 cm) apart. This was mounted in back of a high-flux monochromator[8] attached to the SURF-II electron storage ring. Since the beam emerging from the monochromator is approximately 80% polarized,[8] data were obtained with the field both parallel and perpendicular to the preferred direction of polarization. Gas pressures in the cell were typically 5–10 mTorr (0.07–0.13 Pa). Transmitted light was detected via a photomultiplier mounted in front of a sodium salicylate coated window at the exit of the absorp-