Resonances in ^{12}C + ^{13}C†

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Resonant structures at 9.4 and 10.3 MeV c.m. energy have been observed in both the reaction $^{12}C(^{13}C,\alpha)^{21}Ne$ and the elastic scattering of ^{13}C from ^{12}C. Unambiguous assignments of $l=7$ for both of the resonances are made.

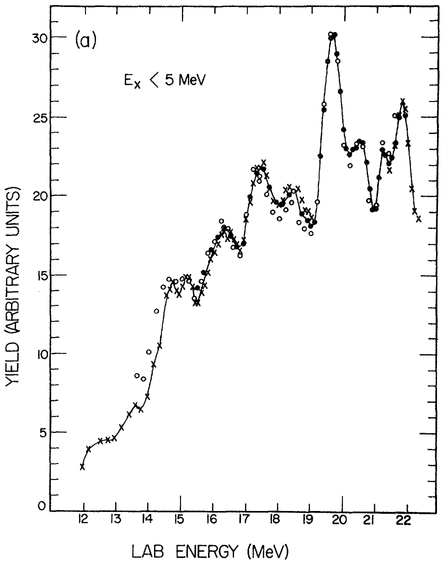
Considerable effort has been devoted to the search for resonances in heavy-ion systems. Previously, such resonances had been found in the systems $^{12}C+^{12}C$ ^{1,2} and $^{12}C+^{16}O$ ^{3,4,5} but had been considered nonexistent in $^{12}C+^{13}C$.^{6,7} In the present paper, we report the observation of resonances in the system $^{12}C+^{13}C$.

To reexamine the system $^{12}C+^{13}C$, we measured the excitation function of the reaction $^{12}C(^{13}C, \alpha)^{21}Ne$ at a lab angle of 10° over a range of lab bombarding energies, $E(^{13}C)=12$ to 22.5 MeV, in 100-keV steps. Elastic scattering was measured at eight lab angles over the same energy range. As a result two definite resonances were observed to be correlated in the two exit channels.

The excitation function for the reaction $^{12}C(^{13}C, \alpha)^{21}Ne$ at a lab angle of 10° is shown in Fig. 1(a); the yield has been summed over the lowest thirteen levels in ^{21}Ne. Statistical fluctuations in summed excitation functions are expected to be damped by a factor which is greater than or equal to the number of levels (13).^{8,9} From examination of Fig. 1(a) it can be seen that variations in the yield considerably in excess of those allowed by the statistical model do occur. Most of the energy range has been measured at least twice with good reproducibility. Prominent structures in the summed α yield are observed near the lab energies $E_{\rm lab}=15$, 16.2, 17.3, 19.5, and 21.5 MeV ($E_{\rm c.m.}=7.2$, 7.8, 8.3, 9.4, and 10.3 MeV, respectively). Less prominent structures are observed near $E_{\rm lab}=20.3$ ($E_{\rm c.m.}=9.7$ MeV).

In order to investigate whether the observed structure in the $^{12}C(^{13}C, \alpha)^{21}Ne$ excitation curves might be due to resonances, we examined a different exit channel, the elastic scattering. The elastic scattering excitation functions for three c.m. angles—73.4, 89.6, and 100.5°—are shown in Fig. 1(b). Resonances at $E_{\rm lab}=19.5$ and 21.5 MeV can be plainly seen.

In order to determine the l values of these resonances, the background elastic scattering was fitted by using the elastic-transfer theory of von



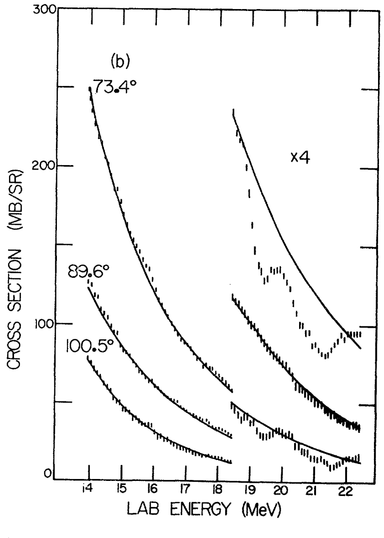


FIG. 1. (a) Excitation function for the reaction $^{12}C(^{13}C,\alpha)^{21}Ne$ at $\theta_{\rm lab}=10°$. Different symbols represent data taken on different days with different targets. The solid curve is intended to "guide the eye" only. (b) Excitation functions for the elastic scattering of ^{13}C from ^{12}C at three c.m. angles. The solid curves are optical-model calculations of the background cross section as described in the text. No resonances were considered in these calculations.

Oertzen.[10] A Woods-Saxon optical-model well with parameters considerably different from those of von Oertzen was used—$V=100$ MeV, $W=15+1.2(E-18)$ MeV, $a=a_i=0.46$ fm, $R_0=R_c=R_i=1.19$ fm. The calculation employed volume absorption and an exchange potential of the form

$$V_{\text{exchange}}=(-1)^l V_e e^{-\alpha r}/\alpha r, \qquad (1)$$

with $\alpha=0.469$ and $V_e=35$ MeV. The calculations were performed by using the program OPTICS[11] which has been modified to include the exchange term. Excellent fits to the nonresonant angular distributions were obtained with the use of these parameters. The smooth curves in Fig. 1(b) are the elastic-scattering predictions with no resonances included. The value of the exchange potential obtained here corresponds to a value for *SN* in von Oertzen's notation[10] of 0.85 which is in reasonable agreement with the values of 0.8 and 0.95 obtained by Bohlen and von Oertzen.[12]

Optical-model parameters differing from those of von Oertzen were chosen for two reasons. First, the angular distributions calculated by Bohlen and von Oertzen[12] at $E_{\text{c.m.}}=9.9$ MeV show an extremely deep minimum at a scattering angle of 110° which does not fit the data well. Second, it was considered desirable to use an optical model with slowly varying parameters and a constant value of *SN*. Calculations using the parameters given above fit the data very well at all measured angles and energies with a smooth, slow variation of the imaginary well depth.

Fits assuming $l=7$ resonances at 19.5 and 21.5 MeV are shown in Fig. 2(a) for five c.m. angles over the energy range 18.4 to 22.5 MeV. Shown for comparison in Fig. 2 are calculations using the same total and partial widths but assuming the following resonances: Fig. 2(b), $l=5$ and $l=9$; Fig. 2(c), $l=3$ and $l=11$; and Fig. 2(d), $l=1$ and $l=13$. It is clear in Fig. 2 that each of these choices of l value produces a very poor fit to the data at a minimum of two angles. No even-l resonance will result in a smooth curve at 89.6°. Resonances with l values higher than those shown in Fig. 2 may be ruled out because of low penetrability. Thus, these resonances may be assigned as $l=7$. A single-level formulation was used to perform the calculations. A resonance mixing phase[13] of 0° was assumed in calculating the fits in Fig. 2. It was found that no l value other than $l=7$ would fit the data at all five angles regardless of the mixing phase assumed. Furthermore, it was found that for $l=7$ only mixing phases less than 30° gave equally good fits.

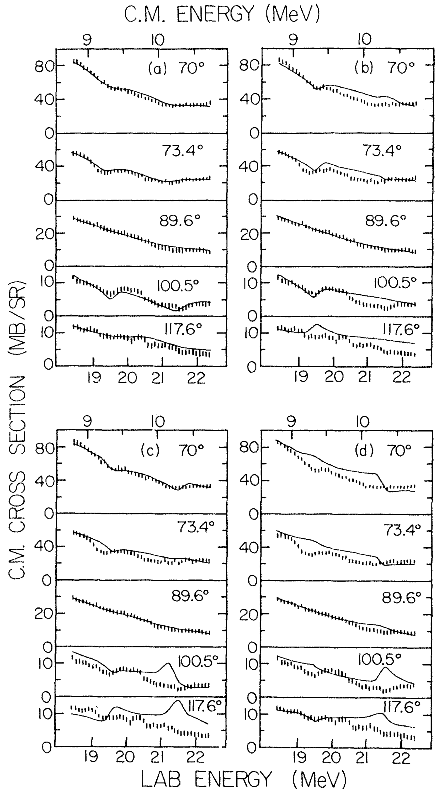


FIG. 2. Fits to the elastic scattering cross section in the energy range from 18.5 to 22.4 MeV for five c.m. angles. Two resonances, one at $E_{\text{c.m.}}=9.36$ MeV with $\Gamma=200$ keV and $\Gamma_{\text{el}}=45$ keV and one at $E_{\text{c.m.}}=10.32$ MeV with $\Gamma=200$ keV and $\Gamma_{\text{el}}=50$ keV, are included in each calculation. (a) Both resonances are assumed to be $l=7$. (b) The two resonances are assumed to be $l=5$ and $l=9$. (c) The two resonances are assumed to be $l=3$ and $l=11$. (d) The two resonances are assumed to be $l=1$ and $l=13$.

The c.m. resonance parameters obtained from the fits for the first resonance are $E_R=9.36$ MeV, $\Gamma=200$ keV, $\Gamma_{\text{el}}=45$ keV; and for the second resonance they are $E_R=10.32$ MeV, $\Gamma=200$ keV, $\Gamma_{\text{el}}=50$ keV. The total estimated uncertainty in the widths is 25%. Reduced widths for these resonances were calculated by using Coulomb-wave-function penetrabilities. At a matching radius of 7 fm the reduced widths are calculated to be 28 keV for the 9.36-MeV resonance and 19 keV for the 10.32-MeV resonance. These reduced widths are 14 and 9% of the Wigner limit, $3\hbar^2/2\mu R^2$. These results are similar to those obtained for the resonances observed in the system $^{12}\text{C}+^{12}\text{C}$.[1]

The use of Coulomb-wave-function penetrabilities in a situation where the nuclear potential is obviously playing an important role is open to question. Schiffer[14] has suggested an alternative method of comparing a resonance width to that of a single-particle resonance. The width of a potential resonance calculated by using the optical model with the absorption set to zero is used as the single-particle width. Calculations with the optical model used here with $W=0$ reveal an $l=7$ resonance at $E_{\text{c.m.}}=9.8$ MeV with $\Gamma=2.9$ MeV. If this is used as the single-particle width, then the observed resonances have elastic partial widths that are approximately 2% of the single-particle width.

These calculations shed some light on the nature of these resonances. They indicate that the observed resonances occur at an energy where the $l=7$ partial wave is resonating. This suggests that these resonances may be explained by a double-resonance effect similar to that[15] used by fitting the structure observed in $^{16}\text{O}+^{16}\text{O}$ scattering.

At present, experiments are being done to investigate reactions at various angles and to extend the excitation functions to higher energies.

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Three-Body Breakup Reaction $^{40}\text{Ca}(^{16}\text{O}, {}^{12}\text{C}\alpha)$

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We report for the first time coincident ^{12}C and α particles emitted in the bombardment of ^{40}Ca with ^{16}O ions of 64 MeV. Events which populate the ground and first excited states of ^{12}C and ^{40}Ca are observed. The coincident ^{12}C energy spectra are dominated by one or two large peaks near the highest allowable ^{12}C energy. Relatively few coincidences are seen at ^{12}C energies which correspond to maximum yield in the $^{40}\text{Ca}(^{16}\text{O}, {}^{12}\text{C})$ singles spectrum.

The $(^{16}\text{O}, {}^{12}\text{C})$ transfer reaction has been of interest for the last few years. In several of these reaction studies with targets in the nuclear *f-p* shell,[1] the ^{12}C energy spectra displayed individual sharp peaks superimposed on a broad, continuous background "bump." This continuum makes its appearance in the spectrum near the threshold for ^{16}O breakup into $^{12}\text{C}+\alpha$. The background, which increases in intensity as the bombarding energy is increased above the Coulomb barrier, has been attributed to the presence of three-body final states.[2] At energies well above the Coulomb