Resonance at $E_{c.m.} = 12.8$ MeV in the $^{12}C + ^{16}O$ system*

P. Taras, G. Rao, N. Schulz,† J. P. Vivien,† B. Haas,† J. C. Merdinger,† and S. Landsberger
Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Canada
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An intermediate-type resonance of width $\Gamma_{c.m.} = 130 \pm 25$ keV has been observed in the excitation functions of the n, p, d, and α-particle exit channels at $E_{c.m.} = 12.77$ MeV in the $^{12}C + ^{16}O$ reaction. The energy of the resonance as well as its probable spin $J = 8\hbar$ are in good agreement with the predictions obtained from the semiclassical expression for the grazing orbit.

[NUCLEAR REACTIONS $^{12}C(^{16}O,n)$, $E_{c.m.} = 10.7-15.9$ MeV; measured $\sigma(n)$; $^{12}C(^{16}O,p)$, $^{12}C(^{16}O,d)$, $^{12}C(^{16}O,\alpha)$, $^{12}C(^{16}O,^{16}O)$, $E_{c.m.} = 12.43-13.93$ MeV; measured $\sigma(p)$, $\sigma(d)$, $\sigma(\alpha)$, $\sigma(^{16}O)$.]

Several anomalies have been observed[1] at energies above the Coulomb barrier in the excitation functions for systems such as $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$, and exotic interpretations for these phenomena have been proposed.[2] However, until a systematic behavior emerges these interpretations must be considered speculative. In the hope of shedding some light on these phenomena, we have been studying the $^{12}C + ^{16}O$ system. In this paper we report on an intermediate-type resonance found at $E_{c.m.} = 12.77$ MeV. This resonance fits rather nicely the grazing orbit picture.

Targets of natural C, 50 $\mu g/cm^2$ thick and deposited on a Ta backing for the n excitation function measurements and 10 $\mu g/cm^2$ self-supporting foils for the charged particle work, were bombarded by beams of ^{16}O ions from the Université de Montréal EN tandem accelerator. The target thickness was carefully monitored during the experiments and contributed to an average beam energy loss of 200 and 45 keV, respectively, in the laboratory system.

Neutron time-of-flight spectra were measured using two 5.1 cm×17.8 cm diam NE213 detectors and a flight path of 1.5 m, at bombarding energies (E_{lab}) between 25.0 and 37.0 MeV, in steps of 500 keV. The time spectrum was generated by start and stop pulses from the counters placed at 8.5 and 150 cm from the target, respectively at 90° and 0° to the beam axis. A resonance ($\Gamma \simeq 200$ keV c.m.) as revealed by a narrow intense peak in these spectra (Fig. 1) was found at $E_{c.m.} = 12.8$ and 13.7 MeV. Such narrow peaks were not observed in neutron time-of-flight spectra obtained as part of a neutron evaporation energy study following ^{16}O induced reactions on ^7Li ($E_{lab} = 30, 36$ MeV), ^{27}Al ($E_{lab} = 30, 42$ MeV), ^{34}S ($E_{lab} = 30, 32, 34, 36$ MeV), and ^{46}Ti ($E_{lab} = 36, 39, 42$ MeV). The resonance at 13.7 MeV has previously been observed in the α and ^{16}O exit channels.[3,4]

The excitation functions, shown in Fig. 2, for the p, d, α, and ^{16}O exit channels were measured from $E_{lab} = 29.0$ to 32.5 MeV in steps of 125 keV, with a surface barrier detector telescope placed at $\theta_{lab} = 30°$. The telescope subtended a half angle of 1° and consisted of a 166 μm thick ΔE counter and a 2000 μm thick E detector. The composite excitation functions for the α particles and the deuterons leading, respectively, to the levels up to 6.6 MeV in ^{24}Mg and up to 3.9 MeV in ^{26}Al, display a definite resonance at $E_{c.m.} = 12.77$ MeV, with a width $\Gamma_{c.m.} = 130 \pm 25$ keV. This width was obtained from the α-particle exit channel data where the resonance peak shapes were reasonably well defined. In particular, the excitation function of the α particles leading to the 3^+, 5236 keV state in ^{24}Mg displayed a fairly flat background outside the resonance energy, thus making it feasible to determine fairly precisely the full width at half-maximum of the resonance peak. The composite excitation function for the protons leading to the region of excitation from 9.2 to 11.0 MeV in ^{27}Al exhibits less structure than the other yield curves but nevertheless shows a rise at $E_{c.m.} = 12.77$ MeV. In addition, the excitation function for the ^{16}O elastic peak contains a resonance of the same width but slightly displaced in energy to $E_{c.m.} = 12.86$ MeV.

The definite correlation among the excitation functions for the various exit channels, and for particles leading to different final states in the residual nuclei, as well as the width of the resonance (corresponding to $\tau = 5.1 \times 10^{-21}$ s) imply that the $^{12}C + ^{16}O$ system at $E_{c.m.} = 12.77$ MeV has an intermediate-type structure.

Very recently, Viggars *et al.*[5] measured the excitation function of the ^{20}Ne particles from $E_{c.m.} = 10$ to 15 MeV, following the $^{12}C(^{16}O, ^{20}Ne)^8Be$

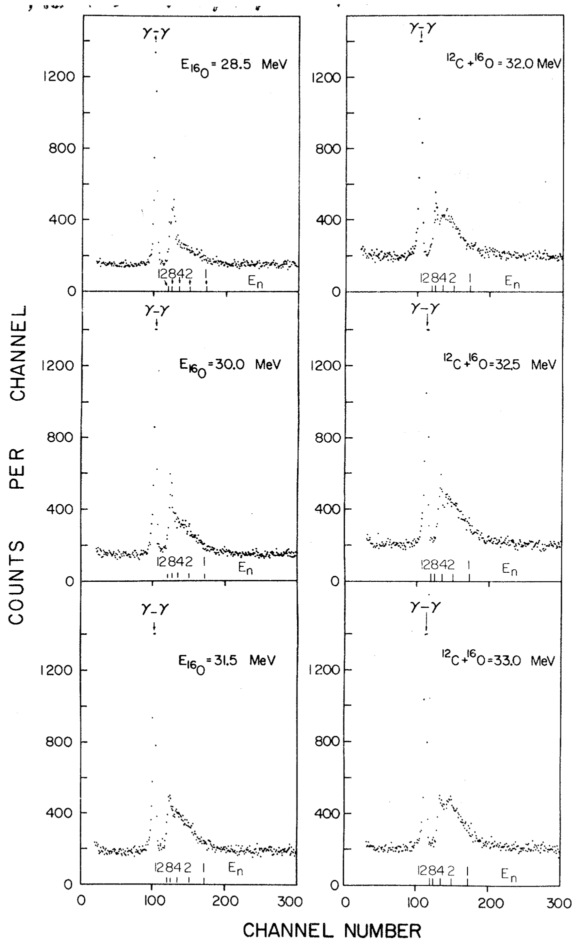

FIG. 1. Neutron time-of-flight spectra measured in the $^{12}C(^{16}O,n)^{27}Si$ reaction, and showing the resonances at $E_{lab}=30.0$ and 32.0 MeV. The flight path was 1.5 m.

reaction. They observed a deep minimum at $\theta_{lab}=12°$, at $E_{c.m.}=12.9$ MeV and 13.7 MeV. They attributed the anomaly at 12.9 MeV to an angular distribution effect since the minimum is not as pronounced at $\theta_{lab}=22°$ and the anomaly had not previously been reported in the other exit channels. However, the anomaly is definitely present in other channels as shown by the present work and thus cannot be accounted for simply as an angular distribution effect. Viggars *et al.* also fitted their ^{20}Ne angular distributions with orbital angular momentum values of $8\hbar$ and $9\hbar$ at 12.9 and 13.7 MeV, thus assigning a spin of 8 and 9, respectively, to the $^{12}C+^{16}O$ system at these two energies. The fact that apart from different l values these two angular distributions are not similar may arise from a different reaction mechanism and does not necessarily eliminate the possibility that both resonances have an intermediate-type structure which may, however, be different.

Finally, if as done by Branford *et al.*,[3] we display the center-of-mass energy of the known resonances in the $^{12}C+^{16}O$ system (9^- state at 13.7 MeV,[5,8] (10^+) state at 14.7 MeV,[3] (11^-) state at 16.0 MeV,[3] 14^+ state at 19.7 MeV,[4,6] and (16^+) state at 22.7 MeV,[7] as a function of $J(J+1)$ we obtain a very good straight line, as shown in Fig. 3. The present $J=8$ resonance at 12.77 MeV fits this

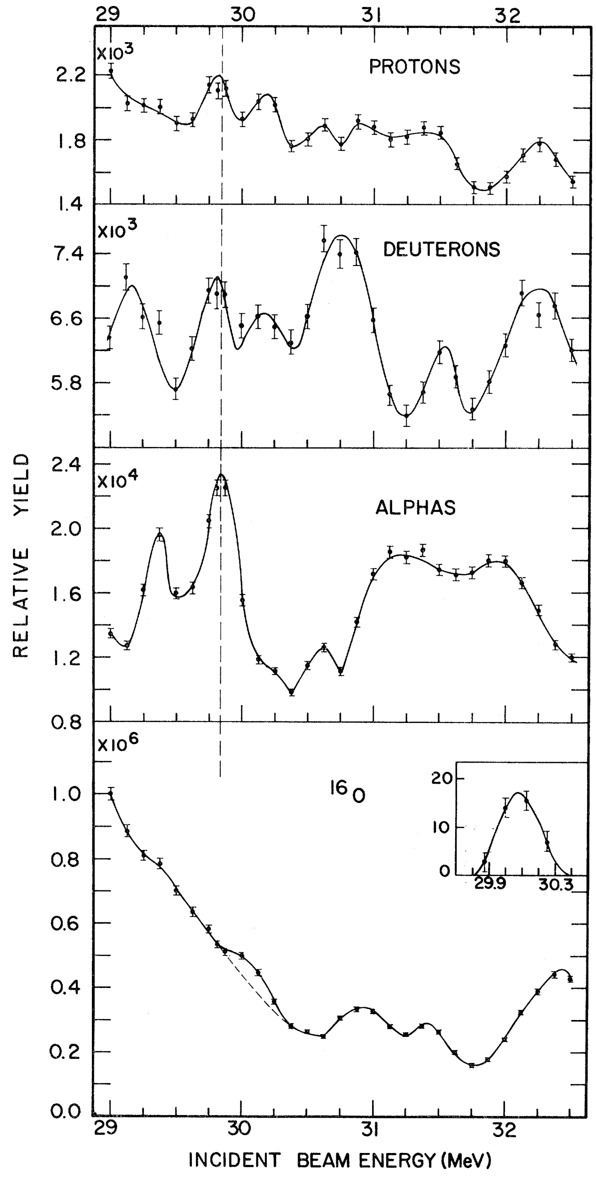

FIG. 2. Composite excitation functions for the protons, deuterons, and α particles leading to several states in, respectively, ^{27}Al, ^{26}Al, and ^{24}Mg (see text). Also shown is the excitation function for the ^{16}O elastic peak which exhibits a resonance of the same width as the other three exit channels, but slightly displaced in energy to $E_{c.m.}=12.86$ MeV. The insert was obtained by removing the continuous background indicated by dashed lines on the figure.

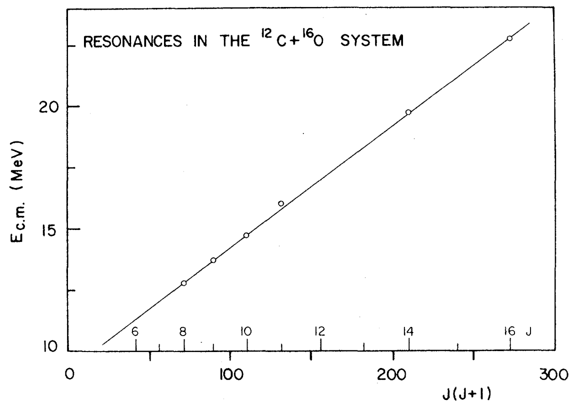

FIG. 3. Center-of-mass energy of the known resonances in the $^{12}C+^{16}O$ system traced as a function of $J(J+1)$. The most probable resonance spins were used. Note, however, the new possible spin-parity assignment of 14^+ for the 22.7 MeV resonance (Ref. 9).

scheme very well. The line corresponds to that obtained from the semiclassical expression for the energy of the grazing orbit where the radius parameter r_0 was found to have a value of 1.60 fm by fitting the expression to the energy and spin of the 14^+ anomaly.[2]

Thus the spin of the resonance at 12.77 MeV is consistent with the orbital angular momentum of the grazing partial wave, indicating that the collision occurs at the surface. In addition, the resonance appears to be more pronounced in the α-particle exit channel. These two facts taken together could suggest that at 12.77 MeV the reaction proceeds via an α particle exchange mechanism and that the resonance might be of the α-cluster type.

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†Permanent address: Centre de Recherches Nucléaires, Strasbourg, France.

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