Persistence of the $^{12}C + ^{16}O \rightarrow ^{28}Si$ Resonance in the Reaction $^{13}C(^{16}O, ^{17}O)^{12}C$†

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An anomaly has been seen in the reaction $^{16}O+^{13}C \rightarrow ^{17}O+^{12}C$ at a center-of-mass energy of 18.7 MeV. The energy, width, and angular distribution suggest that it is related to a $J^{\pi}=14^{+}$ resonance that has been reported in the $^{16}O+^{12}C$ system. The width and cross section imply a value near the single-particle limit. Possible models for such a resonance are mentioned.

A resonance in the $^{16}O+^{12}C$ system was recently found at a center-of-mass energy $E_{c.m.}=19.7$ MeV,[1,2] and its properties have been the subject of continuing investigations.[3] It has been studied extensively not only in elastic scattering, for which careful correlation analyses have shown it to be the one persistent anomaly over an energy interval of some 10 MeV, but also in various inelastic and reaction channels.

From their analysis of the elastic-scattering angular distribution, Malmin *et al.*[2] suggested that the 19.7-MeV anomaly has spin 14. Stokstad *et al.*[3] speculated that this anomaly might, in fact, be a "nuclear molecule" in which the exchange of an α particle between two ^{12}C cores provides the binding. They cited the relatively prominent structure seen at back angles as supporting evidence for such a process. The anomaly also appears in some inelastic channels but not in others, and there seems to be a dip at this energy in the cross section for the reaction $^{16}O(^{12}C, \alpha)^{24}Mg$.

In the present experiment we have chosen the "quasielastic" process $^{16}O+^{13}C \rightarrow ^{17}O+^{12}C$ in order to search for a similar anomaly. The advantage of this quasielastic reaction is that one might expect a similar resonance to appear; but unlike the elastic scattering, only the reaction amplitude could contribute. Thus it should be possible to study the resonance process in more detail.

In this study of the reaction, we used the associated-particle method[4] with an array of large-area detectors. The 50-μg/cm^2 ^{13}C targets were bombarded with the ^{16}O beam from the Argonne National Laboratory tandem; and for angles of observation $\theta_{c.m.} \gtrsim 90°$, Al_2O_3 targets were bombarded with the ^{13}C beam.

Excitation functions for the interval $E(^{16}O)=35$–49 MeV (i.e., for $E_{c.m.}=17$–22 MeV) are shown in Fig. 1. At $\theta_{c.m.}=52.4°$, $\theta_{c.m.}=64.9°$, and other forward angles, a very clear anomaly is apparent at a center-of-mass energy $E_{c.m.}=18.7$ MeV, with a width of ~2.5 MeV. Other forward angles showed very similar behavior, with the anomaly becoming wider and disappearing by $\theta_{c.m.} \approx 90°$.

Angular distributions are shown in Fig. 2. At 18.7 MeV the angular distribution is asymmetric about 90°. Strong forward peaking is seen, with the average cross section at ~135° a factor of ~100 below that at 45°. This strong forward peaking is indicative of a direct reaction. In addition, one notices a slight oscillatory structure with a phase characteristic of $[P_{14}(\cos\theta)]^2$. The oscillations are not nearly as sharp as in the $^{16}O+^{12}C$ elastic scattering, but the angles at which minima and maxima occur cannot be fitted with other values of angular momentum, such as 12, 13, 15, or 16. An angular distribution taken at 20.6 MeV, slightly above the resonance, is also shown in Fig. 2. Here the forward peaking is still clearly present, but the oscillatory pattern is gone. While the direct reaction remains strong, the resonance

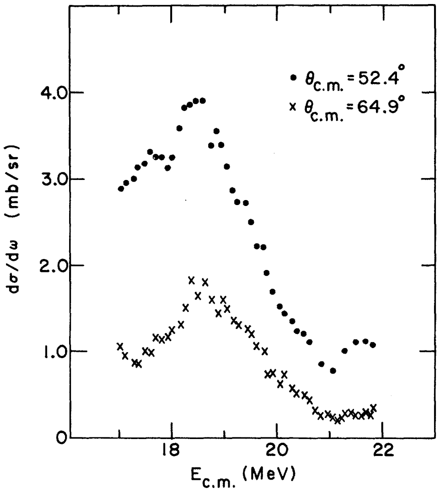

FIG. 1. Excitation function showing the 18.7-MeV anomaly at two forward angles for the reaction $^{13}C(^{16}O, ^{17}O)^{12}C$.

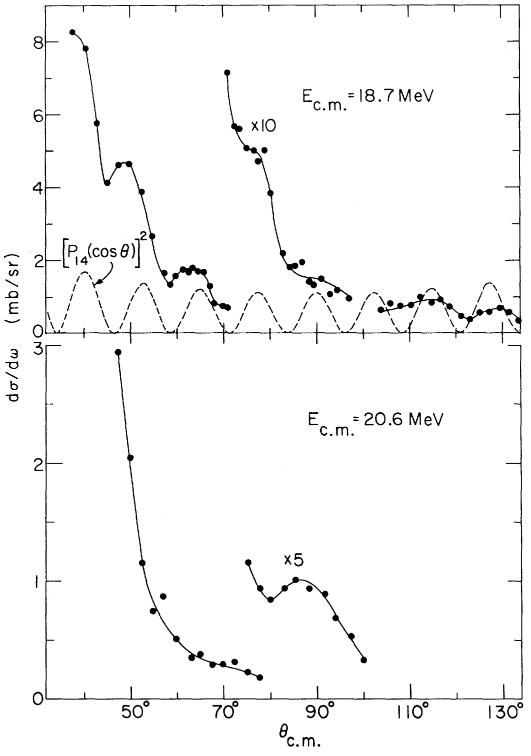

FIG. 2. Angular distributions at the energy of the anomaly and at an energy well above the anomaly. The shape of $[P_{14}(\cos\theta)]^2$ is shown by the dashed curve.

has disappeared. Some of the properties of this resonance will now be discussed.

Malmin *et al.* commented on the width of the resonance and compared it with the width of an $L = 14$ resonance calculated in a purely real Woods-Saxon potential. We have repeated such calculations with the same geometric paremeters ($R = 6.55$, $a = 0.45$ fm) as were used by Malmin *et al.*, but we did not use their energy-dependent real potential. Instead, we calculated the widths in wells of fixed depth. Of course, the position of the resonance changes with well depth. For $V = 13$ MeV, the resonance occurs at ~21.5 MeV with $\Gamma = 3.9$ MeV; for $V = 16$ MeV, it is at 19.5 MeV with $\Gamma = 1.4$ MeV. The width therefore changes by a factor of 2 with a change of ~1.4 MeV in the resonant energy.

The resonance observed in the $^{12}C + ^{16}O$ system had a width of ~0.35 MeV. The resonance seen in the present work is considerably broader, ~2.5 MeV. A possible source of this broadening is the coupling of the extra neutron; in fact, the binding energy of the neutron is 0.8 MeV more for ^{13}C than for ^{17}O, so states of different spin are not likely to be degenerate.

In order to make this argument semiquantitative, we consider that the peak cross section allowed by unitarity for $L = 14$ is $\pi(\lambda/2\pi)^2(2L+1) \approx 150$ mb. The observed peak cross section at 18.7 MeV is roughly 10 mb above the nonresonant cross section at 20.6 MeV. Here our two angular distributions allow us to integrate over ~75% of the total available solid angle. In addition, the width is greater than that for the $^{16}O + ^{12}C$ system; and when this is taken into account, the area under the peak is equibalent to that for a peak cross section of 71 mb. If this correction for the broadening is supplemented with an additional correction for the lower penetrability at the somewhat lower center-of-mass energy at which this resonance occurs, the peak cross section is increased to ~120 mb—almost the limit set by unitarity. This implies that most of the cross section is in the channels we are studying, and the resonance is unlikely to have a large fraction of its width in other channels. The primary source of broadening then is not absorption (mixing into other channels) but is likely to be the consequence of the extra neutron. Clearly, the actual angular momentum will be determined by the coupling of the spin of this neutron (which is $\frac{1}{2}^-$ in ^{13}C, $\frac{5}{2}^-$ in ^{17}O) to the $^{16}O + ^{12}C$ resonance. Therefore, what one is likely to have is a superposition of resonances of different spins and different incident and outgoing L values in such a way that the averaging over all possible combinations retains the $[P_{14}(\cos\theta)]^2$ shape. What we have in ^{29}Si is the remnant of the 14^+ resonance in ^{28}Si, somewhat smeared in both energy and spin.

How should one think of the 14^+ resonance at 36.5-MeV excitation in ^{28}Si? Two possible models suggest themselves. As was stated by Malmin, a potential with $V = 13$ MeV will have an $L = 14$ resonance at about the correct energy. This would, in fact, be the first (nodeless) $L = 14$ resonance in this potential. However, such a shallow potential also has other resonances ($L = 13$ and $L = 15$) within less than 2 MeV. No such resonances are seen experimentally. The nearest anomaly, similar to the one at 19.7 MeV but less distant, was seen at 13.5 MeV, i.e., spaced 6.2 MeV away from the 19.7-MeV resonance. If this were the $L = 13$ resonance, the spacing would imply $V > 100$ MeV. An alternative assumption would be a rotational band. If the 13.5-MeV anomaly is assumed to correspond to the 12^+ member of a rotational band, the $J(J+1)$ dependence implies that a 0^+ band head should occur at 12.9-MeV excitation in ^{28}Si. Actually, the moment of inertia might be expected to increase somewhat with J, and thus the band head could be considerably lower in excitation.

The energy of the resonance is ~1 MeV lower in ^{29}Si than in ^{28}Si. Such a downward shift might be expected if the anomaly is regarded as a size resonance between two pieces of nuclear matter; increasing the radius of the potential would lower the energy of a given resonance. How a rotational band would be changed by the addition of a neutron is less clear.

Stokstad *et al.* remarked that the 19.7-MeV anomaly seemed more prominent at backward angles. They inferred that this indicated backward peaking in the resonant amplitude, and thus was evidence for a dominant exchange amplitude, namely, α-particle exchange between two ^{12}C cores. The forward peaking indicated by the present data seems to contradict this picture. A very sharp backward peak may still be present at very large angles, but the bulk of the angular distribution is in the forward hemisphere.

The present results seem to have improved our understanding of these resonant effects, but they point up the need for more data—especially data on other resonances belonging to this same family. The present technique of studying the resonance in quasielastic reactions rather than elactic scattering may have more general applications.

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[1] R. H. Siemssen, in *Proceedings of the Symposium on Heavy-Ion Scattering, Argonne National Laboratory, 1971,* (Argonne National Laboratory, Argonne, Ill., 1971), p. 145.

[2] R. E. Malmin, R. H. Siemssen, D. A. Sink, and P. P. Singh, Phys. Rev. Lett. 28, 1590 (1972).

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

[4] R. H. Siemssen, H. T. Fortune, J. W. Tippie, and J. L. Yntema, in *Proceedings of the International Conference on Nuclear Reactions Induced by Heavy Ions, Heidelberg, Germany, 1969,* edited by R. Bock and W. R. Hering (North-Holland, Amsterdam, 1970), p. 174.

Absence of Gravity-Wave Signals in a Bar at 1695 Hz

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A 118-kg bar shows vector amplitude changes ("impulses") in successive 24-msec intervals which correspond to bar energies E distributed with a probability $N = N_0 \exp(-E/kT_e)$, with $T_e \sim 30$ K. Not more than one impulse larger than 537 K was observed in 9 days. Calibration impulses giving the bar 600 K of energy were detected with 60% efficiency above a 537-K threshold. In the following Letter, these results are contrasted with the gravity-wave detections of Weber.

Very large energy fluxes observed for several years by Weber in gravitational radiation have not yet been confirmed by others.[1,2] To verify that such intense gravity waves do not exist, it would suffice to have a *single* detector at f_{Weber} which does not show excitations of the magnitude which would be induced by the gravity-wave events described by Weber.

We report here results for such an experiment, which are contrasted in the following Letter with the expected results if gravity waves of the nature, intensity, and numbers reported by Weber in 1970 existed in March and April 1973.

The antenna proper is a bar of aluminum alloy, type 2024-T4, 150 cm long by 19 cm diam. The lowest longitudinal compressional mode has $f_B = 1695$ Hz. The bar is operating in a vacuum $\leqslant 0.3$ Torr in a normal laboratory. It is supported, axis horizontal and oriented east-west, by a steel cable from a three-stage mechanical filter of 50-kg cast-iron masses separated by rubber vibration isolators (Barry type 670-7ST). The vacuum chamber and its contents is further isolated at low frequencies by suspension from a pneumatic servo isolation frame.

The amplitude of vibration of the resonant bar