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Resonance in $^{12}C + {}^{16}O$ Scattering at $E_{c.m.} \approx 19.7$ MeV*

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A strong resonancelike structure (~400 keV wide) has been observed in elastic $^{16}O + {}^{12}C$ scattering. Inelastic scattering excitation functions with ^{16}O in the unresolved $0^+, 3^-$ states at 6.1 MeV show structure correlated with the elastic channel. An analysis of the angular distribution measured on the resonance indicates a spin $I = 14$.

The observation[1,2] of possible "molecular states" in the $^{12}C + {}^{12}C$ and $^{12}C + {}^{16}O$ systems at energies close to the Coulomb barrier has led to much interest in this phenomenon. Narrow structures observed in the excitation functions at higher energies were found to be consistent with statistical fluctuations.[3,4] More recently, however, there has been increasing evidence[5] for the existence of structure of nonstatistical origin in addition to the fluctuation phenomena. In a study of $^{12}C + {}^{16}O$ elastic scattering we observe a strong anomaly which, as discussed below, is indicative of a high-spin ($I = 14$) resonance in the ^{28}Si compound system. A preliminary report of this anomaly has already been given elsewhere.[6] Recently, an investigation of this anomaly has also been undertaken at Yale.[7]

Elastic-scattering excitation functions for the $^{12}C + {}^{16}O$ system (Fig. 1) were measured in the energy range $E_{lab} = 20-60$ MeV with targets whose thicknesses were chosen to match the 250-keV energy steps. The forward-angle data have been omitted from Fig. 1 since they show much less structure. The associated-particle method was used with an array of large-area detectors, and the back-angle data (taken at 140°, 150°, and 160° c.m.) were obtained with detector telescopes in which the recoil ^{12}C ions were recorded.

The data in Fig. 1 exhibit strong rapid fluctuations superimposed on a broad gross structure (~2 MeV wide). A statistical analysis (with a running average cross section taken over a 1.3-MeV subinterval) yields a coherence width of approximately 110 keV in good agreement with the results of Halbert, Durham, and Van der Woude[4] and indicates no significant angular cross correlations.

However, at ~19.7 MeV a prominent structure[8]

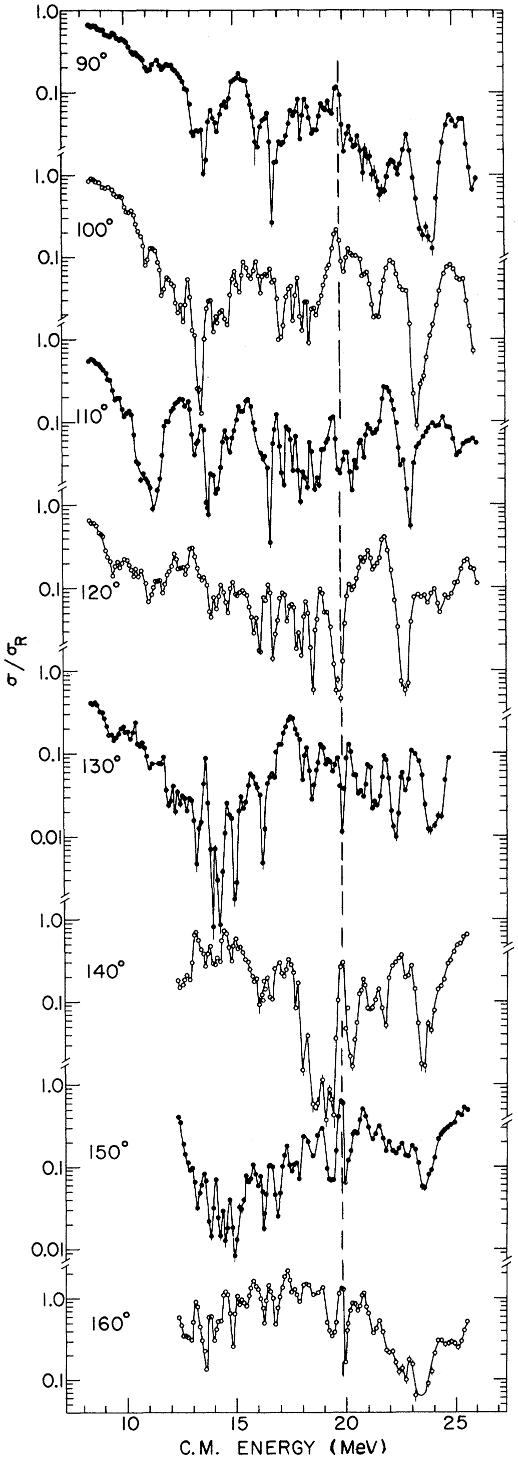

FIG. 1. Elastic-scattering excitation functions plotted as ratios of differential cross sections to Rutherford-scattering cross sections. The dashed vertical line indicates the position of the 19.7-MeV anomaly.

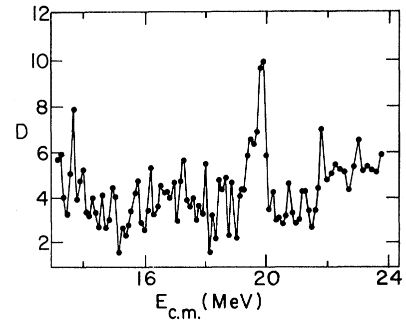

FIG. 2. Angle-integrated correlation function D indicating the deviations from the mean cross section.

~400 keV wide stands out as a sharp peak at 90°, 100°, 140°, 150°, and 160° and as a sharp dip at 120° and 130°. In the presence of strong statistical fluctuations, conclusive identification of isolated nonstatistical effects presents a well-known difficulty. In order to separate the structures that are correlated in angle from those that are not, we have plotted (Fig. 2) the energy dependence of the quantity

$$D(E) \equiv \sum_i |[\sigma_i(E) - \langle\sigma_i(E)\rangle]/\langle\sigma_i(E)\rangle|,$$

where $\sigma_i(E) \equiv \sigma(\theta_i, E)$, the average $\langle\sigma_i(E)\rangle$ is taken over a 1.3-MeV interval centered on E, and the summation is over the angles $\theta_i = 40°-160°$. At energies at which there is no correlated structure, $D(E)$ fluctuates around an average value, whereas in the vicinity of 19.7 MeV there is a very sharp peak in $D(E)$. The statistical probability for finding deviations from the average cross section as large as those observed at 140°, 150°, and 160° are 5×10^{-5}, 2×10^{-3}, and 4×10^{-2}, respectively.

We have also measured thin-target elastic- and inelastic-scattering cross sections across the anomaly in 125-keV (lab) (54 keV, c.m.) energy steps. These measurements (Fig. 3) do not reveal any finer structure in the elastic-scattering data. The transition to the respective unresolved 0^+, 3^- states at 6.06 and 6.14 MeV in ^{16}O shows a definite correlation with the anomaly in the elastic scattering. The correlation with the respective unresolved 2^+, 1^- states at 6.96 and 7.12 MeV in ^{16}O is less obvious, and there is no apparent correlation with the inelastic scattering to the 2^+ state at 4.43 MeV in ^{12}C (not shown).

Elastic-scattering angular distributions on and off the 19.7-MeV anomaly are presented in Fig. 4. The angular distributions exhibit well-developed diffractionlike oscillations. On the reso-

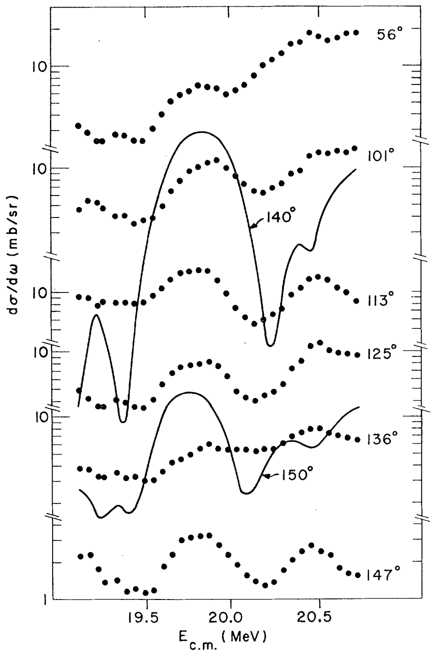

FIG. 3. $^{12}C(^{16}O, ^{16}O^*)^{12}C$ inelastic-scattering cross sections for transitions to the unresolved $0^+, 3^-$ states at 6.1 MeV in ^{16}O, as measured with a thin target. Solid curves, unnormalized elastic scattering excitation functions at 140° and 150°, which also have been measured with a thin target.

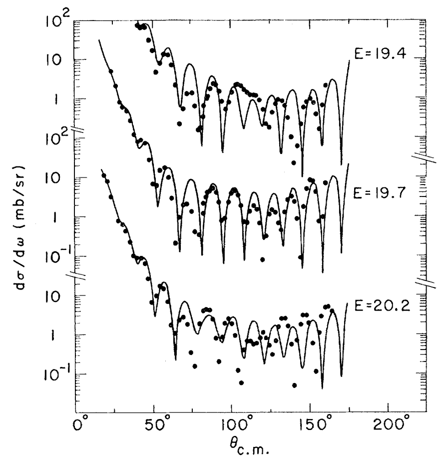

FIG. 4. Elastic-scattering angular distributions on and off resonance. Solid curves, calculated with an optical model plus a Breit-Wigner resonance term for $I = 14$.

nance the cross sections at back angles are larger than those off resonance and the oscillations are more regular. Moreover, in going through the resonance a small change in energy results in an abrupt change in the pattern of oscillations, the change in the positions of the maxima and minima corresponding roughly to replacing a Legendre polynomial of order $L = 13$ off resonance to $L = 14$ on resonance.

Indeed, a good fit (solid curves in Fig. 4) to the angular distribution on the anomaly is obtained by adding a Breit-Wigner resonance in $L = 14$ to an optical-model background. However, since the background is not well determined for the back angles, the fit to the data off the resonance is at best qualitative, and resonance parameters extracted from this fit are not very meaningful except for the L, which is well established. It is of considerable interest to note that the real part of the optical-model potential[9] derived from fits to the forward-angle excitation functions supports an $L = 14$ resonance at 19.8 MeV with a width of approximately 1.3 MeV.

The strong correlation with angle and the anomalously large deviations from the average cross section, as well as the correlation with at least one inelastic channel, argue strongly in favor of a genuine resonance at 19.7 MeV and against a simple fluctuation phenomenon. The width of ~400 keV suggests that it is an intermediate-structure state since the width is significantly greater than that of the underlying compound-nucleus states, and it is only about $\frac{1}{3}$ of that of an $L = 14$ single-particle resonance calculated with the optical model with the imaginary potential removed.

Another possible anomaly appears at 13.7 MeV; but since it is less pronounced, the attention in this Letter is concentrated on the 19.7-MeV anomaly. However, it is of considerable interest to note that in a very careful statistical-model study of the reaction $^{12}C(^{16}O, \alpha)^{24}Mg$, Halbert, Durham, and van der Woude[4] find a strong anomaly at this same energy (13.6 MeV). The anomalies observed at 13.7 and 19.7 MeV in the present investigation may not be the only ones in the elastic-scattering excitation functions, but they are clearly the most pronounced structures of narrow width.

Explanations of the observed resonance at 19.7 MeV are necessarily speculative at this stage. For strongly absorbed particles, Moldauer[10] predicts "intermediate resonances" even on a purely statistical basis in the framework of the R-matrix theory. A specific model for intermediate structure (one based on strong coupling to the collective 2^+ and 3^- states, which are preferentially excited in inelastic scattering) has been put forward by Imanishi[11] and by Scheid, Greiner, and Lemmer[12]; and an α-particle model for intermediate structure has recently been proposed by Michaud and Vogt.[13] In the framework of the model of Imanishi and Scheid, Greiner, and Lemmer, the observed correlation in the unresolved $0^+, 3^-$ transitions would be due primarily to coupling to the 3^- level. In the α-particle mode, however, the major contribution to this unresolved peak would be expected to arise from the four particle, four-hole 0^+ state. It would therefore be of considerable interest to determine which of these two levels is correlated with the ground state. Since intermediate structure so far has been found only in the collision of heavy ions that are α-particle nuclei, the model of Michaud and Vogt is especially attractive.

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