Intermediate-structure resonances in the $^{16}O + ^{16}O$ total reaction cross section

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(Received 9 May 1983)

The $^{16}O+^{16}O$ total reaction cross section has been deduced from the elastic data in the energy region from 15.5–18 MeV (c.m.) using the sum-of-differences method. It exhibits intermediate-width resonant structures which are attributed to quasimolecular resonances in the $A=32$ system. Reduced partial widths of three resonances have been calculated. They indicate that the structure of the resonant states may not be that of a dinuclear molecule.

[NUCLEAR REACTIONS $^{16}O(^{16}O,^{16}O)$, $E=15.5$–18.0 MeV (c.m.), $\Delta E=50$ keV; measured $\sigma(\theta,E)$, deduced total reaction cross section and quasimolecular resonances.]

The $^{16}O+^{16}O$ system has played an important role in the history of molecular resonances. This system, like the $^{12}C+^{12}C$ system, was one of the first systems studied in the early days of heavy-ion physics. In contrast to the $^{12}C+^{12}C$ reaction,[1] the collision between the ^{16}O nuclei did not exhibit resonant structures in the region of the Coulomb barrier. This system was, however, the first system in which broad gross structures were found in the region above the Coulomb barrier.[2] It was observed that as well as gross structure there also appeared intermediate structure in the excitation functions of different exit channels in the gross-structure region. This indicated that molecular resonances might nevertheless exist. Recent experiments performed by Gaul *et al.*[3] led to similar observations in the barrier region.

Very recently, evidence for the existence of molecular resonances in the $^{16}O+^{16}O$ system was given by Gai *et al.*[4] They observed three resonances in the energy region $E_{c.m.}\approx 16$ MeV in the angle-integrated cross section of the α-particle exit channel and were able to make J assignments.

In the present paper we also investigate this energy range in order to reexamine the existence of resonances. We measure the total reaction cross section σ_R because it is known from the investigations of the $^{12}C+^{12}C$ and $^{16}O+^{12}C$ systems[5,6] that this cross section allows a reliable determination of resonances. In addition, the total reaction cross section offers a unique possibility to determine elastic widths (see Ref. 6), and thus to extract information on the structure of a resonant state.

We deduce the total reaction cross section for the $^{16}O+^{16}O$ system from the data on $^{16}O+^{16}O$ elastic scattering using the sum-of-difference method.[7] According to this method, σ_R can be determined from the measured elastic cross section $\sigma_{el}(\theta)$ by using the expression (for identical particles)

$$\sigma_R = A + 2\pi \int_{\theta_0}^{\pi/2} \{\sigma_c(\theta) - \sigma_{el}(\theta)\} \sin\theta \, d\theta \,, \qquad (1)$$

where $\sigma_c(\theta)$ is the cross section of Mott scattering and θ_0 is an angle which should be equal to or smaller than the angle θ_c at which $\sigma_{el}(\theta)$ starts to deviate from $\sigma_c(\theta)$. The term A may be assumed to be small in heavy-ion reactions with moderate absorption and large values of the Sommerfeld parameter.[8] We have omitted this term in our calculation.

Measurements were performed at the Erlangen EN tandem accelerator in the energy range $E_{c.m.}=15.5$–18 MeV in steps of 50 keV (c.m.). Angular distributions were measured simultaneously for each energy at 28 angles equally spaced in the range from 4.5° to 45° (lab). For this purpose, a multidetector array was used in which silicon detectors were mounted at the loci above and below the horizontal plane (±3° as seen from the target center) and left and right of the beam direction. Such an arrangement enabled us to achieve an angle step of 1.5° in a scattering chamber of 60 cm in diameter.[9] Only detectors with small depletion depths (<100 μm) were used to discriminate elastically scattered ^{16}O ions from light particles. Reaction products from the $^{12}C+^{20}Ne$ exit channel could be eliminated owing to different energies. Detectors placed at the most forward angles had to be changed frequently because of radiation damage. The apertures of these detectors consisted of Ni foils 25 μm thick with holes 100 μm in diameter.[10] The scattering angles defined by the aperture of the holes were determined from the position of the image of these holes projected onto a screen by an electric bulb (with a thread filament) mounted exactly in the center of the multidetector array. The accuracy achieved in this way was about ±0.02°. The solid angle defined by the apertures was determined from an elastic scattering experiment at $E_{lab}=14$ MeV with an Ar target (pure Rutherford scattering). A slit of 2 mm in diameter connected to a galvanometer and a small Faraday cup mounted closely behind the target was used to focus the beam onto the target.

A windowless, differentially pumped gas target[11] was used. The gas was natural oxygen with a chemical purity of 99.6%. The main impurities were water vapor and Ar (0.12%). Oxygen ions scattered on Ar could not be resolved from those scattered on O at angles smaller than 15° (lab). The contribution from the Ar to the yield of the ^{16}O scattering was, however, smaller than the error due to statistics and uncertainties in the peak integration, and

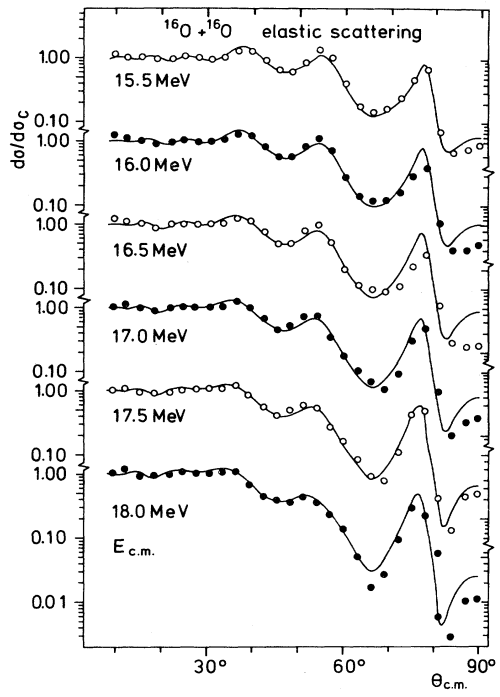

FIG. 1. Angular distributions of the $^{16}O + ^{16}O$ elastic scattering together with optical model calculations (parameters of Ref. 12).

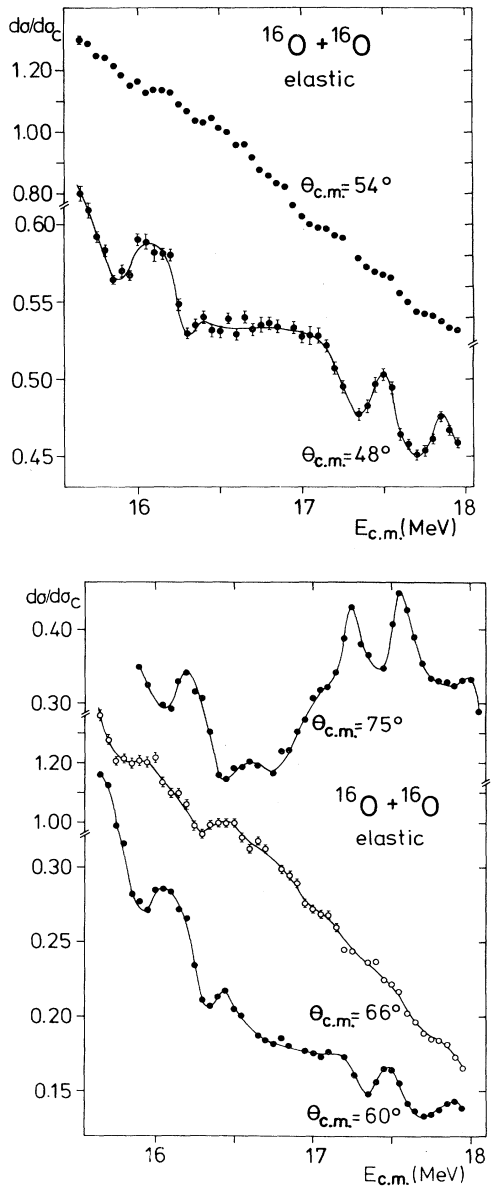

FIG. 2. Excitation functions for the $^{16}O + ^{16}O$ elastic scattering measured at different angles. The angles chosen correspond to maxima (minima) of $[P_{12}(\cos\theta)]^2$.

therefore no corrections for this contribution were made. The target was 15 $\mu g\,cm^{-2}$ thick. This thickness corresponded to the energy loss of the incoming ^{16}O ions of 100 keV (lab). In order to avoid oxidation of oil in the roughing pumps, both air and He gas were additionally fed as gas ballast into the pumps.

Figure 1 shows some of the 50 angular distributions measured. The absolute normalization of these and all other angular distributions was performed by adjusting the cross sections at the most forward angles to the cross section of Mott scattering. The figure also shows optical-model calculations (solid lines) performed using the parameter set of Ref. 12. Figure 2 shows elastic excitation functions for a few selected angles.

The total reaction cross section σ_R deduced from the elastic data by using Eq. (1) is shown in Fig. 3. This cross section is affected by two types of errors, the magnitudes of which have to be known before further conclusions can be drawn. First, there is a relative error which determines whether the existing structure is significant. This error depends on the precision of angular distribution measurements. In our case, it is of the order of 0.5% or smaller. This means that the structures observed in σ_R (see Fig. 3) are real. It should be noted that the choice of the cutoff angle θ_0 does not influence these structures if chosen within reasonable limits. Owing to the large number of effective channels involved in σ_R, the probability that the observed structures are due to statistical fluctuations is negligibly small. These structures must therefore be attributed to the eigenstates of the $A = 32$ system.

The absolute height of the cross section depends, however, on θ_0. We have chosen θ_0 to be the angle which gives best agreement between σ_R as obtained from an optical-model calculation (parameters of Ref. 12) and σ_R as obtained from the sum-of-differences method applied to the optical-model angular distributions (see Fig. 1). The difference between the two values of σ_R in the energy range studied is found to be 10% at most. The actual total reaction cross section is therefore believed to be also accurate within 10%. Comparison with existing fusion cross sections (Refs. 13 and 14) shows that our total reaction cross section is slightly higher (up to 10%).

We have identified four quasimolecular resonances in the total reaction cross section within $E_{c.m.} = 15.5$ and 18.0 MeV (see Table I). The resonant structure at 15.89

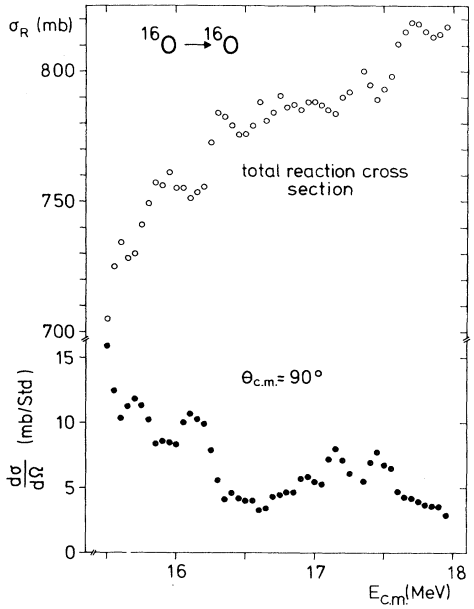

FIG. 3. $^{16}O+^{16}O$ total reaction cross section (upper part) and 90° elastic excitation function (lower part).

MeV is of particular interest since it seems to correspond to the resonance triplet reported by Gai *et al.*[4] at 15.8, 15.9, and 16.1 MeV. It is interesting to note that all resonances in the total reaction cross section are correlated with the minima in the 90° elastic excitation function. Additional minima are correlated with weaker structures in σ_R which might be due to additional quasimolecular resonances. The same correlation has already been observed for the $^{12}C+^{12}C$ and $^{16}O+^{12}C$ systems.[6,15]

The existence of quasimolecular resonances in the $^{16}O+^{16}O$ system seems to be in contrast to the empirical rules given by Hanson *et al.*[16] and Voit *et al.*[17] who relate the observability of resonances to a small number of open channels and a low density of compound nuclear states. The rules refer to the situation for Coulomb-barrier resonances, which is characterized by small values of the grazing partial wave. At higher energies, such as those used in the present experiment, these rules have to be applied only to the grazing partial wave ($l=l_{gr}$), since it may be assumed that this partial wave is responsible for the formation of the nuclear molecule. Thus, in the present case, the observability of resonances seems to indicate that both the number of open channels G and the level density for compound nuclear states ρ with $J=l_{gr}$ are relatively small. This means that the grazing partial wave ($l=12$) populates those states in the composite system which are close to the corresponding yrast line. In fact, the $J=12$ yrast state in ^{32}S as obtained from an extrapolation of the ground-state band is just 5 MeV below these states. The relatively small effect observed in the $^{16}O+^{16}O$ system shows that either G and ρ are larger than in the $^{12}C+^{12}C$ system or/and that the structure of the states observed exhibits a larger overlap with compound nuclear states.

TABLE I. Resonances observed in the $^{16}O+^{16}O$ total reaction cross section together with resonance parameters. The quantities in the last two columns are calculated assuming $J=12$ for the resonances. The accuracy of Γ_{el} was estimated to be correct within 10–30%.

E_{res} (MeV)	σ_R^{Res} (mb)	Γ (keV)	Γ_{el} (keV)	γ_{el}^2/γ_w^2 (%)
15.89				
16.32	22	153	4	1.2
17.31	15	156	3	0.5
17.67	19	156	3	0.6

We have shown[6] that the total reaction cross section offers a unique possibility to extract the elastic widths Γ_{el} of quasimolecular resonances since σ_R can be decomposed into a background contribution and a resonant contribution σ_R^{res}. The assumptions made are the following.

(i) There must be a sufficiently large number of channels into which the compound nuclear states can decay.[18]

(ii) The resonant states are eigenstates of the composite system rather than doorway states. Then, the resonant part of the total reaction cross section can be written as (identical particles, nonoverlapping resonances)

$$\sigma_R^{res}=8\pi\lambda\!\!\!^{-2}(2J+1)\frac{\Gamma_{el}(\Gamma-\Gamma_{el})}{\Gamma^2}\ , \tag{2}$$

where Γ and J are the total width and the spin value of the resonance, respectively.

Unfortunately, the J values for the resonances observed are not known, with the exception of the resonance structure at 16 MeV which probably is a triplet with J values of 8 and 10 (Ref. 4). Since we cannot apply the simple expression of Eq. (2) to the case of overlapping resonances we will, however, only investigate the remaining three resonances in the following.

In order to estimate the magnitudes of Γ_{el} one has to make assumptions regarding the possible J values of these resonances. We know from investigations of the $^{12}C+^{12}C$ system that resonances with the same J values are grouped together in certain energy ranges.[19] The J value of the group corresponds to the grazing l value of the entrance channel. Only a very few resonances within a group have J values which are smaller than the grazing l value by a few units of $\hbar$.

We assume that the same features apply to the $^{16}O+^{16}O$ system. Since the grazing l value is 12 in the energy range considered and since $J=8$ and 10 assignments have been made for the 16 MeV resonance structure,[4] we think that the resonance spins are most probably $J=12$, with a small chance of being $J=8$ or 10. Figure 2 provides evidence that the choice of $J=12$ is most probably correct. The figure shows elastic excitation functions measured at angles which correspond approximately to maxima (75°,61°,47°) and minima (68°,54°) of the $[P_{12}(\cos\theta)]^2$ function. The former exhibit anomalies at the resonance energies; the latter are rather structureless. Besides this the minima of $[P_{12}(\cos\theta)]^2$ at $\theta=68°$ and 54° correspond to maxima in the $[P_8(\cos\theta)]^2$ and $[P_{10}(\cos\theta)]^2$ functions, respectively. One would expect anomalies in the 68° and 54° excitation functions if J values of 8 and 10 are involved (in fact a $J=8$ assignment for the 16.38 MeV resonance cannot be ruled out with this argument).

Assuming $J=12$ for the resonances at $E_{c.m.}=16.32$,

TABLE II. Elastic widths and ratios of reduced elastic width to the single particle width assuming $J=8$ and 10 for the resonance spin.

	$J=8$		$J=10$	
E_{res} (MeV)	Γ_{el} (keV)	γ_{el}^2/γ_w^2 (%)	Γ_{el} (keV)	γ_{el}^2/γ_w^2 (%)
16.32	5.1	0.5	4.1	0.6
17.31	3.8	0.3	3.1	0.3
17.67	4.8	0.4	3.9	0.4

17.31, and 17.67 MeV we have calculated elastic widths using Eq. (2). The equation gives two solutions, one of which is not a physical solution. Fortunately the magnitude of the elastic cross section at the resonance energy allows us to put limits on the physical solutions. We have used the 90° and 75° excitation functions in order to establish these limits. Table I contains the physical solutions of Eq. (2). It is obvious that these Γ_{el} values represent only a small fraction of the total width.

In order to eliminate penetrability effects involved in a comparison between Γ_{el} and Γ we have calculated reduced elastic widths γ_{el}^2 (using $r_0=1.5$ fm). The γ_{el}^2 values are compared with reduced single particles widths (in the Wigner limit) γ_w^2 in column five of Table I. This comparison also shows that the elastic widths are very small compared to the single particle widths. We conclude, therefore, that the structure of the three resonances investigated is not that of a dinuclear molecule.

In order to examine if this conclusion has to be changed if resonance spins $J=8$ or 10 are assumed, we have performed calculations with these two spin values. The results are given in Table II. Comparison with Table I shows that one obtains the largest γ_{el}^2/γ_w^2 values for $J=12$ and that the conclusion given above is valid also for $J=8$ and 10.

In summary, we have found resonant structures in the total reaction cross section for $^{16}O+^{16}O$ which we attribute to quasimolecular resonance states in the $A=32$ system. The examination of the elastic widths shows that the structure of these states is most probably not that of a dinuclear molecule.

This work was supported in part by the Deutsche Forschungsgemeinschaft, Bonn, Federal Republic of Germany, and by the Internationales Büro der Kernforschungsanlage Jülich, Jülich, Federal Republic of Germany.

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