Intermediate and compound structure in the $^{16}O+^{16}O$ system

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Excitation function measurements in the $^{16}O+^{16}O$ system in the energy range $E_{c.m.}=8.5-12.5$ MeV in 25 and 5 keV steps reveal intermediate and compound structures simultaneously. Decay widths of compound ($\Gamma=25$ keV) and intermediate ($\Gamma=130$ keV) states have been determined using the spectral density method and the peak counting method. Relative cross sections for the decay of compound and intermediate states are deduced.

Early measurements of elastic scattering and reactions in the $^{12}C+^{12}C$ system[1] close to the Coulomb barrier unexpectedly revealed pronounced and correlated structures in all open channels, thereby pioneering a new field in nuclear physics. Whether these structures and similar ones observed in other systems like $^{12}C+^{16}O$ and $^{16}O+^{16}O$ can be attributed to molecular-type configurations or to more complicated types of doorway states or even compound nuclear fluctuations has controversially been discussed during the last decades.[2]

While theoretical calculations on a microscopic basis[3] yielded isolated resonances of molecular type, clearcut evidence has not been provided by experiment in spite of appreciable effort in this field. It has been suspected that coupling to other degrees of freedom may lead to a strong fragmentation of these states,[4,5] making it hard to analyze them in terms of well-isolated resonances. Thus, the verification of intermediate resonances in these systems requires a simultaneous observation of both compound and intermediate widths over the same range of excitation energies under experimental conditions which allow a clear separation of these different classes of states.

In order to establish the existence of intermediate and compound structure in the $^{16}O+^{16}O$ system at the Coulomb barrier, high precision experiments have been performed at the 4 MV dynamitron accelerator at Bochum. Excitation functions and angular distributions were measured in the energy range $E_{c.m.}=8.5-12.5$ MeV in steps of $\Delta E_{c.m.}=25$ keV. In the energy region $E_{c.m.}=10-10.75$ MeV data were collected in steps of 5 keV. The energy resolution of the $^{16}O^{5+}$ beam was better than 4 keV. The use of a differentially pumped jet gas target[6] facilitated the adjustment of the target thickness to the various energy step sizes. The corresponding target thicknesses were equivalent to 2–10 $\mu g/cm^2$. Elastic scattering cross sections were measured at $\theta_{c.m.}=62°$, 90°, and 100°, whereas the angular distributions of the reaction $^{16}O(^{16}O,\alpha)^{28}Si$ were measured in the angular range $\theta_{lab}=8°-80°$ in steps of 6°. As high current (20 μA $^{16}O^{5+}$) was available, the statistical errors of the elastic scattering data could be reduced to less than 0.5% and for integrated cross sections in the α channels to less than 5%.

Due to these small statistical errors and the reduced energy step size, fine structure not observed in previous measurements[7,8] has been resolved in excitation functions in the elastic channel and in α channels as well.[9] For example, the structures of about 100 keV width observed in the $^{16}O(^{16}O,\alpha_2)$-excitation function in 25 keV steps (Fig. 1) clearly are fragmented into much smaller structures of approximately 20 keV width when measured in 5 keV steps. Obviously, this fine structure has a width much smaller than compound widths resulting from previous analyses.[10,11] Therefore, it is immediately evident that these widths of about 80 keV cannot be attributed to the decay of the compound nucleus ^{32}S. In order to analyze fluctuating cross sections, various methods like peak counting or the autocorrelation method have successfully been applied whenever the reaction cross section contains only direct and compound contributions.[12] If, however, several classes of states, as, e.g., compound and intermediate states, contribute to the cross section, the application of these conventional methods meets with difficulties. For example, autocorrelation analyses of synthetic excitation functions which contained both a 300 and an 800 keV component have not been sensitive enough to detect the presence or demonstrate the absence of the broad struc-

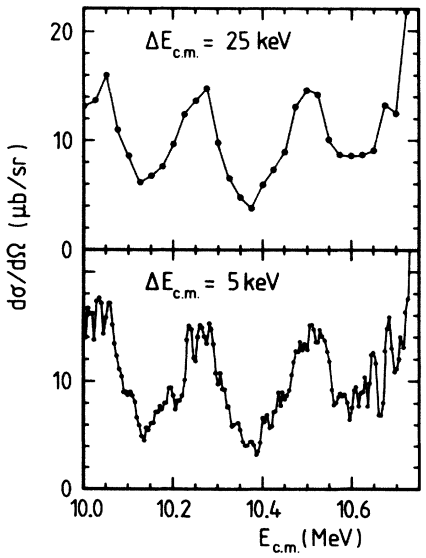

FIG. 1. Excitation function of the reaction $^{16}O(^{16}O,\alpha)^{28}Si$ ($E_x=4.62$ MeV) at $\theta_{lab}=75°$ in 25 and 5 keV steps. The statistical errors are approximately 8%.

ture.[13] On the other hand, the results obtained by the peak counting method are very sensitive to statistical errors, to direct components, and to the energy step size selected.[14,15] Inconsistencies observed in analyses[10,11] mentioned above are very likely to result from neglecting appropriate corrections.

In order to analyze the experimental data, a detailed reinvestigation of standard methods like peak counting and autocorrelation and the more unconventional spectral density method[16,17] has been performed.[9] Using simulation techniques, special emphasis has been put on the importance of intermediate structures in addition to compound states in heavy ion reactions. It turned out that the spectral density method is the most effective one in determining both types of structures simultaneously.

The starting point in the analysis of fluctuating cross sections is the autocorrelation function $C(\epsilon)$. The spectral density $S(t)$, being the Fourier transform of

$$\rho(\epsilon)=C(\epsilon)/C(\epsilon=0) ,$$

is given by

$$S(t)=\pi\Gamma \exp(-\Gamma t/\hbar) .$$

The width Γ can therefore easily be extracted from a $\log S(t)$ plot.

When analyzing experimental autocorrelation functions measured in discrete energy steps ΔE, the Fourier sum has to be used. The corresponding spectral density is given by

$$S(\alpha)=1+2\sum_{k=1}^{\infty}\rho(\epsilon_k)\cos k\alpha \; ; \; \epsilon_k=k\Delta E , \qquad (1)$$

with $\alpha=\Delta E t/\hbar$.[9] $S(\alpha)$ can be expressed in a closed form. In the case of $\alpha<\pi-1.5/\gamma$, $(\gamma=\Gamma/\Delta E)$, the spectral density $S(\alpha)$ can be simplified to

$$S(\alpha)=\pi\gamma \exp(-\gamma\alpha) ,$$

yielding

$$d(\log S(\alpha))/d\alpha \propto \Gamma/\Delta E .$$

Since the experimental autocorrelation is only known in a limited energy interval $I=k_{\max}\Delta E$, the summation in (1) terminates at $k_{\max}$. This sharp cutoff introduces, under certain circumstances, high frequency oscillations in the Fourier transform, making it impossible to extract Γ from $\log S(\alpha)$. The choice of a proper filtering function[16] can, however, damp these oscillations without influencing the slope of $\log S(\alpha)$.[9]

If N classes of states with widths Γ_n and average cross sections $\langle\sigma_n\rangle$ contribute to the total fluctuating cross section $\langle\sigma\rangle$, the autocorrelation function is given by[18]

$$C(\epsilon)=\left|\sum_{n=1}^{N}\langle\sigma_n\rangle\frac{\Gamma_n}{\Gamma_n-i\epsilon}\right|^2 . \qquad (2)$$

The resulting spectral density is just the weighted sum of the spectral densities related to the decay of the various classes of states:

$$S(\alpha)=\sum_{n=1}^{N}A_n S_n(\alpha) .$$

The coefficients A_n are related to the average cross sections $\langle\sigma_n\rangle$ by a set of coupled equations.[9] This clearly emphasizes the advantage of the spectral density method which allows one to determine the relative cross sections $\langle\sigma_n\rangle/\langle\sigma\rangle$ of the decay of the different classes of states in addition to the widths Γ_n.

The existence of these states becomes obvious by distinct slopes in a $\log S(\alpha)$ plot if $\Gamma_1\gg\Gamma_2\gg\cdots\gg\Gamma_N$. States with a small decay width result in long-ranged contributions to $S(\alpha)$ and *vice versa*.

Figure 2 shows the logarithms of the experimental spectral densities in the elastic and in α-reaction channels for different energy step sizes. In the case of the elastic scattering the excitation functions measured at $\theta_{\text{c.m.}}=62°$, 90°, and 100° were used to calculate $S(\alpha)$. In the α channel the angle integrated cross sections of the transitions to all excited states up to 5 MeV and the differential cross sections for the transitions to the ground and first three excited states in ^{28}Si were used in the analyses. In each case the spectral densities calculated from the individual excitation functions have been summed up to yield the total $S(\alpha)$ shown in Fig. 2, which therefore reflects an average time dependence of the decay of the corresponding nuclear states into the final nuclei.

Obviously the $\log S(\alpha)$ plots (Fig. 2) of the measurements in steps of 25 keV reveal three regions which distinct slopes can be attributed to, thus establishing the existence of three classes of states with well-separated widths Γ_1, Γ_2, and Γ_3 (Table I). Despite the fact that the energy dependence of the cross sections on a large scale is quite different in the elastic and in α channels, the largest widths $\Gamma_1=975$ keV observed in these channels coincide. The measurements in steps of 5 keV (Fig. 2, Table I) reproduce the widths Γ_2 and Γ_3, but give no indication of structures of widths less than 25 keV. Therefore the smallest width Γ_3 of about 25 keV observed in the

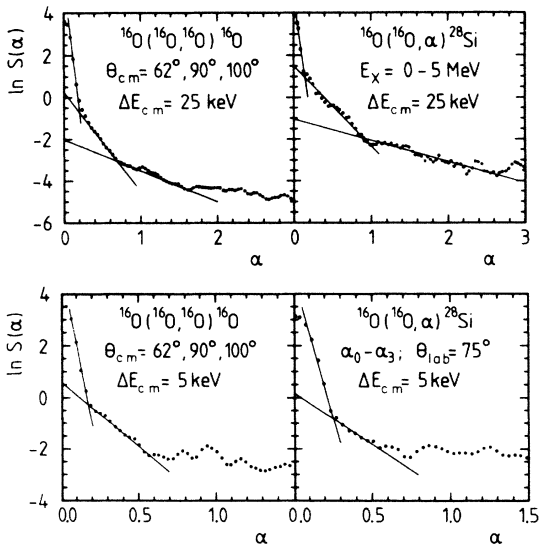

FIG. 2. Logarithms of spectral densities $S(\alpha)$ in the elastic $^{16}O+^{16}O$ channel and in α reaction channels for energy steps of 25 and 5 keV. The various lines correspond to the widths given in Table I.

TABLE I. Widths Γ_n of compound and intermediate states in the $^{16}O+^{16}O$ system at the Coulomb barrier obtained by the spectral density method. The errors are approximately 20%.

Reaction	$\Delta E_{c.m.}$ (keV)	Γ_1 (keV)	Γ_2 (keV)	Γ_3 (keV)
$^{16}O(^{16}O,^{16}O)^{16}O$	25	975	152	36
$^{16}O(^{16}O,\alpha)^{28}Si$	25	975	125	25
$^{16}O(^{16}O,^{16}O)^{16}O$	5		200	25
$^{16}O(^{16}O,\alpha)^{28}Si$	5		130	21

$^{16}O+^{16}O$ system at the Coulomb barrier must inevitably be attributed to the decay of the compound nucleus ^{32}S. The observation of this narrow width structure Γ_3, on the other hand, assures one that the width Γ_2 of approximately 130 keV must be ascribed to the decay of intermediate states.

The relative cross sections $\langle\sigma_1\rangle/\langle\sigma\rangle$ (Table II) belonging to the structures of about 1 MeV width are of the same order as direct contributions Y_d resulting from standard autocorrelation analyses of heavy ion reactions.[13] A comparison of the cross sections $\langle\sigma_n\rangle/\langle\sigma\rangle$ (Table II) shows that compound nuclear contributions are very small, emphasizing the importance of intermediate processes in the $^{16}O+^{16}O$ system.

In order to confirm the above results, analyses using the peak counting method have been performed. The width Γ determined by the peak counting method is given by the number K of maxima per energy interval I in the excitation function: $\Gamma=bI/2K$. Since the parameter b is dependent on the ratio $\Delta E/\Gamma$ and the energy resolution,[14,19] the width Γ has to be calculated by an iterative procedure. The influence of the finite energy step size can, however, in the case of negligible energy straggling, be expressed in a closed form[9]

$$\Gamma=\Delta E\frac{(3-\tau^2)^{1/2}}{\tau}\ ;\ \tau=\tan(\pi K/N)\ , \tag{3}$$

K being the number of peaks and N the total number of points in the energy interval I. In the limit of $\Delta E=0$ Eq. (3) yields the well-known expression $\Gamma=0.55I/K$.[20]

In excitation functions measured in steps of 25 keV we observe 11 peaks/MeV on the average. Therefore the width resulting from Eq. (3) is $\Gamma=27$ keV. Since $\Gamma\approx\Delta E$ the influence of statistical errors is small.[15] Taking into account appropriate corrections given by Put *et al.*,[15] analyses of the excitation function measured in 5 keV steps yield a width of $\Gamma=18\pm8$ keV. These values are in excellent agreement with the smallest width Γ_3 determined by the spectral density method.

Obviously, even in the presence of several classes of decaying states, the different methods of analyzing nuclear fluctuations yield consistent results if correctly taking into account their range of applicability and their dependence on various parameters. Thus, the combined results of our analyses using the peak counting and the spectral density method give convincing evidence of a compound nuclear decay width of about 25 keV in the $^{16}O+^{16}O$ system at the Coulomb barrier. This small decay width of compound states in ^{32}S at $E_x=27$ MeV is apparently very different from the systematics given by Stokstad[21] (Fig. 3) which represent an average behavior of Γ over a wide range of compound nuclei. Analyses of selected heavy ion reactions which populate the compound nuclei ^{32}S, ^{28}Si, and ^{24}Mg give compound widths much smaller than expected from these general systematics (Fig. 3). The compound width resulting from our experiments nicely follows the dependence of Γ on the excitation energy deduced from these heavy ion experiments (Fig. 3).

While previous analyses were often unable to disentangle compound and intermediate structures, we have been able for the first time to observe them simultaneously in excitation function measurements[22] of heavy ion reac-

TABLE II. Relative contributions of various classes of states (Table I) to the cross section in the elastic $^{16}O+^{16}O$ channel and in α-reaction channels at the Coulomb barrier [see also Eq. (2)].

Reaction	$\langle\sigma_1\rangle/\langle\sigma\rangle$	$\langle\sigma_2\rangle/\langle\sigma\rangle$	$\langle\sigma_3\rangle/\langle\sigma\rangle$
$^{16}O(^{16}O,^{16}O)^{16}O$	0.92	0.066	0.014
$^{16}O(^{16}O,\alpha)^{28}Si$	0.74	0.22	0.04

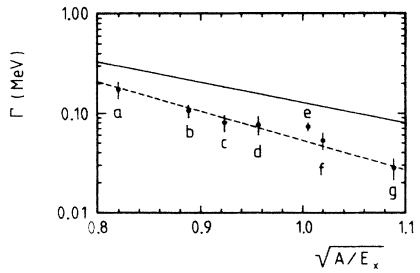

FIG. 3. Scaling behavior of the compound nuclear decay width in ^{32}S (c—e and g), ^{28}Si (b and f), and ^{24}Mg (a). The solid line shows the overall behavior of Γ in a wide range of compound nuclei given by Stokstad (Ref. 22)

$$(\Gamma=14\exp[-4.69\sqrt{(A/E_x)}])\ .$$

The broken line gives the dependence of Γ on the excitation energy for the compound nuclei ^{32}S, ^{28}Si, and ^{24}Mg from selected analyses of heavy ion reactions.

$$(\Gamma=41\exp[-6.64\sqrt{(A/E_x)}])\ .$$

(a—Refs. 24 and 25; b—Ref. 26; c—Ref. 27; d—Ref. 28; e—Ref. 10; f—Ref. 15; and g—this work.) Averaged values have been used in the cases of Refs. 24, 25, and 27, and the values given by the authors explicitly in the cases of Refs. 10 ($^{16}O+^{16}O$ channel), 15, 26, and 28.

tions. The importance of these intermediate processes in the $^{16}O+^{16}O$ system at the Coulomb barrier is emphasized by the fact that the cross section for the decay of intermediate states into α channels or into the elastic channel is about five times larger than for the decay of the compound nucleus (Table II). A close look at the excitation functions[9] suggests that even these structures of approximately 130 keV are slightly overlapping. They are much more numerous than expected from a simple molecular-type configuration and may therefore result from the coupling of these states to more complex ones by residual interaction. A detailed partial wave analysis will be presented in a forthcoming paper[23] to eluciate the nature of these intermediate processes.

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