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# Total reaction cross section for $^{12}C + ^{12}C$ in the vicinity of the Coulomb barrier

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The total reaction cross section for $^{12}C + ^{12}C$ has been deduced in the energy range $E_{c.m.} = 5.5$–$12.8$ MeV from elastic angular distributions using the sum-of-differences method. It exhibits as pronounced structures all quasimolecular resonances found in the $\alpha$-particle exit channel and additional new resonances.

[NUCLEAR REACTIONS $^{12}C(^{12}C, ^{12}C)$, $E = 5.5$–$12.8$ MeV (c.m.), $\Delta E = 25$ keV; measured $\sigma(\theta, E)$, deduced total reaction cross section and quasimolecular resonances.]

Ever since the discovery of the quasimolecular resonances in the $^{12}C + ^{12}C$ reaction,[1] it was a problem to separate resonance structures from statistical fluctuations. This is due to the lack of criteria which allow us to determine true resonances unambiguously. Thus, often controversies arose as to whether to call a structure a resonance or not.

The aim of this paper was to investigate if the total reaction cross section $\sigma_R$ measured in fine energy steps allows an unambiguous determination of true resonances. It is expected that problems which arise from the existence of statistical fluctuations are absent if $\sigma_R$ is used for this determination. On the other hand, it is, however, not *a priori* clear if resonances are not completely damped as well. We have measured the $^{12}C + ^{12}C$ reaction cross section at Coulomb barrier energies. It contains resonance structures which must be attributed to the quasimolecular $^{12}C + ^{12}C$ resonances.

Total reaction cross sections can be obtained in different ways: (i) from $\gamma$-yield measurements, (ii) from the total yield of all reaction products, and (iii) from elastic scattering data. In this work we have determined $\sigma_R$ from elastic data using the sum-of-differences (SOD) method[2,3] since rather reliable data can be obtained in this way as will be shown later.

We have measured elastic angular distributions in steps of 25 keV between $E_{c.m.} = 5.5$ and 12.8 MeV. Each angular distribution was measured simultaneously at 30 angles between $\theta_{c.m.} = 6.4°$ and 90°. It is sufficient to take data only up to 90° due to the identity of the scattered particles.

The detectors were mounted in a multidetector array on both sides of the beam axis and in two different planes above and below the horizontal plane. This geometry allows us to place the necessary number of detectors within an angular range of 90 degrees ($\theta_{lab} = \pm 45°$) inside our 60 cm scattering chamber. Moreover, it is possible in this way to monitor the position of the beam spot and to determine exactly the actual scattering angles (assuming pure Coulomb scattering for the most forward angles). The exact knowledge of the scattering angles is very essential in particular for the forward angular range. Surface barrier detectors were used, having a depletion depth equal to the range of the scattered $^{12}C$ ions. This enables a separation of all light particles from heavy ions originating in the $^{12}C + ^{12}C$ reaction.

The $^{12}C$ targets had a thickness of approximately 10 $\mu g\,cm^{-2}$ and were frequently changed in order to keep the increase of the target thickness due to carbon buildup small. The angular distributions were normalized to the Mott cross section at the four most forward angles ($\theta_{c.m.} < 18°$).

Figure 1 shows typical angular distributions together with the results of an optical model (OM) calculation. The parameters used for this calculation were $V = 100$ MeV, $r_{0r} = 1.19$ fm, and $a_r = 0.48$ fm for the real part and $W = 15$ MeV, $r_{0i} = 1.26$ fm, and $a_i = 0.26$ fm for the imaginary part of the potential.

The total reaction cross section $\sigma_R$ can be written in terms of the elastic cross section and the nuclear part of the scattering amplitude $f_N(0)$ as

$$\sigma_R = 2\pi \int_{\theta_0}^{\pi} \left(\frac{d\sigma_{Cb}}{d\Omega} - \frac{d\sigma_{el}}{d\Omega}\right) \sin\theta\, d\theta + 4\pi |f_N(0)|^2 \sin^2\theta_0/2 + 4\pi ƛ\, \mathrm{Im}[f_N(0) \exp 2i\eta \ln \sin\theta_0/2 - 2i\sigma_0], \qquad (1)$$

where $d\sigma_{Cb}/d\Omega$ is the Coulomb cross section, $d\sigma_{el}/d\Omega$ is the measured elastic cross section, $\eta$ is the Sommerfeld parameter, $\sigma_0$ is the Coulomb phase shift for $l = 0$, and $\theta_0$ is a scattering angle for which $\theta_0 < l_{grazing}$ should be fulfilled.

The absolute value of $f_N(0)$ is usually small in the case of heavy ion reactions. This is due to the fact that both the Sommerfeld parameter and

 

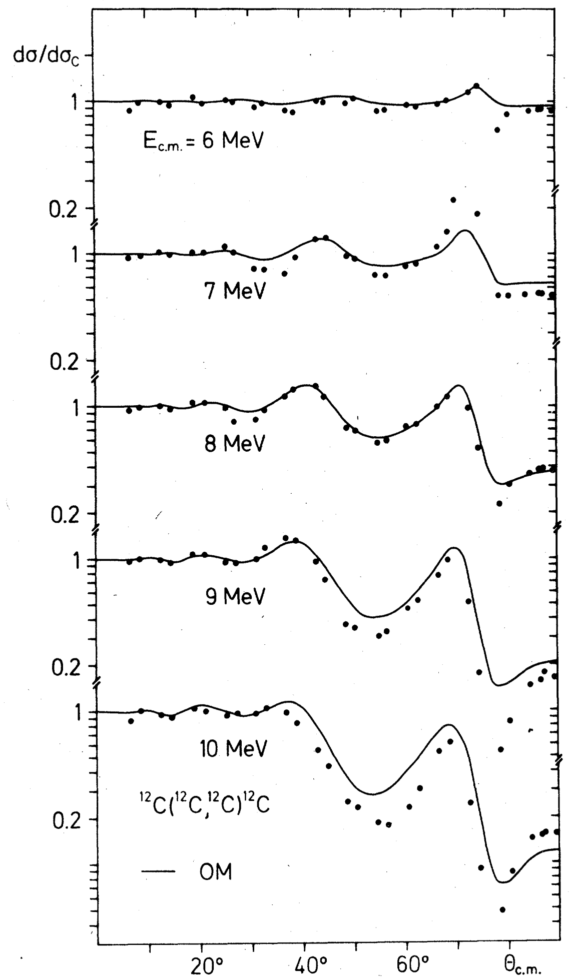


FIG. 1. Angular distributions of the elastic scattering $^{12}C+^{12}C$ normalized to the Mott cross section. The solid lines are the results of an optical model calculation using the parameters given in the text.

the absorption are rather large for these reactions. In fact, Wojciechowski *et al.*[3] have shown that the last two terms on the right side of Eq. (1) can be dropped for heavy ion reactions.

Equation (1) has to be modified if applied to identical particles such as $^{12}C+^{12}C$. Then it reads

$$\sigma_R = 2\pi \int_{\theta_0}^{\pi/2} \left(\frac{d\sigma_M}{d\Omega} - \frac{d\sigma_{el}}{d\Omega}\right)\sin\theta\, d\theta\,, \tag{2}$$

where $d\sigma_M/d\Omega$ is the Mott cross section. Terms containing $f_N(0)$ and $f_N(\pi)$ are already dropped in Eq. (2), using the same arguments as given above.

The possibility of getting reliable values for $\sigma_R$ from elastic data using Eq. (2) was tested. For this purpose, $\sigma_R$ was deduced according to Eq. (2) from OM angular distributions, which were calculated with the parameters given above (a few of these distributions are shown in Fig. 1). The cutoff angle $\theta_0$ was chosen to be $\theta_0 = 2\arctan(\exp - 3\pi/2\eta)$ and corresponds to the angle of the third minimum of the Mott interference structure. The total reaction cross section $\sigma_R$ deduced in this way was compared with the total reaction cross section $\sigma_R^{OM}$ calculated according to

$$\sigma_R^{OM} = 2\pi\lambda\!\!\!^{-2} \sum_{l=\text{even}} (2l+1)T_l\,. \tag{3}$$

It turns out that $\sigma_R$ differs at most by approximately 10% from $\sigma_R^{OM}$. Since the OM angular distributions reproduce the measured distributions fairly well it is expected that $\sigma_R$ values deduced from the measured data contain comparable errors.

Figure 2 shows the total reaction cross section $\sigma_R$ deduced from the actual scattering data. It exhibits pronounced structures superimposed on a smooth background. Since one can safely assume that statistical fluctuations are completely damped, those structures must be true resonances of the quasimolecular type. Figure 2 also shows a comparison between these resonance structures and resonances found in our earlier investigations of the $\alpha$-particle reaction channel.[4] The additional curves in Fig. 2 are angle integrated cross sections for $^{12}C(^{12}C, \sum_i \alpha_i)^{20}Ne$ summed up over contributions from the maximum number of final states which were accessible to our measurement.

It is obvious that a remarkable correspondence exists in most cases between resonances found in $\sigma_R$ and those found in the $\alpha$ channel, even though

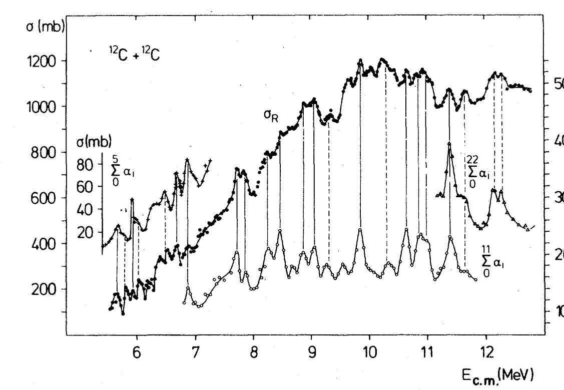


FIG. 2. Total reaction cross section $\sigma_R$ for $^{12}C+^{12}C$ and angle integrated cross sections of the reaction $^{12}C(^{12}C, \sum_i \alpha_i)^{20}Ne$. The vertical lines connect resonances found in $\sigma_R$ with resonances (solid lines) deduced from the $\alpha$ channel and with structures which were originally not assigned to be resonances (Ref. 4) (dashed lines). Note the different scales for $\sigma_R$ (left scale) and the angle integrated cross sections of the $\alpha$-particle channel (right scale).

TABLE I. Resonance energies deduced from $\sigma_R$ (first and sixth column). Columns 2–5 and 7–8 indicate ($R$) if the resonances have been found already in particular reaction channels. The following references have been used for this compilation: $\alpha$ channel, Refs. 1, 4, 6, 7; $^8Be + ^{16}O$ channel, Refs. 8, 9; elastic channel, Refs. 10, 11; $(^{12}C, \gamma)$ channel, Ref. 12.

| $E_{res}$ (MeV) | $\alpha + ^{20}Ne$ | $^8Be + ^{16}O$ | elastic | $(^{12}C, \gamma)$ | $E_{res}$ (MeV) | $\alpha + ^{20}Ne$ | $^8Be + ^{16}O$ |
|---|---|---|---|---|---|---|---|
| 5.65 | $R$ | | $R$ | | 9.05 | $R$ | $R$ |
| 5.82 | $R$ | | | | 9.30 | | $R$ |
| 5.93 | $R$ | $R$ | | | 9.66 | | |
| 6.04 | | | $R$ | $R$ | 9.85 | $R$ | |
| 6.25 | $R$ | | | | 10.03 | $R$ | $R$ |
| 6.39 | | $R$ | | | 10.25 | | $R$ |
| | | | | | 10.42 | $R$ | |
| 6.53 | | | | | 10.66 | $R$ | $R$ |
| 6.68 | $R$ | $R$ | $R$ | $R$ | 10.83 | $R$ | $R$ |
| 6.87 | $R$ | | $R$ | | 10.96 | | |
| 7.72 | $R$ | | $R$ | $R$ | 11.39 | $R$ | $R$ |
| 7.82 | $R$ | $R$ | | | 11.65 | | |
| 8.26 | $R$ | | | | 12.16 | | |
| 8.48 | $R$ | | $R$ | | 12.31 | | |
| 8.87 | $R$ | | $R$ | | | | |

not all of the structures which exist in the $\alpha$ channel have been attributed to resonances in our earlier work due to rather severe resonance criteria. In any case, it is interesting to note that all resonances found in the $\alpha$ channel show up in $\sigma_R$ as well.

The absolute height of $\sigma_R$ is in good agreement with the results of Patterson *et al.*,[5] who have determined $\sigma_R$ from the measured yield of light particles. This can be interpreted as additional support for the validity of the SOD method applied in this work.

In Table I we have listed all resonances showing up in $\sigma_R$. In addition, it is indicated in which reaction channels these resonances have already been found. Table I shows that the majority of the resonances has been known already. New resonances exist at $E_{c.m.} = 6.53$, 9.66, 11.65, 12.16, and 12.31 MeV.

In conclusion, we find that the total reaction cross section for $^{12}C + ^{12}C$ deduced from elastic scattering data exhibits pronounced resonance structures, most of which are already known from investigations of different reaction channels. Thus the total reaction cross section seems to be well suited for an unambiguous determination of quasimolecular resonances in heavy ion reactions. Moreover, comparison with OM calculations and already existing $\sigma_R$ values[5] shows that the cross sections determined with the aid of the SOD method are rather reliable. This offers a unique possibility for the determination of partial widths for these resonances.

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