Entrance-Channel Resonance Effects in the $^{24}Mg + ^{16}O$ Reaction

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Backward-angle cross sections for the reactions $^{24}Mg(^{16}O, ^{12}C)^{28}Si$(g.s.; 1.78 MeV) and $^{24}Mg(^{16}O, ^{16}O)^{24}Mg$(g.s.; 1.37 MeV) were obtained for 17 MeV $\leq E_{c.m.} \leq$ 31 MeV, $\bar{\theta}_{c.m.} \simeq 176°$. The first reaction shows gross and fine resonant structures; the second shows mainly gross structures. Angular distribution measurements give L values of 15 and 21, respectively, at $E_{c.m.}$ = 21.6 and 28.0 MeV. The resonant gross structures for $^{24}Mg(^{16}O, ^{12}C)^{28}Si$(g.s.) are governed by the entrance channel and are discussed from the shape-resonance point of view.

Recently, oscillatory behavior in the elastic and inelastic scattering excitation functions have been observed for the systems[1,2] $^{16}O + ^{28}Si$ and $^{12}C + ^{28}Si$ and for other systems such as ^{12}C on ^{32}S[3,4] and ^{24}Mg.[3] Though some theoretical efforts[5] have been made to explain the energy-dependent oscillatory structures of elastic scattering, no exact theory is established yet.

The ($^{16}O, ^{12}C$) reaction is a good candidate to investigate resonances for heavier systems since $L_i \approx L_f$ due to the small Q value and the similar reduced mass for entrance and exit channels. Moreover, this reaction may proceed in the second stage of the doorway process with α exchange[6] and thus it may be a suitable reaction for observing intermediate structures. For systems like $^{24}Mg(^{16}O, ^{12}C)^{28}Si$, the question arises whether gross structures at backward[7] and forward angles[8] are due to entrance- or exit-channel effects. To study this subject, we have extended our earlier measurements on the $^{16}O + ^{24}Mg$ system[7] studying elastic, inelastic, and ($^{16}O, ^{12}C$) backward-angle cross sections.

The ^{24}Mg beam from the Strasbourg MP Van de Graaff accelerator was used to bombard Ta_2O_5 (~ 80 $\mu g/cm^2$) self-supporting targets. The recoiling ^{16}O and ^{12}C were detected in a ΔE ionization chamber and a Si E detector at 0° to the beam direction. The direct beam was stopped before reaching the detectors, and particles were accepted within an annular solid angle of 6.23 msr ($0.97° \leq \theta_{lab} \leq 2.83°$). The ^{24}Mg diffused particles were stopped in an absorber system (Ni foil + Ar gas) whose thickness could be varied to suit the incident energy. The experimental resolution clearly allows the separation of the studied lines. Cross sections were evaluated by means of the Rutherford-scattered ^{24}Mg from Ta detected in a monitor counter at $\theta_{lab} = 55°$. This yields an absolute uncertainty of ~ 15%. The constancy of the Ta/O ratio was checked by detecting at forward angles the scattered ^{24}Mg from both Ta and ^{16}O. In addition, the target thickness was measured by α-particle energy loss. No noticeable thickness change was observed after the experiments. Slight carbon buildup does not affect the reported measurements due to the lower Q value for the $^{24}Mg + ^{12}C$ reaction. To measure angular distributions, we used a position-sensitive Si detector combined with an ionization chamber. This system distinguished easily between α, ^{12}C, and ^{16}O. Over the measured range (5.5°–42°) the resolution was better than 0.3°. The scattered ^{24}Mg particles were stopped in a Ni absorber.

The excitation functions of the $^{24}Mg + ^{16}O$ reaction are shown in Fig. 1 for the ^{28}Si(g.s.; 1.78

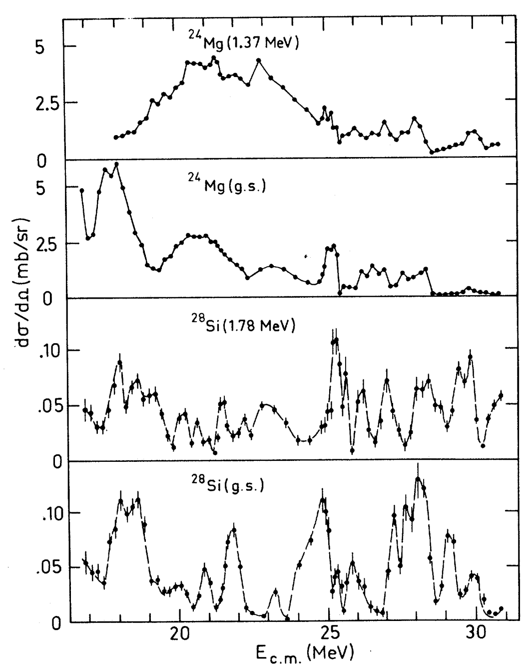

FIG. 1. Excitation functions at $\bar{\theta}_{c.m.} \simeq 176°$ for $^{24}Mg(^{16}O, ^{16}O)^{24}Mg$ (1.37 MeV) (upper part), ^{24}Mg(g.s.) (second part), $^{24}Mg(^{16}O, ^{12}C)^{28}Si$ (1.78 MeV) (third part), and ^{28}Si(g.s.) (lower part). The lines are guides for the eyes. Statistical errors, if not drawn, are smaller than the point size.

MeV) + ^{12}C channels and for the elastic and inelastic ^{24}Mg(g.s.; 1.37 MeV) + ^{16}O channels in the energy range $E_{c.m.}$ = 17–31 MeV. The chosen angular range (175° ≲ $\theta_{c.m.}$ ≲ 178°) for the excitation-function measurement minimizes the effect due to the energy-dependent position of extrema in the angular distributions taking into account the largest L value encountered (L = 21). The elastic and inelastic excitation functions are dominated by broad structures having cross sections about 50 times larger than those of the ^{12}C channels. The number of broad structures for the elastic channel is about half the number of L grazing values ($L_{gr} = 10\hbar - 22\hbar$). The ^{12}C channels also exhibit broad structures superimposed on narrow ones as was seen in the elastic channel of the ^{12}C + ^{28}Si system.[1] The lack of narrow structures in the ^{16}O + ^{28}Si elastic- and inelastic-scattering excitation functions has been discussed in Ref. 1 to be due to greater oxygen target thickness. However, we also found strong narrow structures mainly for the ^{12}C channels, although the target thickness is the same for both ^{16}O and ^{12}C channels. The elastic, inelastic, and ^{28}Si(1.78 MeV) channels show a strong resonance at $E_{c.m.}$ = 25.2 MeV (Fig. 1) with a 1-MeV width. This resonance was also observed at $\theta_{c.m.}$ = 58°, 82°, and 109° in the ^{24}Mg(1.37 MeV) inelastic channel,[9] and in the ^{12}C + ^{28}Si(g.s.; 1.78 MeV) channels[8] at forward angles.

Angular distributions for the ^{28}Si(0$^+$, g.s.) and ^{28}Si(2$^+$, 1.78 MeV) channels are shown in Fig. 2 at indicated c.m. energies. At $E_{c.m.}$ of 21.6 and 28.0 MeV the fitted curves are obtained, respectively, for L = 15 and L = 21. Note that for the ground state and the excited state satisfactory fits are obtained for the same single L values. Best fits are obtained for three odd adjacent L values but still centered around the dominant values of 15 and 21 (not shown in Fig. 2). At off-resonance, $E_{c.m.}$ = 22.4 MeV, the angular distributions are quite different compared to that at $E_{c.m.}$ = 21.6

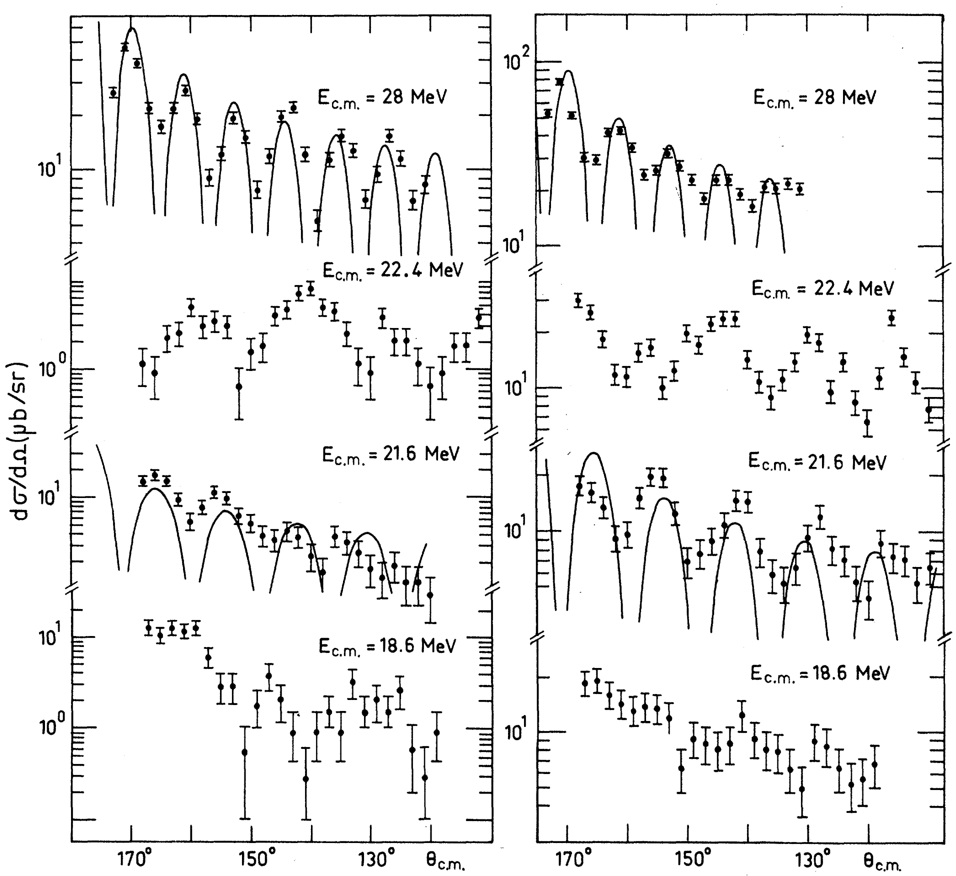

FIG. 2. Angular distributions for ^{24}Mg(^{16}O, ^{12}C) ^{28}Si(0$^+$, g.s.) (left curves) and ^{28}Si(2$^+$, 1.78 MeV) (right curves). The lines shown are the fits obtained for $|P_L(\cos\theta)|^2$ functions with L = 15 and 21 at $E_{c.m.}$ = 21.6 and 28.0 MeV, respectively.

MeV. The angular distributions at $E_{c.m.}=18.6$ MeV do not show pronounced oscillations because of the Coulomb barrier effect in the entrance channel.

Possible interpretations of these broad resonances can be considered from the shape-resonance point of view.

(a) For heavier systems ($A>32$) studied until now, the number of structures usually is about half of the number of L_{gr} values occurring in the energy range $17 \lesssim E_{c.m.} \lesssim 35$ MeV. With the assumption that the resonant structures are due to shape resonances with a single L, this feature requires the real or imaginary part of the optical potential to be strongly parity dependent.[5,11]

(b) Recently it has been emphasized[12] that the complex phase shifts have the parity dependency $\delta_{L-1} \simeq \delta_{L+1}$ in the case of large V and R real optical parameters as may be the case for heavy-ion reactions. Combining this result and the fact that $P_L \sim \frac{1}{2}(P_{L-1}+P_{L+1})$ for large L and backward angles, the angular distribution at a resonance energy fitted by $|P_L(\cos\theta)|^2$ with only one L can be fitted as well using two $L-1$ and $L+1$ values. This L-group resonance consideration may also explain why the number of resonant structures is different from that of L_{gr} values without missing any particular L value.

Several features show that the angular momentum states for the resonant gross structures appearing in the reaction $^{24}Mg(^{16}O,{}^{12}C)^{28}Si$ are rather governed by the entrance channel.

(a) The long-dashed lines in Figs. 3(b), 3(c1), and 3(d) show, respectively, the measured excitation functions of the reactions $^{16}O+{}^{24}Mg \rightarrow {}^{24}Mg$(g.s.)$+{}^{16}O$, $^{16}O+{}^{24}Mg \rightarrow {}^{28}Si$(g.s.)$+{}^{12}C$, and $^{12}C+{}^{28}Si \rightarrow {}^{28}Si$(g.s.)$+{}^{12}C$ (from Ref. 1). The relevant cross sections are, respectively, labeled by σ_α, σ_β, and σ_γ. A channel correlation-function analysis in which the cross sections were interpolated in steps of 10 keV yields $C(\alpha,\beta)=(\langle\sigma_\alpha\sigma_\beta\rangle/\langle\sigma_\alpha\rangle \times\langle\sigma_\beta\rangle)-1=0.181$ and $C(\beta,\gamma)=0.05$. To eliminate fine-structure effects, we performed this analysis for averaged cross sections with a sliding interval width $\Delta=1$ MeV: $\sigma_\Delta=\Delta^{-1}\int_{\epsilon-\Delta}^{\epsilon+\Delta}\sigma d\epsilon$. In this way, $\overline{C}(\alpha,\beta)_\Delta=0.183$ and $\overline{C}(\beta,\gamma)_\Delta=0.07$. We conclude that most of the correlation comes from the gross structures and that fine-structure effects are very small. As $C(\alpha,\beta)>C(\beta,\gamma)$ the resonant gross structures in $^{24}Mg(^{16}O,{}^{12}C)^{28}Si(0^+$, g.s.) are rather correlated with those of the entrance channel.

(b) In Fig. 3(a), known experimental dominant L values are represented at the corresponding

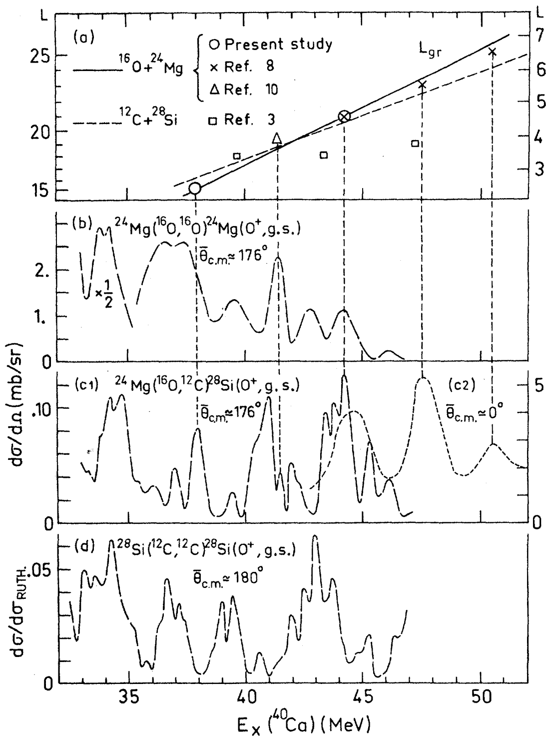

FIG. 3. (a) Energy dependence of L_{gr} in the entrance channel (solid line) for $^{24}Mg(^{16}O,{}^{12}C)^{28}Si$(g.s.) using Pot.II of Ref. 9. The dashed line for the exit channel is taken from Ref. 1. Experimentally determined L values are shown. Excitation curves in terms of ^{40}Ca energies are compared from present work (b), (c1), from Ref. 8 (c2), and from Ref. 1 (d). An ^{16}O beam was used for (c2) while ^{24}Mg and ^{28}Si beams were used for the other curves ($\theta_{lab} \simeq 0°$ for all cases).

energies. The line of L_{gr} in the entrance channel was calculated by using optical-potential parameters of Pot. II in Ref. 9 and that in the exit channel was taken from Ref. 1. The dominant L values for $^{24}Mg(^{16}O,{}^{12}C)^{28}Si$ at the resonance energies are close to the calculated L_{gr} lines. On the contrary, the series of resonant structures observed in the $^{12}C+{}^{28}Si$ system for the elastic scattering does not follow the $L(L+1)$ sequence and shows L_{res} values much less than the L_{gr} ones.[3] Furthermore, in the present work, a $^{24}Mg(^{16}O,{}^{16}O)^{24}Mg(0^+$, g.s.) angular distribution was obtained at $E_{c.m.}=28.0$ MeV in the angular range $170° \geqslant \theta_{c.m.} \geqslant 150°$ and the location of the minima is consistent with $L=21$ as obtained in the ^{12}C exit channel and calculated for L_{gr}.

It is of interest to know if the resonant structures observed in the reaction $^{24}Mg(^{16}O,{}^{12}C)^{28}Si$ at forward and backward angles have the same physical origin. As an example we take the gross structures at $E_x(^{40}\mathrm{Ca}) = 44.2$ MeV overlapping in backward (present work) and forward[8] measurements [Figs. 3(c1) and 3(c2)]. The same $L = 21$ value was found in both cases but with different absolute cross sections. The differential cross section is written as $\sigma(\theta) = |f_{\mathrm{dir}} + f_{\mathrm{res}}|^2$. From the background in Fig. 3(c2) we estimate $|f_{\mathrm{dir}}(0°)|^2 \sim 2$ mb/sr. The value $|f_{\mathrm{res}}(176°)|^2 \sim 0.1$ mb/sr taken from Fig. 3(c1) and the $L = 21$ dominant L value allows as to extrapolate 0.4 mb/sr $\sim |f_{\mathrm{res}}(180°)|^2 = |f_{\mathrm{res}}(0°)|^2$. Then $\sigma(0°) \sim 4$ mb/sr which is consistent with the measured value of Ref. 8 and indicates a common origin for these gross structures.

The width of the structures appearing in the ^{12}C channels are nearly equal to the energy loss of the ^{24}Mg beam in the Ta_2O_5 target. At present, it is hard to make a conclusion as to whether they are intermediate structures or compound states in ^{40}Ca.

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Narrow $I^\pi = 10^+$ Resonance for $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ in the Region of Strong Absorption

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A 10^+ resonance with a width of about 700 keV (c.m.) for $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ has been observed in the reaction $^{12}\mathrm{C}(^{16}\mathrm{O}, {}^{8}\mathrm{Be}_{\mathrm{g.s.}})^{20}\mathrm{Ne}$ at $E_{\mathrm{c.m.}} = 18.8$ MeV leading to the ground state and several excited states in ^{20}Ne. The spin value of $I = 10$ is four units of angular momentum below the grazing value of $l = 14$ obtained from elastic scattering, and is still two units below the strong-absorption l value obtained from $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ total fusion cross sections.

The $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ system has been under intense study throughout recent years and various resonances have been reported.[1] For some of these structures spin values were assigned and found to be close to the grazing angular momentum in the entrance channels. This has lead to the assumption of surface transparent complex potentials.

In this Letter for the first time evidence is reported that the concept of surface transparency probably needs to be extended even farther into the nuclear interior: The novel phenomenon observed is a *narrow* resonance ($\Gamma_{\mathrm{c.m.}} \approx 700$ keV) for $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ with a spin value four units below the grazing l value of the entrance channel and well inside the region where strong absorption