Transparency to the $l=9$ Partial Wave in the Region of the 14.7-MeV Resonance in $^{12}C+^{16}O$

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A comparison of elastic scattering and total reaction cross-section data in the region of the 9^-, 14.7-MeV resonance in $^{16}O+^{12}C$ is presented. The comparison provides firm evidence that there is very little background absorption of the $l=9$ partial wave. The implications are discussed. A partial-width decomposition of the resonance is made.

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A partial-width analysis of a resonance is very valuable, since it provides direct information about the wave function of the resonant state. However, a simple partial-width decomposition, such as that carried out by Malmin *et al.*[1] for resonances in $^{16}O+^{12}C$, is only valid if the resonance may be regarded as a single level. This requires that there is no significant mixing with underlying levels of the same spin and parity. From the available evidence this would seem to be unlikely for above-the-barrier resonances in $^{16}O+^{12}C$, since the observed spins[2,3] usually are below the grazing angular momentum (defined as the l value which is 50% absorbed) given by the optical model and, in fact, many resonances have spins below the strong absorption limit obtained[2] from a sharp-cutoff model applied to total fusion cross-section data. The extent to which a resonance is mixed with underlying "background" states may be investigated by comparing elastic-scattering and total reaction cross-section data in the region of the resonance. If the fine structure due to the background states is averaged out, the collision matrix element for elastic scattering may be written[4]

$$S_{cc}=\exp(2i\xi_c)\left[\exp(-2\mu_0)+\frac{i\Gamma_c\exp(2i\varphi_c{}^R)}{E_R-E-\frac{1}{2}i\Gamma}\right], \quad (1)$$

where $\exp(2i\xi_c)\exp(-2\mu_c)$ is the contribution from the energy-averaged background and $\varphi_c{}^R$ is the resonance mixing phase. The contribution to the total reaction cross section from S_{cc} is obtained from the transmission coefficient $T_c=1-|S_{cc}|^2$, i.e.,

$$T_c=1-e^{-4\mu_c}+\frac{B_c(E_R-E)+C_c\Gamma_c}{(E_R-E)^2+\frac{1}{4}\Gamma^2}, \quad (2)$$

where

$$B_c=2\Gamma_c\sin 2\varphi_c{}^R\exp(-2\mu_c),$$

and

$$C_c=\Gamma\cos 2\varphi_c{}^R\exp(-2\mu_c)-\Gamma_c.$$

The resonant contribution to the total reaction cross section is sharply reduced in the presence of strong background absorption because the entrance-channel flux must be shared between the resonance and the background states in such a way that unitarity is not violated. There is little effect on the size of the anomaly observed in the elastic scattering, however. In the event that there is no background absorption, $\varphi_c{}^R$ becomes zero and $\exp(-2\mu_c)$ becomes unity. In such a case Eq. (2) reduces to the single-level formula. We note that Eq. (1) is not strictly appropriate for the case of heavy-ion resonances in $^{16}O+^{12}C$, since there is not enough difference between the resonance widths and fluctuation widths to allow us to average out the statistical fluctuations. However, Eq. (1) should describe the average behavior in the region of the resonance.

We have chosen to study the 14.7-MeV resonance in $^{16}O+^{12}C$ because it was shown by Taras *et al.*[5] to produce a measurably large effect in the total fusion cross section, and because a very convincing $J^\pi=9^-$ assignment is available from the work of Soga *et al.*[6]

All measurements were made with ^{16}O beams from the Florida State University super FN tandem Van de Graaff accelerator. Targets of ~20 $\mu g/cm^2$ (~60 keV c.m.) natural carbon were used for all excitation-function measurements. The overall cross-section normalization was obtained by measuring the yield of elastically scattered ^{16}O at $\theta_{1ab}=15°$ and $E_L(^{16}O)=20$ MeV and comparing with the calculated Rutherford scattering cross section. Absolute cross sections are believed accurate to ±10%. In the energy region of interest here, the total-reaction cross section is given by the sum of the inelastic scattering cross sections and what we will call, for convenience, the "fusion" cross section. The fusion measurements were made using a time-of-flight system consisting of a 450-mm^2 surface barrier detector separated by 2.7 m from a channel-plate start detector. A time resolution of about 450 psec was obtained, allowing complete separation of the residual mass groups. Yield curves were measured at $\theta_L = 8°$ from $E_L(^{16}O) = 32.6$ MeV to 35.3 MeV in steps of 200 and 150 keV. Figure 1 shows a comparison of various measurements of the total fusion yield at 8°. Angular distributions were measured between 3° and 25° at $E_L(^{16}O) = 33.2$, 33.65, 33.95, 34.4, 34.85, and 35.3 MeV. These give, for each residual mass, the energy dependence of the ratio of the 8° yield to the integrated cross section. Figure 2 shows the resulting total cross sections for all residual mass groups ($A > 16$) having observable yields. The overall cross-section normalization and the trend of the gross structure in the total fusion cross section are in very good agreement with the results of Sperr *et al.*[7] Significant inelastic-scattering yields were observed only to the 4.43-MeV state in ^{12}C and the doublets at 6 and 7 MeV in ^{16}O. Partial angular distributions were measured from $E_L(^{16}O) = 33.2$ MeV to 35.2 MeV in steps of 200 keV. The angular range 90°–160° c.m. was covered by detecting ^{12}C recoil groups. The integrated cross sections are shown in Fig. 2. The resonant contribution to the total reaction cross section was estimated to be ~2.5 mb by doubling the resonant contribution at back angles.

A single elastic-scattering angular distribution was measured at $E_L(^{16}O) = 33$ MeV with a target of ~75 $\mu g/cm^2$ thickness (~230 keV c.m.) and this is shown in Fig. 3(a) along with a typical optical-model fit (solid curve) employing a standard Woods-Saxon potential. All optical-model fits gave transmission coefficients of 80–87% for the $l = 9$ partial wave, and gave a grazing l value of a little less than 11. The optical-model parameters of Malmin *et al.*[1] reproduce the angular distribution reasonably well and give very similar transmission coefficients. Shown in Fig. 3(b) are elastic-scattering excitation functions measured at five c.m. angles from 58.3° to 79° and from $E_L(^{16}O) = 33.2$ to 35.2 MeV in steps of 200 keV. A 9^- resonance was added to the optical-model background, with the result shown as a solid curve in Fig. 3(b). The resonance energy and width were taken to be 14.7 MeV and 280 keV, respectively, from the reaction data. The values

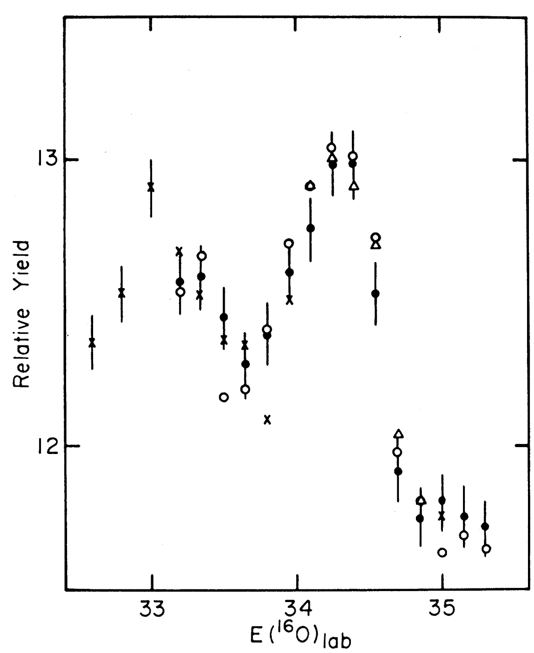

FIG. 1. Comparison of various measurements of the total fusion excitation function at 8°. Separate measurements are distinguished by the use of different symbols for the data points. The error bars shown are typical statistical errors and are less than 1%.

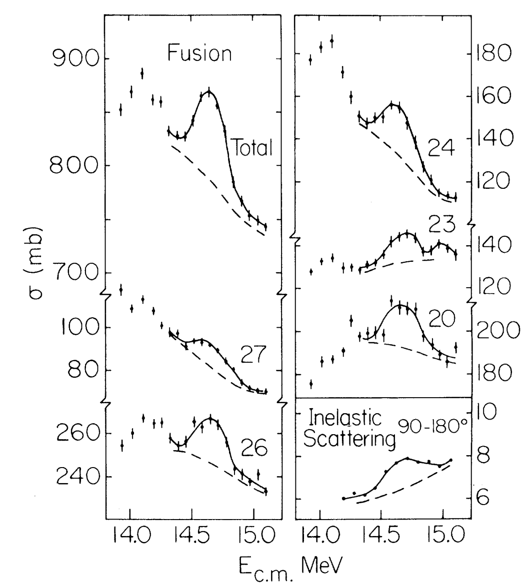

FIG. 2. Fusion cross sections for $^{16}O + ^{12}C$ together with the total inelastic-scattering cross section integrated from 90° to 180° c.m. The dashed curves indicate the assumed nonresonant background. The solid curves are merely guides to the eye. Data are plotted at c.m. energies corrected to the center of the target.

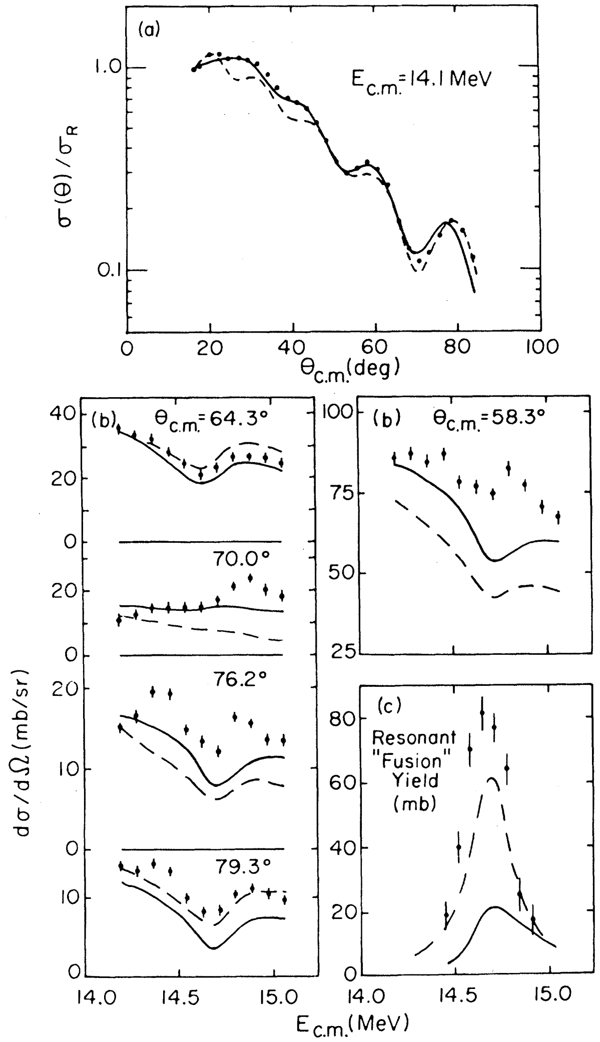

FIG. 3. The solid and dashed curves are discussed in the text. (a) "Off-resonance" angular distribution. (b) Elastic-scattering excitation functions with the c.m. angles indicated. (c) Net yields obtained by subtracting nonresonant backgrounds from the total fusion cross section and the integrated inelastic scattering cross section.

of Γ_c/Γ and $\varphi_c{}^R$ were optimized by eye and found to be 0.18 and −25°, respectively. Similar values were obtained when the other optical-model parameter sets were used, and when the parameter set (set 1) of Malmin *et al.*[1] was used. When the smooth background (dashed curve in Fig. 2) is subtracted from the total "fusion" and total inelastic cross sections of Fig. 2, we obtain the resonant part of the total reaction cross section shown in Fig. 3(c). The solid curve in Fig. 3(c) is the resonant cross section obtained by subtracting a smooth background from the total reaction cross sections predicted by the optical-model-plus-resonance calculation. Clearly, the agreement is very poor. However, we note that if the $l=9$ background absorption were zero, a value of Γ_c/Γ of 0.18 would give a resonant reaction cross section of $\sigma_R = 70$ mb, close to the observed value of 82 mb. We note further that with background transmission coefficients as large as those obtained from the optical model, there is *no* set of resonance parameters which could give a value of σ_R comparable with that observed.

Since all partial waves up to $l=8$ are almost completely absorbed in our optical-model calculations, attempts to make the absorption for the $l=9$ partial wave small by varying the well parameters simply result in grossly insufficient total absorption. The absorption for the $l=9$ partial wave may only be decreased if the absorption is increased for some higher partial wave or waves. Some complicated l-dependent absorption effect is implied, and more data will be needed before it can be defined.

A fit was made to the elastic-scattering angular distribution in which the $l=9$ collison matrix element was constrained to have a predetermined value, while those for all other l values were derived from a standard Woods-Saxon optical potential. The $l=9$ collision matrix element was determined by setting $\exp(-2\mu_c)=1$ and choosing a zero mixing phase. The phase $\xi_c = \omega_c - 27°$ was found to reproduce best the shapes of the resonance anomalies in the elastic scattering yields. It is worth noting that this is the value of ξ_c which is characteristic of a background composed entirely of Coulomb and hard-sphere scattering effects for a channel radius of 7.2 fm. The fit to the angular distribution is shown as a dashed curve in Fig. 3(a), and the corresponding calculations with a resonance added are shown similarly in Figs. 3(b) and 3(c). Again the value of Γ_c/Γ was optimized by eye, and a value of 0.15 was obtained. The prediction of σ_R, at 75% of the observed value, is much more satisfactory.

These results illustrate clearly that the elastic-scattering and total-reaction cross-section data can be reconciled only if the background absorption for $l=9$ is quite small.

We have made a partial-width decomposition of the 14.7-MeV resonance based on this conclusion. From the measured resonant reaction cross section of 82 mb, we obtain $\Gamma_{el}/\Gamma = 0.22$. The results for the various residual-mass groups are presented in Table I. The nonresonant backgrounds which were assumed are shown in Fig. 2.

TABLE I. Resonant cross sections and partial widths.

	Elastic	Inelastic	Mass 20	23	24	26	27
σ_R	...	2	19	12	22	20	9
Γ_c/Γ	0.22	0.02	0.18	0.11	0.20	0.19	0.08

Finally, we emphasize that our result for the 14.7-MeV resonance is by no means a guarantee that background absorption is small for above-the-barrier heavy-ion resonances in general. As we pointed out earlier, a substantial decrease in the large $l=9$ absorption given by the optical model requires a compensating *increase* in absorption for higher l values, as otherwise the overall absorption becomes much weaker than the data will allow. Therefore, the evidence favors l-selective transparency. Chan *et al.*[8] have suggested parity-dependent absorption as a possible explanation of the oscillations in the $^{16}O + ^{12}C$ fusion cross section. This will be tested very effectively by experiments of the type described here.

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Determination of the Electric Quadrupole Moment of ^{7}Li by Coulomb Scattering of an Aligned ^{7}Li Ions

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The electric quadrupole moment of ^{7}Li was determined by Coulomb scattering of aligned ^{7}Li ions to be $Q = (-34 \pm 6)\ e \cdot$mb. This compares favorably with the value $Q = (-41 \pm 6)\ e \cdot$mb determined by atomic-beam spectroscopy.

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The first suggestion to determine the electric quadrupole moment of a strongly deformed nucleus by nuclear physics methods was to look for deviations from the Rutherford cross section.[1] However, for unpolarized projectiles or targets the deviation from pure Rutherford scattering is due to only a second-order term in the quadrupole moment[2] and is therefore very small. For

