sociated fission channels. These points are intimately related to shell structure and nuclear stability of the heavy elements.

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Intermediate-Structure Effects in the Reaction $^{12}C(^{16}O, ^{20}Ne)^{8}Be$

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We have measured the angular distributions of the reaction $^{12}C(^{16}O, ^{20}Ne)^{8}Be$ in the c.m. energy range 12.22 to 15.07 MeV. The data and analysis, indicate a broad ($\Gamma_1 \simeq 650$ keV) $L=8$ resonancelike structure centered at $E_1 \simeq 13.15$ MeV. The severe damping of the $L=8$ structure of the angular distribution and the deep minimum in the integrated cross section at $E_2 \simeq 13.7$ MeV appear to be due to interference between the broad resonance at E_1 and a narrow ($\Gamma_2 \simeq 100$ keV) $L=8$ resonance at E_2. This interpretation is consistent with two-level R-matrix fits.

Heavy-ion interactions offer a powerful tool for investigating intermediate nuclear structure in that the various stages of interaction (doorways, etc.) leading to compound-nucleus formation are quite different as compared to the nucleon-nucleus case. In addition, since strong absorption is an important feature, only a few $L \simeq L$(grazing) may be important at each energy and the effect of an intermediate structure of appropriate L more apparent.

The $^{16}O + ^{12}C$ interaction has been extensively studied in both elastic and reaction channels in recent years. A number of interesting features have been uncovered.[1] One of the most prominent anomalies is near 13.7 MeV c.m. system, where Halbert, Durham, and van der Woude[2] first observed a nonstatistical enhancement in the $^{24}Mg + \alpha$ channel. The differential elastic cross section at most angles exhibited[3-5] narrow ($\simeq 100$ keV) dips near 13.7 MeV. Additional study of the $^{24}Mg + \alpha$ channel[6] showed evidence for a narrow ($\simeq 70$ keV) nonstatistical enhancement at 13.7 MeV, and a spin of $J=9$ or 10 was suggested largely on the basis of grazing angular momentum arguments. In a study of the $^{20}Ne + ^{8}Be$ channel (ground states) Viggars *et al.*[7] observed anomalous behavior in both the angular distribution and excitation function at 13.7 MeV and a diffraction-model analysis indicated that the $L=9$ partial wave is strongly absorbed at this energy.

In a present work additional angular distributions of the reaction $^{12}C(^{16}O, ^{20}Ne)^{8}Be$ (ground states) have been measured in the c.m. energy range 12.25 to 15.07 MeV and an analysis carried out which includes these and the earlier data.[7] The importance of the present work is that the data and analysis indicate (a) the presence of a broad ($\Gamma_1 \simeq 650$ keV) $L=8$ resonancelike structure centered at $E_1 \simeq 13.15$ MeV, and (b) severe damping of the $L=8$ angular distribution and the deep minimum observed in the total $^{20}Ne+{}^{8}Be$ channel cross section near 13.7 MeV appear to be due to interference between the broad resonance at E_1 and a narrow ($\Gamma_2 \simeq 100$ keV) resonance at $E_2 \simeq 13.7$ MeV. The latter, on this basis, would be assigned $J^\pi = 8^+$ as well.

Angular distributions were measured using beams of ^{16}O ions from the Harwell tandem Van de Graaff to bombard ^{12}C foils, nominally 10 μg/cm^2. The momentum-to-charge ratio and energy of the ^{20}Ne ions were measured in a Buechner magnetic spectrometer using position-sensitive solid-state detectors mounted in the focal plane of the magnet. These measurements allow positive mass identification and momentum measurements[8] yielding energy resolutions to better than 1%. A fixed detector monitored the carbon content of the target. Absolute cross sections have been obtained from normalization to elastic values.

Four angular distributions are shown in Fig. 1. Besides the point-to-point (largely statistical) uncertainties shown, there are absolute normalization uncertainties of 30, 20, 15, and 20% at 12.92, 13.17, 13.37, and 13.75 MeV, respectively. The three angular distributions in the neighborhood of E_1 (upper three panels of Fig. 1) exhibit a strong diffraction pattern dominated by $L=8$. Distorted-wave Born-approximation (DWBA) calculations using the program LOLA[9] do not predict the shape or magnitude of these three distributions or their energy variation. Optical-model parameters of Refs. 4 and 5 and a considerable variation of these and of the bound-state radii were tried. Spectroscopic factors several times theoretical estimates[10] are required to match the absolute magnitude of the cross sections. Compound-nucleus-model predictions based on parameters which fit related compound-nucleus (CN) data are nearly an order of magnitude too small,[11] and the width, Γ_1, is about 5 times larger than the mean coherence width in this energy range.[2]

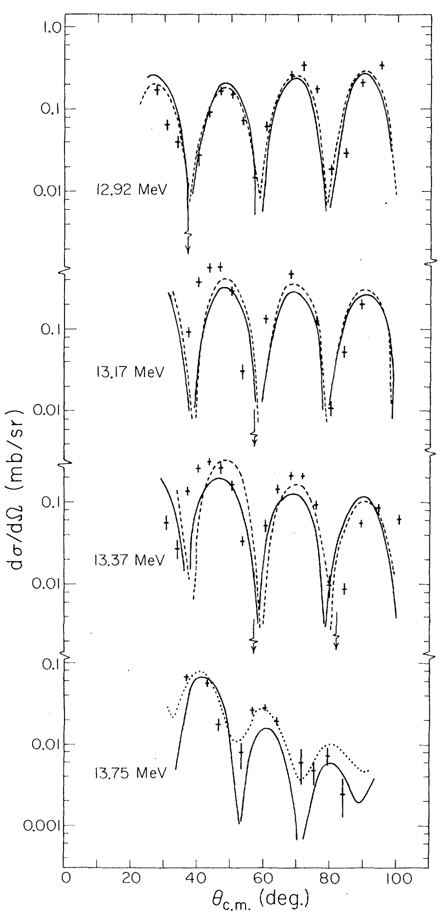

FIG. 1. Angular distributions and DWBA fits. The dashed curves are given by fit A, the solid by fit B, and the dotted by fit C of Table I.

Reasonable fits to the three angular distributions near E_1 and their energy variation can be obtained by adding a Breit-Wigner (BW) resonance amplitude to the DWBA $L=8$ amplitude as calculated in LOLA:

$$A_8 = A_8(\text{DWBA}) + G/(E_1 - E - i\Gamma_1/2). \qquad (1)$$

The parameters of this broad $L=8$ resonancelike structure can be estimated from the experimental excitation functions shown in Fig. 2. These were

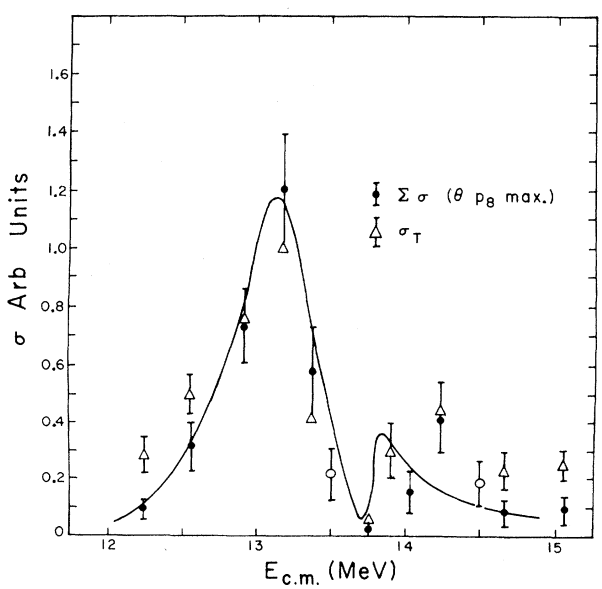

FIG. 2. Prediction of two-level R-matrix theory compared to excitation-function data of the $^{20}Ne+{}^{8}Be$ channel.

TABLE I. The optical-model parameters used in the fits A, B, and C of Fig. 1. The interaction radii are $r_0(A_1^{1/3}+A_2^{1/3})$ and the bound-state radii are $r_0 A_c^{1/3}$.

	Volume real			Volume imaginary			Bound state		Coulomb
Fit	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0 (fm)	a (fm)	r_0 (fm)	a (fm)	r_0 (fm)
A^{a}	−13	1.25	0.55	−3	1.25	0.55	1.22	0.55	1.25
B^{b}	−15	1.30	0.55	−5	1.20	0.55	1.28	0.55	1.30
C^{c}	−15	1.30	0.55	−6	1.25	0.55	1.28	0.55	1.30

[a]Dashed line. [b]Solid line. [c]Dotted line.

obtained in one case (denoted σ_T) by fitting the measured angular distributions with a sum of Legendre functions and obtaining from this fit an integrated cross section at each energy. In the second case the sum of cross sections measured at angles corresponding to the maxima of $P_8(\cos\theta)$ are plotted. In some cases (open circles) the cross section is based only on the 22° excitation function.[7]

The classic Breit-Wigner (BW) resonance shape with $E_1 \simeq 13.15$ MeV, width $\Gamma_1 \simeq 650$ keV, is modified by (at least) two factors which further analysis points up: The DWBA amplitude interferes with the resonance amplitude. There is apparently a narrow ($\Gamma_2 \simeq 60$–100 keV) $L=8$ resonance at $E_2 \simeq 13.7$ MeV which interferes coherently with the ($L=8$) amplitude of the broad resonance at E_1 (and with the $L=8$ partial-wave DWBA amplitude).

Fits to three angular distributions using the form of Eq. (1) are shown in the upper three panels of Fig. 1. For these fits the absolute ratio σ(expt)/σ(theor) using Eq. (1) is 0.18 ± 0.03. At E_1, the amplitude of the resonance term is ~3.5 times that of the $L=8$ DWBA term of LOLA. Thus, these three fits are not very sensitive to the LOLA amplitudes. The optical-model parameters used are based on those of Ref. 5 and are given in Table I. In order to fit the rising angular distributions at 12.92 MeV, the relative phase of the BW and the ($L=8$) DWBA amplitude must be close to 180° at 12.92 MeV.

In Fig. 2 the solid line shows a prediction for the total cross section, $\sigma_{cc'}$, derived from the two-level formula of R-matrix theory.[12] The parameters, in the notation of Ref. 12, are given in Table II. Channel c is $^{16}O + ^{12}C$, c' is $^{20}Ne + ^{8}Be$ (ground states), c'' represents $^{24}Mg + \alpha$ channels, and c''' other channels. Unfortunately few data are available for most of the open channels; so a unique set of parameters cannot be determined. However, some investigation showed that the calculated $\sigma_{cc'}$ depend largely on the parameters E_λ and Γ_λ ($\lambda = 1, 2$), on the ratio $(\Gamma_{1c}\Gamma_{1c'})^{1/2}/(\Gamma_{2c}\Gamma_{2c'})^{1/2}$, and much less on the partial widths $\Gamma_{\lambda c''}{}^{1/2}$ and $\Gamma_{\lambda c'''}{}^{1/2}$. No contribution from the DWBA amplitude is included in Fig. 2. A calculation assuming many open channels with partial widths of random sign and amplitude gives a curve similar to that shown in Fig. 2 except that an effective background raises the minimum and second maximum about 0.1 units.

The LOLA fits to the 13.75-MeV data, shown in the bottom panel of Fig. 1 give spectroscopic factor products $S^2 = 0.17$ (solid curve) and $S^2 = 0.26$ (dotted curve). [S^2(theor) = 0.16.[10]] These fits must be taken with reservation since appreciable CN contributions are expected, and because the effect of the resultant amplitude from the resonances has been neglected. It was found that the DWBA ($c \to c'$) and the elastic amplitude (from LOLA) interfere destructively at ~E_2 with the resultant (largely E_2) resonance amplitude, possibly

TABLE II. Typical parameters for two-level fits. See the text.

Level	E_λ (MeV)	Γ_λ (keV)	$\Gamma_{\lambda c}{}^{1/2}$ (keV$^{1/2}$)	$\Gamma_{\lambda c'}{}^{1/2}$ (keV$^{1/2}$)	$\Gamma_{\lambda c''}{}^{1/2}$ (keV$^{1/2}$)	$\Gamma_{\lambda c'''}{}^{1/2}$ (keV$^{1/2}$)
$\lambda = 1$	13.15	650	4.6	4.6	−1.0	1.0
$\lambda = 2$	13.75	100	1.4	1.0	1.0	6.0

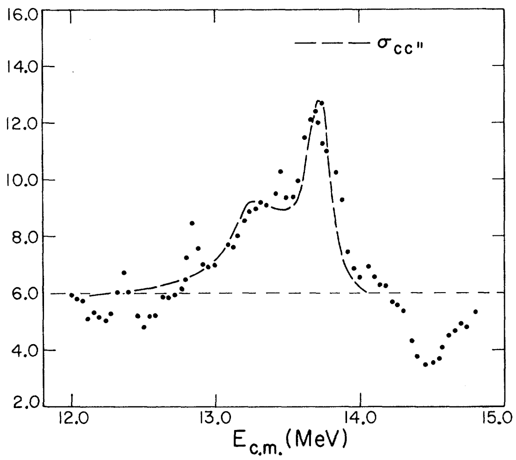

FIG. 3. Prediction of two-level R-matrix theory compared to $^{24}Mg+\alpha$ data (see text).

accounting for the sharp dips seen in the elastic cross section at this energy.[3-5]

An attempt has been made to apply the two-level formula to the $^{24}Mg+\alpha$ data.[2] To smooth the fluctuations, the channel-integrated data were further integrated over the three available angles. The results are plotted in Fig. 3 along with a two-level prediction for $\sigma_{cc''}$ using the parameters of Table II. The fit is certainly suggestive that the picture of interfering resonances is plausible.

In general, the phenomena of interfering (intermediate) resonances may be particularly important in these ion-ion interactions because strong absorption (producing grazing angular momenta) tends to enhance the excitation of states of equal or nearly equal angular momenta in a relatively small energy range.

The form of Eq. (1) is that given in a theory of direct reactions which includes intermediate structure (IS).[13] In the present case of $^{16}O+^{12}C$, a plausible first stage which could produce a doorway IS at E_1 and would be α sharing (exchange) possibly in (deformed) Nilsson *sd* orbitals. (States up to $L=12$ can be constructed in $^{16}O+^{12}C$ using asymptotic *sd* orbitals.[14]) This IS at E_1 may decay back into the elastic channel or via direct reaction into the $^{20}Ne+^{8}Be$ channel, as it appears to do here. Alternatively it may evolve into more complicated states which can decay outward, or inward towards CN formation. There is evidence for enhancement in $^{24}Mg+\alpha$ channels in the averaged data of Ref. 2 and the two-level fit thereof (see Fig. 3 and Table II). At 13.7 MeV (E_2) the reaction appears to excite (or lead to) a more complicated IS which decays strongly into the two-α transfer, $^{24}Mg+\alpha$, channels. The decay amplitude into $^{20}Ne+^{8}Be$ is also appreciable (Table II) and interferes with that due to the IS centered at E_1.

It seems reasonable to conclude that there are intermediate structures, possibly one- and two-α-exchange doorway states, at E_1 and E_2 with $J^\pi=8^+$; and that these are responsible for the anomalous behavior near E_2 in the elastic, α-particle, and ^{8}Be channels.

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