$\psi' \to \psi\eta$, with a branching ratio of $(4.3 \pm 0.8)\%$, and that the ψ' has zero isospin and negative G parity. The decay $\psi' \to \psi\eta$ is suppressed by SU(3) if the ψ and ψ' are both SU(3) singlets, as predicted in the charm model. It has limited phase space since the available kinetic energy is only 40 MeV. To conserve parity it must be a P-wave decay; thus there is an additional angular-momentum-barrier suppression. In light of these considerations, it is surprising to us that the $\psi' \to \psi\eta$ branching ratio is as large as it is.

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[8]The mass differences between $\pi^{\pm}$ and π^0 modify these predictions slightly. If the expected rates are taken as just proportional to available phase space, the predictions become 0.524 for isospin 0 and 2.10 for isospin 2.

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[13]Our result (1) was obtained by assuming that the angular distribution of the muons in

$$\psi' \to \psi + \text{neutrals}, \quad \psi \to \mu^+\mu^-$$

is $1+\cos^2\theta$. For $\psi' \to \psi\eta$, the true distribution is $5-3\times\cos^2\theta$, while for $\psi' \to \psi\gamma\gamma$ we have assumed that the muons are isotropic. The corrected ratio is 0.73 ± 0.09.

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[15]This upper limit was calculated before the $\psi' \to \psi\pi^0\pi^0$ subtraction, and thus does not depend on the π-π isospin assumption.

Oscillations in the Excitation Function for Complete Fusion of $^{16}O + ^{12}C$†

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The total fusion cross section for the $^{16}O + ^{12}C$ system has been measured in the ranges 13 MeV $\le E_{c.m.} \le$ 27 MeV. The cross section is found to increase with bombarding energy up to $E_{c.m.} \approx$ 17 MeV but to stay roughly constant at higher energies, in qualitative agreement with predictions of current models. Superimposed on this average cross-section behavior we observe unexpected oscillations with a period of about 3–4 MeV (c.m. energy).

Fusion cross sections in reactions induced by heavy ions have been measured in recent years for a variety of projectiles, targets, and bombarding energies.[1-3] In reactions between light- and medium-weight nuclei, fusion processes have been found to account for most of the total reaction cross section (σ_{reac}) at energies not too far above the Coulomb barrier.[1,2] In these systems at much higher bombarding energies, however, the fusion cross section (σ_{fus}) constitutes a significantly smaller fraction of σ_{reac}.[3] The energy dependence of σ_{fus} is qualitatively explained by semiclassical models which assume that fusion occurs whenever the projectile and target nuclei reach a certain critical separation.[4-6] However, fusion measurements have not been made over a sufficiently wide energy and mass range to test stringently the predictions of these models. In the present Letter we report measurements of σ_{fus} for the light-mass system $^{16}O + ^{12}C$ at bombarding energies spanning the region where σ_{fus} is predicted to begin to deviate significantly from σ_{reac}. Superimposed on an average energy dependence consistent with calculations of Glas and

Mosel,[4] we observe unexpected oscillations in $\sigma_{fus}(E)$.

The experiment was performed with ^{16}O beams of energies 30 MeV $\leq E_{lab}(^{16}O) \leq 63$ MeV obtained from the Argonne National Laboratory tandem accelerator. Self-supporting ^{12}C targets of 20 $\mu g/cm^2$ (with ^{16}O contamination $\leq 2\%$) were used. Heavy fragments resulting from fusion and subsequent particle evaporation were detected in a conventional ΔE-E silicon surface-barrier detector telescope with a 3.6-μm-thick ΔE detector. Anticoincidence spectra, corresponding to ΔE signals unaccompanied by E signals, were collected at the same time as the coincidence spectra, and contained $\lesssim 2\%$ of the fusion residues.

Data were stored in a two-dimensional (E versus ΔE) matrix. The top inset of Fig. 1 shows a ΔE spectrum corresponding to a narrow E window. The ΔE resolution is sufficient to distinguish isotope groups of different Z. All events identified as isotopes of Ne, Na, Mg, and Al were included in determining the total fusion cross section; very few counts corresponding to F or Si nuclides were observed. Although many low-energy oxygen nuclei were detected, we believe that a negligible fraction of these results from complete fusion since the process $^{28}Si \rightarrow 3\alpha + {}^{16}O$ ($Q = -24$ MeV) is unlikely (the available c.m. energy is insufficient to allow for appreciable α-particle penetration of the Coulomb and centrifugal barriers).

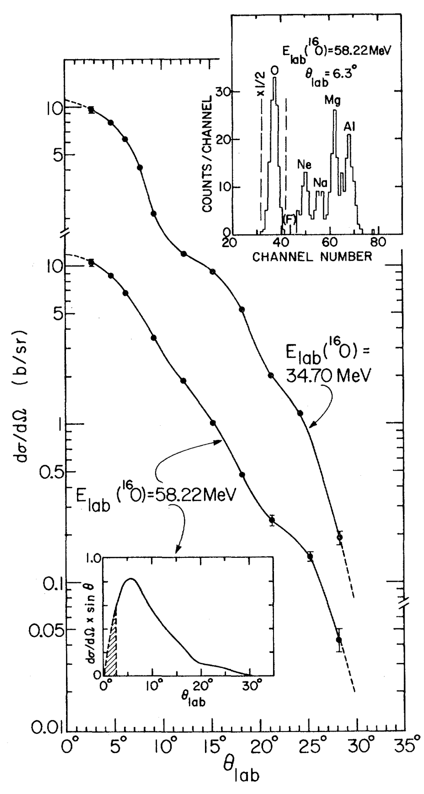

FIG. 1. Angular distributions at $E_{lab} = 34.70$ and 58.22 MeV summed over all outgoing energies and all fusion residues. The top inset shows a ΔE spectrum in coincidence with a narrow window on E. The bottom inset shows $(d\sigma/d\Omega)\sin\theta$ for E_{lab}=58.22 MeV.

While the compound nucleus ^{28}Si is kinematically constrained to emerge from the reaction at 0°, the fusion residues are spread in angle, mainly by their recoil from particle boil-off.[7] In order to determine the total fusion cross section it is necessary to know the angular distribution of the fusion products between 0° and their maximum kinematically allowed laboratory angle (~30° for ^{20}Ne). We have measured angular distributions in the range $\theta_{lab} = 3° - 28°$, relative to the number of elastically scattered particles detected in a monitor counter fixed at $\theta_{lab} = 10°$. The representative angular distributions shown in Fig. 1 for $E_{lab} = 34.70$ and 58.22 MeV have been summed over all outgoing energies and all fusion residues. The cross section $d\sigma/d\Omega$ is strongly forward peaked, falling by a factor of ~500 from 3° to 28°. The oscillations in the angular distributions reflect the dominance of different residual nuclides in different angular ranges.

The absolute normalization of the angular distribution at each energy was determined from a comparison of the number of fusion (N_{fus}) and elastic scattering (N_{el}) events detected in the telescope at forward angles ($\theta_{lab} = 3° - 9°$):

$$\left(\frac{d\sigma_{fus}}{d\Omega}\right)_{lab} = \frac{N_{fus}}{N_{el}}\left(\frac{d\sigma_{el}}{d\sigma_R}\right)\left(\frac{d\sigma_R}{d\Omega}\right)_{lab},$$

where $d\sigma_R/d\Omega$ is the Rutherford cross section and $d\sigma_{el}/d\sigma_R$ was taken from optical-model calculations using an energy-dependent parameter set determined from previous elastic-scattering measurements.[8] Since the telescope angle setting is known to $\pm 0.02°$ from measurements on opposite sides of the beam direction, uncertainty in the value of $d\sigma_R/d\Omega$ at the forward angles contributes ~1% to the normalization uncertainty. The energy dependence of $d\sigma_{el}/d\sigma_R$ predicted by the optical model is in excellent agreement with that observed for the 6° elastic-scattering yield measured relative to the integrated target current. Therefore only the overall absolute normalization of the fusion excitation function is subject to uncertainties associated with the choice of optical-model parameters.

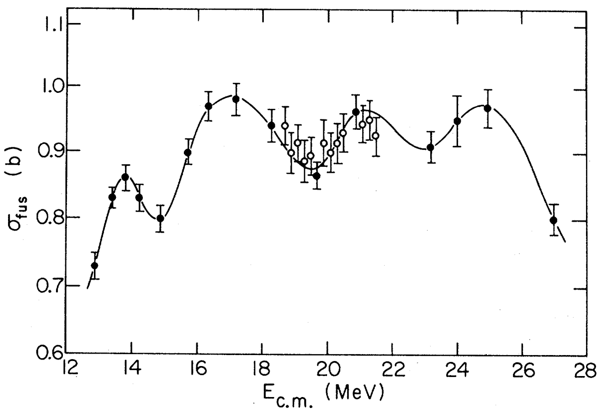

FIG. 2. Total fusion cross section as a function of the c.m. energy. The closed circles represent measurements of the complete angular distribution. The open circles represent measurements at $\theta_{lab} = 6°$ only, where the total fusion cross section was estimated from the ratio $\sigma_{fus}/[d\sigma_{fus}/d\Omega(6°)]$ at neighboring energy points. The solid line is only to guide the eye. Note the suppressed zero on the cross-section scale.

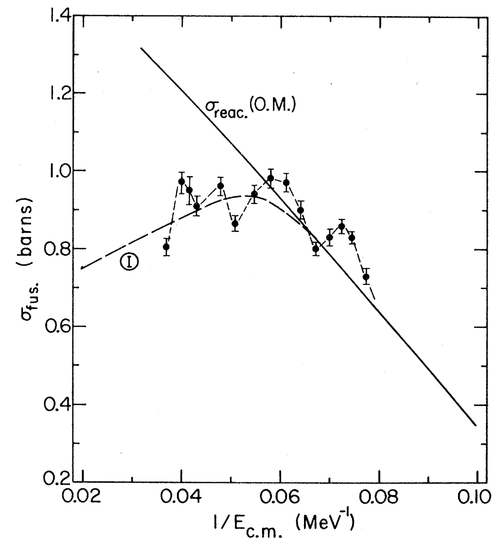

FIG. 3. Total fusion cross section as a function of $1/E_{c.m.}$. The dashed line connecting the datum points is to guide the eye. The solid line represents an optical-model calculation of the total reaction cross section. The dashed curve I is a theoretical prediction for σ_{fus} calculated using Eq. (7) of Ref. 4. The parameters used are $V_B = 8.1$ MeV, $r_B = 1.58$ fm, $V_C = -10$ MeV, $r_C = 0.93$ fm, and $\hbar\omega = 5$ MeV. For an explanation of the notation see Ref. 4.

The total fusion cross section was derived by integration of the measured angular distributions. As can be seen from the bottom inset of Fig. 1, a smooth extrapolation into the angular regions not measured indicates that ~8% of the total cross section arises from angles smaller than 3°, while angles larger than 28° contribute <0.3%. The total fusion cross section is plotted as a function of the c.m. energy in Fig. 2. The error bars (≲ 2.5%) include uncertainties from the counting statistics, from the estimate of the number of fusion residues stopped in the ΔE counter, from the extrapolation of the differential cross section to 0°, and from the normalization procedure for the absolute cross sections.

As can be seen in Fig. 2, the fusion cross section oscillates as a function of energy, with magnitude variations of ~10%. Suggestions of such structure exist in previous measurements of various channels which contribute to the total fusion cross section.[9-12] The oscillations are not expected from current fusion models and their interpretation is not yet clear. With sufficiently weak surface absorption, resonances in the nucleus-nucleus potential[13,14] can cause enhancements in σ_{reac} for each successive resonating partial wave.[15] However, with potentials based on $^{16}O + ^{12}C$ elastic-scattering analyses,[16] the spacing and width of the predicted enhancements are too small, by a factor of ~2, in comparison with the observed structure in Fig. 2.

It is possible that oscillations in $\sigma_{fus}(E)$ are correlated with resonances in $^{16}O + ^{12}C$ elastic and inelastic scattering.[17] Resonances have been observed in these channels at $E_{c.m.} = 13.7$, 19.7, and 22.7 MeV.[18,19] The fusion cross section exhibits a maximum near 13.7 MeV but minima near the latter two energies. The oscillations in σ_{fus} are considerably broader than observed in the elastic and inelastic channels, and a correlation is not at all clear.

The average energy dependence of σ_{fus} may be compared to the predictions of current models of heavy-ion–induced fusion.[4,5] For this purpose we plot σ_{fus} as a function of $E_{c.m.}^{-1}$ (Fig. 3). In the low-energy region Glas and Mosel[4] assume that penetration of the combined Coulomb and centrifugal barriers is sufficient to ensure fusion, so that the energy dependence should be the same as that calculated with the optical model for the total reaction cross section. Indeed, an optical-model prediction (solid curve, Fig. 3), using the energy-dependent parameters of Ref. 8, adequately represents the data for $E_{c.m.} \lesssim 17$ MeV. At higher energies, where the measurements deviate dramatically from the calculated σ_{reac}, the predictions of Glas and Mosel[4] depend on the assumed critical distance R_c and on the corresponding value V_c of the $(l=0)$ nucleus-nucleus potential.[4,6] Agreement with the average trend of the present measurements can be obtained with values of R_c and V_c (see Fig. 3) consistent with those extracted in the literature[1,6] from fusion data for heavier systems.

In conclusion, we find that the fusion cross section for $^{16}O + ^{12}C$ tends to increase with bombarding energy up to $E_{c.m.} \approx 17$ MeV, but remains roughly constant from 17 to 27 MeV. Superimposed on this average energy dependence are unexpected oscillations whose origin is not yet understood. Additional measurements are necessary to determine whether the oscillations are peculiar to the present system or are a more general feature of fusion of "light" heavy ions.

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[17]We cannot rule out non-negligible contributions to our measured cross sections from mechanisms other than complete fusion and statistical evaporation of the compound nucleus. Contributions associated with the nonstatistical decay of two-nucleus states of special structure might well be correlated with resonances in other channels.

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