

ENERGY DEPENDENCE OF COMPLETE AND INCOMPLETE FUSION FOR MASS 56
ENTRANCE CHANNEL SYSTEMS AT $E_{lab} > 10$ MeV/NUCLEON

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ABSTRACT

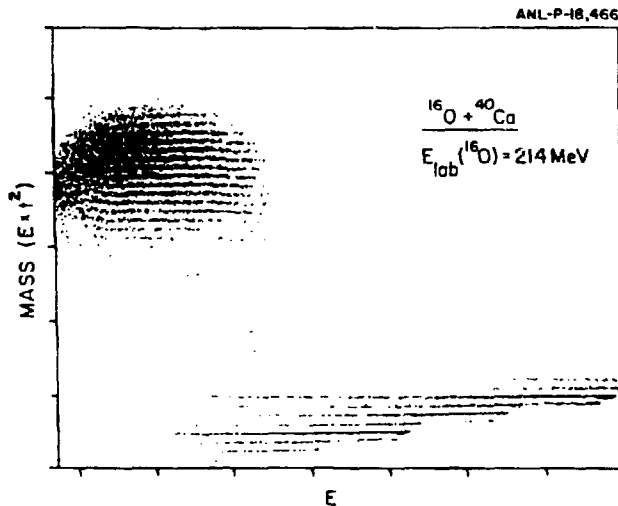
Three entrance channels $^{16}\text{O} + ^{40}\text{Ca}$, $^{28}\text{Si} + ^{28}\text{Si}$, and $^{32}\text{S} + ^{24}\text{Mg}$ forming the ^{56}Ni compound nucleus have been studied in the energy range 5 - 17 MeV/nucleon. Time-of-flight measurements provided mass identification and allowed for extraction of velocity distributions. These distributions were used to identify evaporation residues and to decompose the evaporation residues yields into complete and incomplete fusion components using evaporation code calculations. The velocity centroids as function of angle and mass are found to put constraints on the possible pre-equilibrium emission of light particles.

The three entrance channels $^{16}\text{O} + ^{40}\text{Ca}$, $^{28}\text{Si} + ^{28}\text{Si}$, and $^{32}\text{S} + ^{24}\text{Mg}$, forming the ^{56}Ni compound nucleus, were studied to establish their respective complete-fusion, total evaporation-residue (ER) cross sections. The study was motivated by the observation of substantial ER cross-sections for the $^{16}\text{O} + ^{40}\text{Ca}$ system¹ at higher energies as compared to that observed for the $^{28}\text{Si} + ^{28}\text{Si}$ system.^{2,3} The question raised³ was whether the differences reflected experimental difficulties in the identification of the ER yields, or represented an entrance channel dependence.

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Time-of-flight measurements were performed to obtain mass identification and to allow extraction of the velocity spectra of the individual mass products. Figure 1 for the $^{16}\text{O} + ^{40}\text{Ca}$ reaction shows an example of the mass resolution obtained. To distinguish ER yields from binary reaction processes, the ER Galilean-invariant cross section $(\frac{1}{2} \frac{d^2\sigma}{d\Omega dv})$ was assumed to have a Gaussian-shaped distribution, with a possible shift of the velocity centroid with respect to that expected for complete fusion. Comparison of this shape to the observed velocity distributions provided a relatively unambiguous identification of the ER yields, except for the lighter masses (dependent on the reaction and bombarding energy) at larger angles where some uncertainties exist. Predictions of the Monte Carlo evaporation codes LILITA⁴ and PACE⁵ were used to identify complete fusion yields. For all systems a single source decomposition was performed, where the predicted velocity distributions were compared to the individual mass velocity spectra to extract a maximum yield consistent with complete fusion. For the $^{16}\text{O} + ^{40}\text{Ca}$ system two-source and multiple-source simulation calculations were performed and compared to the velocity distribution dependences with mass and angle, and to the observed mass and angular distributions.

Fig. 1 Mass versus energy spectrum observed at $\theta_{\text{lab}} = 6^\circ$ for the $^{16}\text{O} + ^{40}\text{Ca}$ reaction.



The $^{16}\text{O} + ^{40}\text{Ca}$ reaction was studied at $E_{\text{lab}}(^{16}\text{O}) = 214 \text{ MeV}$.⁶ The angular distributions for the summed ER yields ($\sigma = 762 \pm 100 \text{ mb}$), extracted using the procedure described above, and for the total yields in the mass range $32 < A < 50$ ($\sigma = 929 \pm 100 \text{ mb}$) are shown in Fig. 2. Also shown for comparison in the figure is the angular distribution reported by Vigdor et al.¹ ($\sigma = 1127 \pm 100 \text{ mb}$). The angular distributions obtained for the complete fusion ER yields from the single-source decomposition is shown in Fig. 3 for $M = 43$ and for $40 < M < 50$, compared to the total ER yields. A complete fusion ER cross section of $476 \pm 100 \text{ mb}$ was obtained. The extracted angular distribution is still significantly broader than that predicted by LILITA.

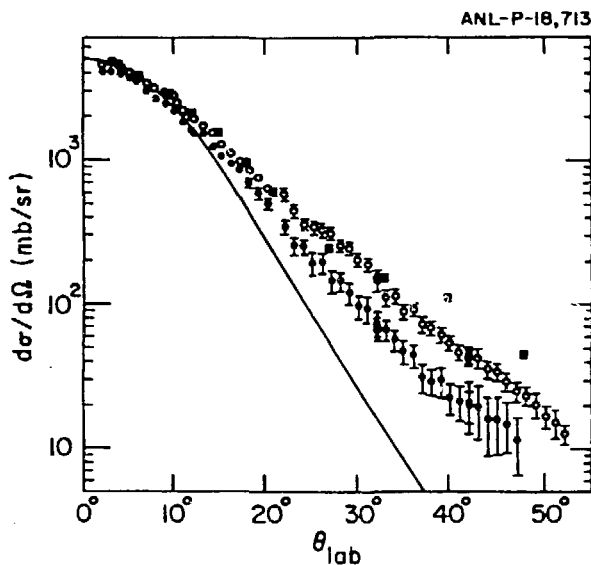


Fig. 2 Angular distribution for ER yields (solid circles) and total yields $32 < M < 50$ (open circles) extracted for the $^{16}\text{O} + ^{40}\text{Ca}$ reaction at $E_{\text{lab}} = 214 \text{ MeV}$. The solid squares are the results of Vigdor [Ref. 1] and the solid line is the prediction of LILITA.

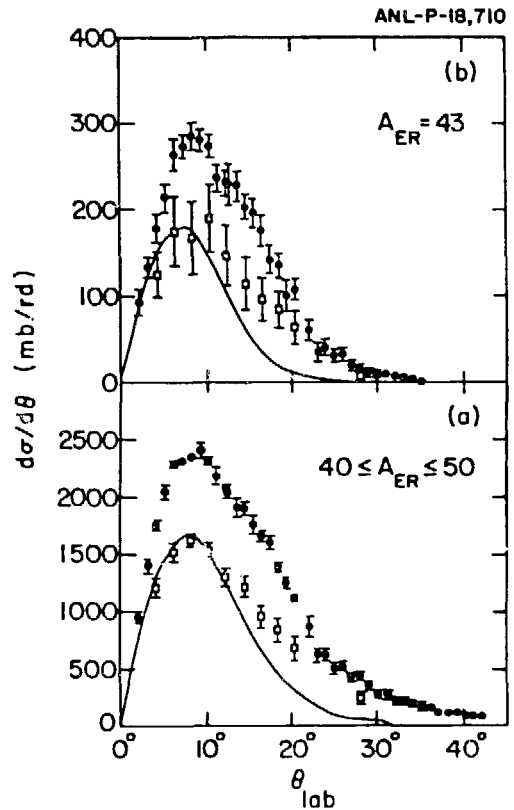


Fig. 3 Angular distributions of total ER yields (solid circles) and complete fusion ER yields, extracted in a single-source decomposition (open circles). The solid line is the prediction of LILITA.

A two-source decomposition was performed, assuming for one source the $^{16}\text{O} + ^{40}\text{Ca}$ complete fusion reaction and for the other the $^{12}\text{C} + ^{40}\text{Ca}$ incomplete fusion reaction (with emission of an alpha particle with beam velocity at 0°). The strengths of the two sources were adjusted to reproduce the angle dependence of the velocity centroids for masses $39 < M < 48$ (See Fig. 4), resulting in scale factors of 0.60 ($\sigma = 457$ mb) and 0.40 ($\sigma = 305$ mb) for the complete and incomplete fusion sources,

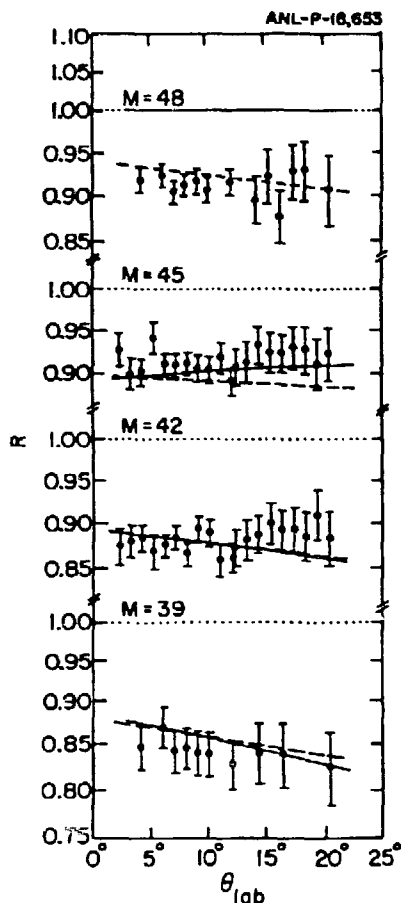


Fig. 4 ER velocity deficit R plotted vs. θ_{lab} for various masses. Solid and dashed curves are two-source and multiple-source predictions (see text).

and incomplete fusion sources, respectively. The ER velocity centroids are expressed in Fig. 4 in terms of the velocity deficit ratio R , defined as the ER velocity centroid divided by the velocity centroid expected for complete fusion (taken to be $v_{\text{cm}} \cos \theta_{\text{lab}}$,⁷ where v_{cm} is the center-of-mass velocity and θ_{lab} is the laboratory angle).

While the observed ER mass distribution is reasonably well reproduced by this simulation, it was not possible to reproduce the velocity deficits observed for masses $M > 45$ since the ^{12}C source is not predicted to produce these residue masses. Variations of the excitation energy of the ^{12}C source (assuming different alpha particle emission energies) was not able to rectify this. This implies that one- or two-nucleon emission is important, and three- and four-source simulations were performed (including $^{15}\text{N} + ^{40}\text{Ca}$, and $^{14}\text{N} + ^{40}\text{Ca}$ sources) which reproduced the velocity centroid behaviors for masses $39 < M < 48$

(Fig. 4), and improved the fit to the observed mass distribution as well. The simulations are too schematic to be taken literally, but support the suggestion that one- or two-nucleon emission is responsible for the heavy ER mass behavior.

Based on these analyses we quote an upper limit for the complete fusion ER cross section of 476 ± 100 mb. Using this value, we obtain a $\sigma_{CF}/(\sigma_{CF} + \sigma_{ICF})$ ratio of 0.63 ± 0.10 which is in agreement with the Morgenstern systematics⁹ shown in Fig. 5. In Fig. 6 the total complete-fusion ER cross section is plotted as an open circle together with previously reported results. The plus symbols indicate the cross sections which were obtained from the angular distributions of Ref. 1, using the predicted LILITA angular distribution scaled by the Morgenstern extracted $\sigma_{CF}/(\sigma_{CF} + \sigma_{ICF})$ ratios of Fig. 5 to estimate the complete fusion contributions. As can be seen, this procedure yields a value at 214 MeV which is in agreement with our present measurement. The solid curves in the figure are model predictions¹¹⁻¹³ for the total complete fusion cross section behavior. The dashed lines are the cross-section limitations imposed by the compound nucleus as predicted by Rotating Liquid Drop Model (RLDM) calculations.¹⁴

The study of the effect of the entrance channel mass asymmetry was initially motivated by the observation that total ER cross sections for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction differed dramatically from that observed for the asymmetric $^{16}\text{O} + ^{40}\text{Ca}$ reaction, and showed no evidence of incomplete fusion contributions. Measurements of the near symmetric $^{32}\text{S} + ^{24}\text{Mg}$ reaction at 194, 239, and 273 MeV¹⁵ gave similar results. In the systematics established by Morgenstern et al.,⁹ it is suggested that the relevant parameter to view the incomplete fusion process is the velocity of the light reaction partner with respect to the center of mass, v_L ;

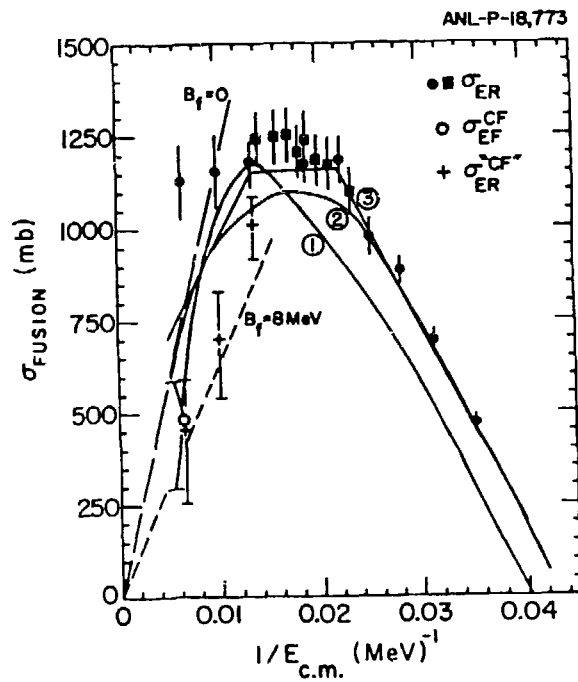
$$v_L = \frac{A_H}{A_H + A_L} v_{\text{rel}}, \quad v_{\text{rel}} = \sqrt{\frac{2(E_{\text{cm}} - V_{\text{Coul}})}{\mu}}, \quad (1)$$

where E_{cm} , V_{Coul} , and μ are the center-of-mass energy, the Coulomb barrier and the reduced mass, respectively. The subscripts H and L



Fig. 5. Figure taken from Morgenstern et al. [Ref. 9], with the present results for ^{16}O , ^{28}Si , and ^{32}S projectiles (as indicated by the labels) included. (See text.)

Fig. 6. Measured ER cross sections [Refs. 1,10] as function of $1/E_{\text{cm}}$. (See text.) The labelled solid curves are the complete fusion cross sections predicted by three entrance-channel models [Refs. 11-13]. The dashed curves represent the limitations for complete fusion ($B_f = 0$ MeV) and for the ER cross sections ($B_f = 8$ MeV) based on RLDM calculations [Ref. 14].



identify the heavy- and light-reaction partners. In this picture the bombarding energies at which the symmetric systems were studied are near the threshold for the onset of incomplete fusion processes.

Measurements were performed for the $^{28}\text{Si} + ^{28}\text{Si}$ reaction at bombarding energies of 309 MeV, 397 MeV, and 450 MeV¹⁶ to search for evidence of incomplete fusion. The ER yields were found to have significantly broader velocity distributions than predicted by evaporation codes. The preliminary single-source decompositions yield $\sigma_{\text{CF}}/(\sigma_{\text{CF}} + \sigma_{\text{ICF}})$ ratios of 0.73 ± 0.15 and 0.59 ± 0.20 at bombarding energies of 309 MeV and 397 MeV, respectively. These ratios (See Fig. 5) are, within the uncertainties, in agreement with the systematics. Also shown on the figure are maximum possible incomplete fusion contributions extracted in the analysis of the $^{32}\text{S} + ^{24}\text{Mg}$ results,¹⁵ which are also consistent with the systematics. While this agreement would tend to provide support for the v_L dependence, it should be stressed that because of the difficulties in the decomposition one should refrain from drawing firm conclusions until verified by coincidence measurements. This is re-enforced if the cross sections are converted to spin using the sharp cut-off approximation and plotted versus excitation energy in the compound nucleus. The $^{16}\text{O} + ^{40}\text{Ca}$ results appear consistent with the fission barrier predicted. On the other hand, both the $^{28}\text{Si} + ^{28}\text{Si}$ and $^{32}\text{S} + ^{24}\text{Mg}$ systems have cross sections implying larger critical angular momenta than are consistent with the RLDM predictions.

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