PHYSICAL REVIEW C VOLUME 27, NUMBER 4 APRIL 1983

# Brief Reports

*Brief Reports are short papers which report on completed research or are addenda to papers previously published in the* **Physical Review.** *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract and a keyword abstract.*

## Fusion cross sections for $^{9}Be + ^{40}Ca$

J. S. Eck and A. R. Omar
*Department of Physics, Kansas State University, Manhattan, Kansas 66506*

J. R. Leigh and T. R. Ophel
*Department of Nuclear Physics, Australian National University, Canberra, ACT 2600, Australia*
(Received 8 November 1982)

The total fusion cross sections for $^{9}Be + ^{40}Ca$ were measured in the $^{9}Be$ bombarding energy range 35–60 MeV in 5 MeV steps by detecting the evaporation residues with a gas ionization $E$-$\Delta E$ detector. The measured fusion cross sections are significantly smaller than the total reaction cross sections calculated using optical model parameters obtained from fitting the elastic scattering cross sections in the same energy range. Similar results were obtained earlier for the case of $^{9}Be + ^{28}Si$ fusion. The fact that $^{9}Be$ is weakly bound and is easily dissociated in the Coulomb and nuclear fields of either the $^{40}Ca$ or $^{28}Si$ nucleus is believed to have a strong influence on the observed fusion and elastic scattering cross sections. Sources of possible discrepancy between fusion cross sections measured by determining the yield of heavy evaporation residues and those by summing the cross sections for the emission of light particles such as protons, neutrons, and alpha particles from the compound system are discussed.

[NUCLEAR REACTIONS $^{9}Be + ^{40}Ca$ fusion, $E(^{9}Be) = 35, 40, 45, 50, 55, 60$ MeV, detected evaporation residues, deduced total fusion cross sections, calculated $^{9}Be + ^{40}Ca$ total reaction cross sections.]

Recent investigations of the interaction of the weakly bound nuclei $^{6}Li$, $^{7}Li$, and $^{9}Be$ (binding energies 1.67, 2.47, and 1.67 MeV, respectively) with various strongly bound nuclei have shown that the facility with which these nuclei dissociate has a strong influence on the measured elastic and inelastic scattering and reaction cross sections.[1-3] The double folding model using a realistic nucleon-nucleon interaction, which is successful in describing the elastic $\alpha$ and heavy-ion ($A \geq 12$) scattering from such nuclei as $^{28}Si$ and $^{40}Ca$, is not successful in describing the elastic scattering of $^{9}Be$ with the same target nuclei unless the real double folding potential is reduced[4-6] by a factor $\sim 0.4$. Recent calculations of the elastic scattering cross section for $^{6}Li$ and $^{7}Li$ scattering have demonstrated that no renormalization of the calculated folding potential is necessary if the breakup channels of $^{6}Li \rightarrow \alpha + d$ and $^{7}Li \rightarrow \alpha + t$ are explicitly included in a coupled channels folding calculation.[3,7] The ratio of the total fusion cross section to the total reaction cross section for $^{9}Be + ^{28}Si$ has been shown to be much smaller than that observed for other systems.[2] Quite recently it has been shown that the maximum fusion cross sections for $^{6}Li + ^{12}C$ and $^{7}Li + ^{12}C$ and the ratio of fusion to reaction cross section at all energies are smaller than those observed in other cases.[8] In order to obtain a better understanding of the interaction of weakly bound nuclei, we have measured the total fusion cross sections for $^{9}Be + ^{40}Ca$ in the $^{9}Be$ bombarding energy range 35–60 MeV. The total fusion cross sections are compared with the reaction cross sections calculated using optical model parameters obtained from fitting the elastic scattering cross sections in the same energy range. Because of discrepancies between measured fusion cross sections for $^{9}Be + ^{28}Si$ obtained using two different techniques[1,2] the definition of the total fusion cross section involving light nuclei such as $^{9}Be$ and $^{7}Li$ and sources of possible discrepancy are investigated.

The fusion cross sections for $^{9}Be + ^{40}Ca$ were measured by detecting the evaporation residues using a ninefold $\Delta E$-$E$ ionization chamber surface-barrier detector system within a 2 m diameter scattering chamber. The $^{9}Be$ beam was extracted from a sputter ion source in the form $BeH^{-}$ and accelerated using the ANU 14UD tandem pelletron accelerator. The targets consisted of $\sim 100\ \mu g/cm^2$ $^{40}Ca$ (greater than 99% enrichment) evaporated onto thin 5 $\mu g/cm^2$ carbon backings. The targets were evaporated, transferred, stored, and bombarded in carbon free vacuum systems, thus minimizing contamination by oxygen, hydrogen, and carbon. A similar detector system has been described in detail elsewhere[9] and only a brief description will be given here. The detector was operated using isobutane at a pressure of 9–16 mm of Hg. Only seven detectors of the possible nine were used. The detectors were 6° apart and by setting the most forward detector at 3° and then 6°, angular distributions were obtained in the range from 3–42° in 3° steps. The data were recorded on tape in the event mode. Each event consisted of a $\Delta E$ signal, and $E$ signal, and an identification that indicated which of the seven detectors recorded the event. A typical two dimensional spectrum is shown in Fig. 1. Evaporation residues with $Z \geqslant 20$ were summed to yield the total fusion cross section. The region of the two dimensional spectrum of Fig. 1 which comprises events contributing to the fusion cross section is indicated by the solid polygon in the figure. Because of the forward angle of the $\Delta E$-$E$ detector system, only $^{40}Ca$ recoils from very backward scattered $^9Be$ projectiles, where the elastic scattering cross section is negligible, could enter the detector. The relative solid angles of the seven $\Delta E$-$E$ detectors and that of the monitor detector at $\theta_L = 19°$ were determined from elastic scattering of $^9Be$ from a

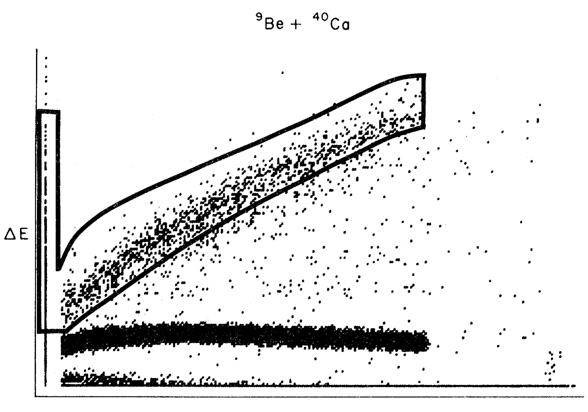


FIG. 1. Energy loss $\Delta E$ is shown as a function of the energy, for the $\Delta E$-$E$ ionization chamber surface-barrier detector used in the reported experiments. Spectrum was measured at $\theta_L = 6°$ and a $^9Be$ bombarding energy of 60 MeV. The events within the solid polygon were integrated to give the yield of evaporation residues for $^9Be + ^{40}Ca$. The vertical line of counts at zero energy represent those events for which there was a $\Delta E$ signal but no $E$ signal. These events introduced an uncertainty of $\sim 4\%$ in the measured evaporation residue yield.

$^{197}Au$ target. The relative normalization at a given energy was obtained using the fixed angle monitor detector. The absolute normalization was obtained by normalizing the yield of evaporation residues to the elastic scattering cross section for $^9Be + ^{40}Ca$ at 19° as measured by the monitor detector. The elastic scattering cross section at 19° was obtained from optical model calculations using parameters determined previously[6] from fitting the elastic scattering cross sections in this energy range. The relative normalization error is of the order of 4%, while the error in absolute nromalization is of the order of 20%. The largest contributing factor to the error in absolute normalization arises from using optical model calculations to obtain the elastic scattering cross section at 19°. The events which have a $\Delta E$ signal but no $E$ signal produce an uncertainty of $\sim 4\%$ in the measured fusion cross section.

Complete angular distributions of evaporation residues for $Z \geqslant 20$ were measured in 5 MeV intervals between 35–60 MeV and are shown in Fig. 2.

The total fusion cross sections for each energy were obtained from

$$\sigma_{\rm tot}^{\rm fus} = 2\pi \int_0^{180°} \frac{d\sigma}{d\Omega}(\theta) \sin\theta \, d\theta$$

and are shown in Fig. 3 plotted as a function of the laboratory energy.

Total reaction cross sections calculated by using optical model parameters which yielded satisfactory fits to the elastic scattering cross sections in the same energy range[6] ( $V = 10.0$ MeV, $r_0 = 1.416$ fm, $a = 0.505\,25$ fm, $W = 23.4$ MeV, $r_w = 1.277$ fm, $a_w = 0.501$ fm, $r_c = 1.416$ fm) are also shown in Fig. 3. In other systems in which a compound nucleus of approximately the same mass is formed the fusion cross section is generally about equal to the reaction cross section in the energy range from below the Coulomb barrier, $E_B$, up to an energy of $\sim 2$–3 times $E_B$. For the case of $^9Be + ^{40}Ca$ the fusion cross section is a factor of 2–2.5 lower than the total reaction cross section in this range. A similar result[2] was obtained for $^9Be + ^{28}Si$. The large difference between the reaction and fusion cross sections is probably due to the ease with which the $^9Be$ breaks up during the interaction. Unlike the fusion of tightly bound nuclei such as $^{12}C$ and $^{16}O$, the breakup cross section for $^9Be$ is a significant fraction of the total reaction cross section even at low energy. The importance of breakup in the interaction of other loosely bound nuclei such as $^6Li$ and $^7Li$ has recently been demonstrated. By properly accounting for the breakup of $^6Li$ into $\alpha + d$ and $^7Li$ into $\alpha + t$, the elastic scattering cross sections for $^7Li$ and $^6Li$ scattering have been successfully calculated using the folding model without the necessity for renormalization of the calculated folding potential.[3,7]

Despite the success of above calculations the re-

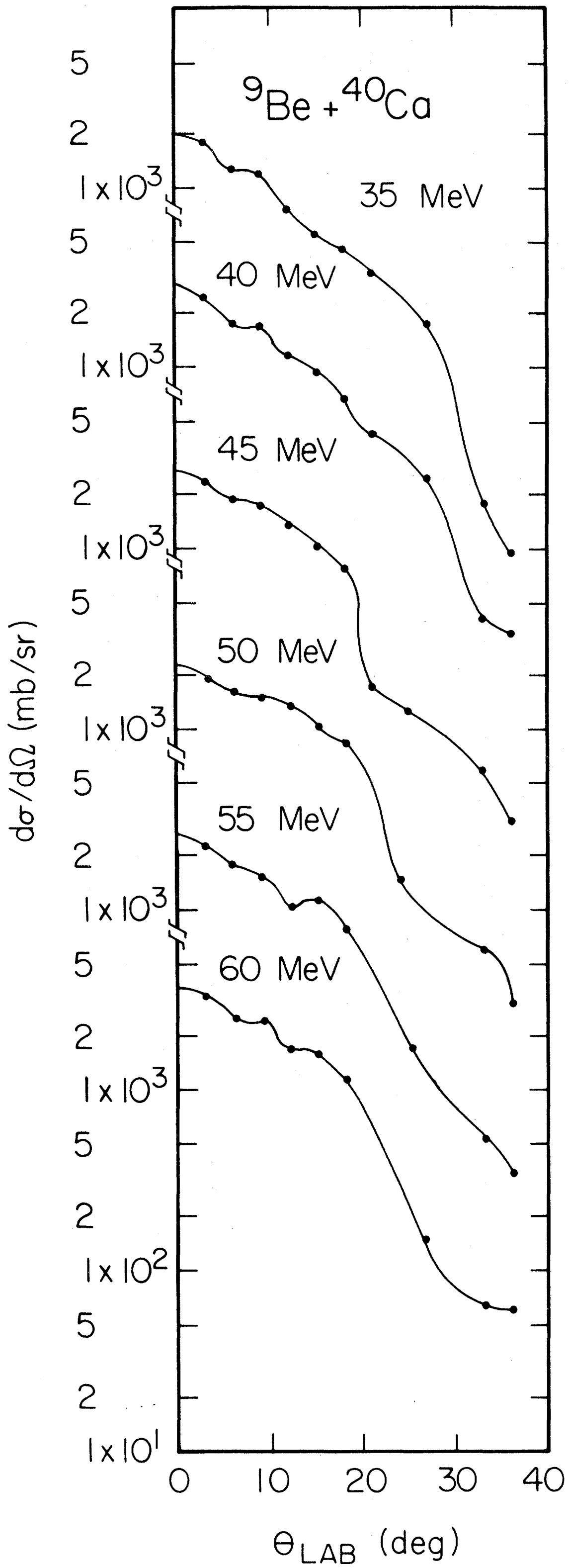


FIG. 2. Measured angular distributions of the evaporation residues for various $^{9}$Be bombarding energies.

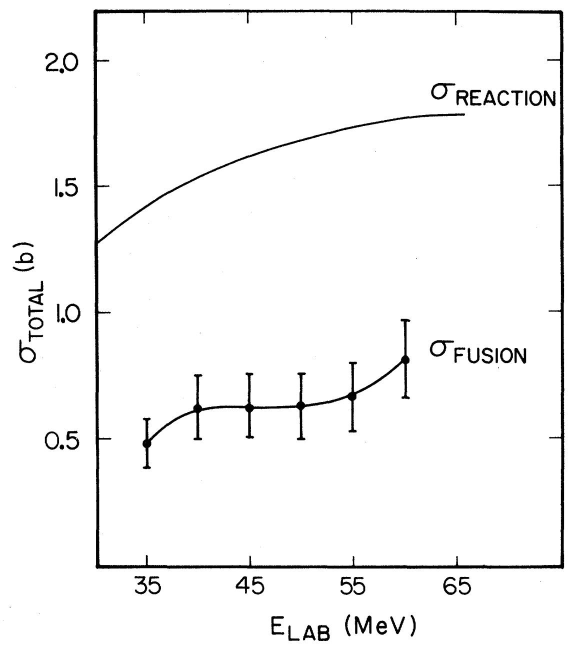


FIG. 3. Points with error bars indicate the total fusion cross section, $\sigma_{\text{fusion}}$, as a function of $^{9}$Be bombarding energy. The line connecting the experimental points has no theoretical significance. Also shown is the total reaction cross section calculated using the optical model parameters which fit the elastic scattering cross sections in the same energy range.

normalization of the folding model potential is still open to question. In other calculations the need for renormalization in the case of $^{9}$Be and $^{7}$Li scattering has been eliminated by including the effect of the large static ground state quadrupole moment in a coupled channels calculation.[10] This technique does not apply to $^{6}$Li, however, which has a small ground state deformation. Further detailed studies of the energy dependence of elastic, inelastic, and reaction cross sections for $^{6}$Li, $^{7}$Li, and $^{9}$Be scattering should be useful in understanding the folding model potential in more detail.

It should be pointed out that, in a similar experiment in which the fusion cross section for $^{9}Be + ^{28}Si$ was determined by measuring the evaporation residues (method 1),[2] the experimental fusion cross section measured at $E(^{9}Be) = 30$ MeV was not in agreement with another measurement of the fusion cross section in which the total fusion cross section was determined by summing the cross sections obtained by measuring the yield of the evaporated light charged particles ($A \leq 4$) from the compound system (method 2).[1] The discrepancy may arise because of the different experimental definitions of what is called the total fusion cross section. Because of the low momentum and energy of evaporation residues from partial fusion events they are not included in method 1, whereas they contribute to method 2. Because of the low energy of the evaporation residues for $^{9}$Be + $^{28}$Si, some of the fusion cross section is not accounted for because of threshold effects in the experimental setup, while in method 2 it is possible to double count the same fusion event by detecting more than one evaporated particle from the same $^{9}$Be + $^{28}$Si interaction. Both these explanations tend to explain why fusion cross sections measured by using method 2 are larger than method 1 at least at low energy. It furthermore indicates a need to find a more precise experimental definition of the fusion cross section when one of the interacting particles is a light projectile such as $^{9}$Be or $^{7}$Li.

The total fusion cross section for $^{9}$Be + $^{40}$Ca was measured in the energy range $E(^{9}\mathrm{Be}) = 35-60$ MeV by detecting the evaporation residues. The measured fusion cross section was lower than that determined for systems in which a similar compound system is formed and also much lower than the total reaction cross section calculated using optical model parameters which fitted elastic scattering cross sections in the same energy range. The large difference between the total fusion and reaction cross sections may arise from the ease with which $^{9}$Be dissociates into $2\alpha + n$ in the nuclear and Coulomb fields of the other interaction partner, although further data on $^{9}$Be interactions as a function of energy would be necessary before a strong conclusion about the reaction mechanisms involved can be ascertained.

This research was supported in part by the Division of Chemical Sciences, U.S. Department of Energy.

[1]M. Hugi, J. Lang, R. Müller, E. Ungrecht, K. Bodek, L. Jarczyk, B. Kamys, A. Magiera, A. Strzaekowski, and G. Willim, Nucl. Phys. A368, 173 (1981).

[2]J. S. Eck, J. R. Leigh, T. R. Ophel, and P. D. Clark, Phys. Rev. C 21, 2352 (1981).

[3]I. J. Thompson and M. A. Nagarajan, Phys. Lett. 166B, 163 (1981).

[4]G. R. Satchler and W. G. Love, Phys. Rep. 55C, 183 (1979).

[5]G. R. Satchler, Nucl. Phys. A279, 61 (1976).

[6]J. S. Eck, T. R. Ophel, P. D. Clark, and D. C. Weisser, Nucl. Phys. A334, 519 (1980).

[7]M. A. Nagarajan, I. J. Thompson, and R. C. Johnson, Nucl. Phys. A385, 525 (1982).

[8]L. C. Dennis, K. M. Abdo, A. D. Frawley, and K. W. Kemper, Phys. Rev. C 26, 981 (1982).

[9]T. R. Ophel, W. Galster, D. J. Hinde, and J. R. Leigh, Nucl. Instrum. Methods 193, 507 (1982).

[10]V. Hnizdo, K. W. Kemper, and J. Szymakowski, Phys. Rev. Lett. 46, 590 (1981).