and 42, 142, 1019(E) (1979).

[16] D. Cutts *et al.*, Phys. Rev. Lett. 41, 363 (1978).

[17] R. Cahn, Phys. Rev. Lett. 40, 80 (1978).

[18] H. M. Georgi *et al.*, Phys. Rev. Lett. 40, 692 (1978).

[19] F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).

[20] L. Resnick *et al.*, Phys. Rev. D 8, 172 (1973).

[21] F. Reines *et al.*, Phys. Rev. Lett. 37, 315 (1976).

[22] Harvard University–University of Pennsylvania–Brookhaven National Laboratory experiment cited by H. H. Williams, Bull. Am. Phys. Soc. 24, 60 (1979).

[23] K. Sato and H. Sato, Prog. Theor. Phys. 54, 912 (1975); D. A. Dicus *et al.*, Phys. Rev. D 18, 1829 (1978).

Fusion Cross Sections for $\alpha + {}^{40,44}$Ca and the Problem of Anomalous Large-Angle Scattering

K. A. Eberhard and Ch. Appel
Sektion Physik der Universität München, D-8046 Garching, Germany

and

R. Bangert, L. Cleemann, J. Eberth, and V. Zobel
Institut für Kernphysik, Universität zu Köln, D-5000 Köln, Germany

(Received 26 February 1979)

Fusion cross sections for the reactions $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca have been measured between 10 and 27 MeV (lab) via the detection of the γ radiation of the evaporation residues. At maximum the cross sections are about 1170 mb for $\alpha + {}^{44}$Ca and about 970 mb for $\alpha + {}^{40}$Ca. This difference supports recent optical-model and semiclassical interpretations that the well-known anomalous large-angle scattering results from different absorption strengths for these two systems.

Cross sections for the elastic and inelastic scattering of projectiles and targets such as ^{16,18}O + ^{28}Si, $\alpha + {}^{40,44}$Ca, and others in the vicinity of closed-shell nuclei differ by orders of magnitude at backward angles.[1] These enhanced back-angle cross sections are under intense study by many experimental and theoretical groups; it is hoped that the great sensitivity of this effect leads to a better, more detailed understanding of heavy-ion collisions in general. At present, however, the interpretation of the anomalous large-angle scattering (ALAS) has led to controversies; in particular, resonance versus potential "explanations" have been suggested. Recently, optical-model studies[2,3] and a semiclassical investigation by Brink and Takigawa[4] have shown that the elastic $\alpha + {}^{40,44}$Ca scattering is described by the interference between the wave reflected at the nuclear radius (i.e., the outer potential barrier) and the wave reflected at the internal angular momentum barrier. Scattering from the internal barrier can give rise to orders-of-magnitude enhancement of the cross section at backward angles (such as observed for $\alpha + {}^{40}$Ca scattering) provided the absorption is moderate enough to permit sufficient transparency for this wave through the outer potential barrier[4] (i.e., the surface region). In case of strong absorption this contribution is suppressed and no back-angle enhancement of the cross section is observed (as, e.g., for $\alpha + {}^{44}$Ca); the "normal" wave, reflected at the nuclear radius, then dominates the cross section over the entire angular range.

In this Letter, for the first time, we report direct experimental evidence that the strengths of absorption for $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca are considerably different in the region of the nuclear surface. This is obtained through the measurement of $\alpha + {}^{40,44}$Ca fusion cross sections.

An α-particle beam of a few nanoamperes from the FN tandem accelerator at the University of Köln was focused on 2.6-mg/cm^2-thick ^{40}Ca and ^{44}Ca targets. The γ radiation was registered with two Ge(Li) detectors (80 cm^3) at $+90°$ and $-90°$ to the beam direction. Two monitor detectors were placed at $+5°$ and $-5°$ to the beam direction to control the beam current integration, the beam spot position on the target, and possible target inhomogeneities. Depending on Doppler broadening a resolution of 2 to 5 keV (full width at half maximum) was achieved for the γ lines in the spectra. A careful dead-time correction and an absolute efficiency calibration with radioactive sources were made.

To obtain fusion cross sections all ground-state

γ transitions from residual nuclei heavier than the target nucleus were added up. This excludes inelastic excitation, i.e., of the 3^- state in ^{40}Ca (about 90 mb at maximum) and of the 2^+ state in ^{44}Ca (about 200 mb at maximum). Transitions from nuclei lighter than the target nucleus are only observed above 20 MeV bombarding energy and are assumed to be of direct-reaction nature. They are weak: For $\alpha + {}^{40}$Ca only γ lines from ^{39}K and ^{36}A are observed (10–120 mb between 20 and 27 MeV); for $\alpha + {}^{44}$Ca γ transitions in ^{43}Ca, ^{43}K, and ^{42}Ca are observed (about 10–70 mb for $E_\alpha = 20$–27 MeV). A more complete set of the experimental results will be published in a forthcoming paper.

The cross sections obtained for $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca between 10 and 27 MeV bombarding energy (lab) along with the corresponding ratio (lower part) are shown in Fig. 1. The reaction cross sections (solid lines) were calculated from the optical-model potentials of Delbar *et al.*[2] (at higher energies) and of Besson, Eberhard, and Davis[5] (at lower energies) and were matched at intermediate energies. The energy loss in the target (about 850 keV at 10 MeV), not corrected for in the energy scale of Fig. 1, is taken into account in the calculated reaction cross sections. The calculated $\alpha + {}^{44}$Ca and $\alpha + {}^{40}$Ca reaction cross sections differ by about 6–8% (dashed line, lower part), whereas the experimental ratio rises to ~30% at 13 MeV and decreases to ~15% towards higher energies. It is interesting to note that the rapid increase of the ratio around 13 MeV is closely correlated with the onset of the ALAS effect for $\alpha + {}^{40}$Ca (Ref. 5). The slight (~10%) oscillatory structure in the $\alpha + {}^{40}$Ca curve, reminiscent of, though less pronounced than, the fusion cross sections for ^{12}C + ^{16}O and similar systems,[6] is not discussed here.

Partial fusion cross sections $d\sigma_F/dl$ were obtained from[7]

$$\sigma_F = \sum_{l=0}^{\infty} d\sigma_F/dl = \pi\bar{\lambda}^2 \sum_{l=0}^{\infty}(2l+1)T_l P_l \tag{1}$$

and are shown for an incident energy of 25 MeV (lab) in Fig. 2. The quantity T_l is the penetration probability through the interaction barrier and P_l gives the probability for fusion to take place once the barrier has been passed. Whereas the penetration T_l can readily be calculated from the optical model, there is no method known at present to calculate the probability P_l for fusion. Glas and Mosel[7] have introduced a sharp angular momentum cutoff for the P_l:

$$P_l = \begin{cases} 1 \text{ for } l \leq l_{\mathrm{cr}}, \\ 0 \text{ for } l > l_{\mathrm{cr}}. \end{cases} \tag{2}$$

In Eq. (2), l_{cr} is the critical (largest) angular momentum for which fusion takes place. Along with the assumption $T_l = 1$ for $l < l_{\mathrm{gr}}$, where l_{gr} is the grazing angular momentum ($l_{\mathrm{gr}} > l_{\mathrm{cr}}$ in our case), one obtains for the fusion cross section

$$\sigma_F = \pi\bar{\lambda}^2(l_{\mathrm{cr}} + 1)^2. \tag{3}$$

From the measured fusion cross sections at 25 MeV (lab), i.e., 950 mb for $\alpha + {}^{40}$Ca and 1110 mb

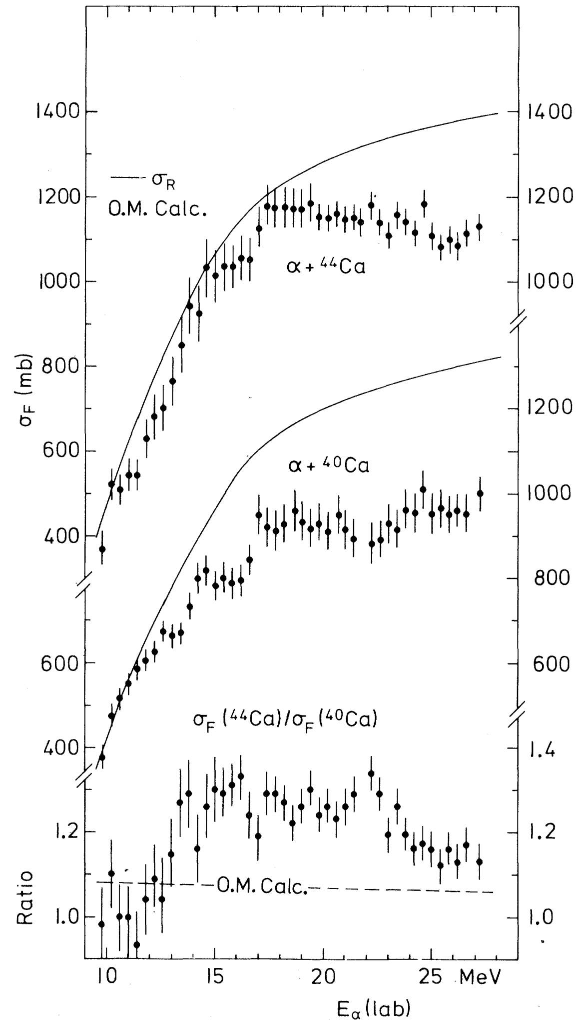

FIG. 1. Fusion cross sections for $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca. In the lower part the ratio of these cross sections is shown. The solid curves show total reaction cross sections calculated with optical potentials of Refs. 2 and 5; the dashed curve (lower part) shows the ratio. "O.M." denotes optical model.

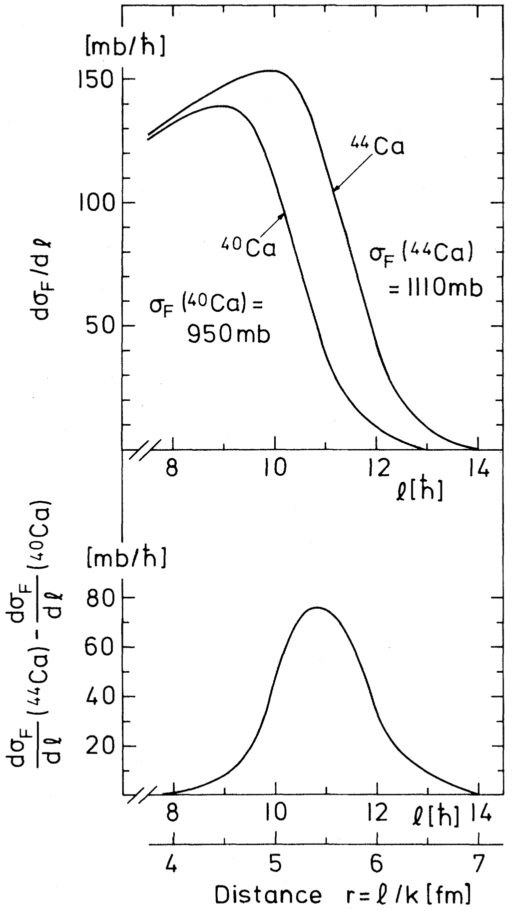

FIG. 2. Fusion cross sections at $E_\alpha = 25$ MeV (lab), plotted as a function of the orbital angular momentum l and of the corresponding relative distance $r = l/k$ of the two colliding nuclei. The lower part depicts the difference of these cross sections for $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca.

for $\alpha + {}^{44}$Ca, values of $l_{\mathrm{cr}} \simeq 9.9\hbar$ for $\alpha + {}^{40}$Ca and $\simeq 10.9\hbar$ for $\alpha + {}^{44}$Ca are derived. To obtain a more realistic dependence of the quantity $T_l P_l$ on l (than the sharp cutoff) we have assumed that this quantity has the same dependence as the transmission coefficients T_l. They were calculated at some lower bombarding energy ($T_l \simeq \frac{1}{2}$ near $l = 10$ for $\alpha + {}^{40}$Ca and near $l = 11$ for $\alpha + {}^{44}$Ca) to satisfy the requirement that the total fusion cross section in Eq. (1) equals the experimental values of 950 and 1110 mb, respectively. The optical potentials of Delbar *et al.*[2] were used, which were recently shown[2] to describe $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca elastic and inelastic scattering between 24 and 166 MeV almost perfectly (see below). As seen in Fig. 2, the partial fusion cross sections obtained for $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca are nearly the same for $l \lesssim 8\hbar$ partial waves, but differ considerably for larger ("surface") partial waves. The dramatic impact of such a difference, which is shown separately in the lower part of Fig. 2, for elastic scattering is, e.g., demonstrated by Eberhard.[8]

Before turning to a discussion of the results some shortcomings of γ-ray measurements to obtain total fusion cross sections are discussed for the case presented here:

(1) Compound-nucleus decays leading directly to ground states are missed; from Ref. 5 and Eberhard *et al.*[9] compound elastic scattering, e.g., is estimated to be a few millibarns or less above $E_\alpha(\mathrm{lab}) \simeq 13$ MeV.

(2) Weak transitions are missed, e.g., high-energy γ rays from the continuum.

(3) The decay of isomeric states with long half-lives could be accounted for by other transitions for which the branching ratios are known.

(4) Isotropy of γ angular distributions (since the γ detector was placed at one angle only, i.e., 90°): For about 96% of the transitions taken into account the multipolaries are known. The spin alignment coefficients could be approximated from the extensive γ-spectroscopic data available in this mass region. Thus, it could be estimated that the corrections for the angular distributions of γ rays in any case should enlarge the total cross section for the reaction $\alpha + {}^{44}$Ca by 1% or less, for $\alpha + {}^{40}$Ca by 5% or less.

The conclusions drawn in this paper depend mainly on the relative ratio of the $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca fusion cross sections rather than on absolute values. It is believed that the uncertainty arising from (1) to (4) is smaller than 10% for the ^{44}Ca/^{40}Ca ratio shown in Fig. 1.

The results of Figs. 1 and 2 are interesting with respect to the backward-angle anomalies of elastic and inelastic $\alpha + {}^{40,44}$Ca scattering. In a comprehensive analysis of $\alpha + {}^{40,44}$Ca scattering between 24 and 166 MeV Delbar *et al.*[2] have recently shown that (for the first time) this large body of data, including back-angle data, could be described consistently by using an optical potential with a squared Woods-Saxon form (as is suggestive from recent folding models). The geometrical factors and the strength of the real part of the potential were found to be very close for $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca; the strength of absorption, however, is about twice as large for $\alpha + {}^{44}$Ca as for $\alpha + {}^{40}$Ca. Comparative calculations with these potentials using the Brink-Takigawa[4] semiclassical method are in excellent (better than 10%) agreement with the (full) optical-model calcula-

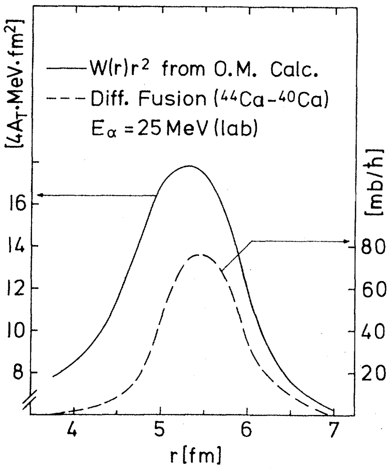

FIG. 3. Comparison of the difference in fusion cross sections (lower curve in Fig. 2) with the difference in absorption $W(r)r^2$ between $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca, empirically found in optical-model studies (from Ref. 2).

tions (and with the data). The semiclassical calculations show that the back-angle enhancement of the cross section for $\alpha + {}^{40}$Ca results from the internal barrier scattering amplitude.[2,4] As expected it disappears at about 60 MeV bombarding energy where the pocket in the potential disappears—in excellent agreement with the experimental observation.

The most important and most critical assumption in these calculations (both optical model and semiclassical) is the *only moderate* absorption for $\alpha + {}^{40}$Ca. The difference from $\alpha + {}^{44}$Ca is illustrated in Fig. 3 at 25 MeV, where the function $W(r)r^2$ (taken from Ref. 2) is a measure of the amount of flux absorbed from the entrance channel in a spherical layer at a distance r from the center of the colliding nuclei.[10] This curve peaks near the nuclear surface indicating that the stronger absorption for $\alpha + {}^{44}$Ca is likely to result from the four additional $f_{7/2}$ neutrons in ^{44}Ca (Ref. 2). The comparison of these different, empirically found $\alpha + {}^{40}$Ca absorption strengths is compared in Fig. 3 with the difference found in the fusion cross sections (Fig. 2), and a surprisingly close correlation is observed between the two curves. Although the presentation of the fusion cross sections in the form of Fig. 2 is somewhat model dependent, it is interpreted as the first experimental evidence that the absorption for $\alpha + {}^{40}$Ca and $\alpha + {}^{44}$Ca indeed is quite different in the vicinity of the nuclear surface. This has been a crucial question in the ALAS interpretations throughout recent years. The present paper seems to settle—along with the work of Refs. 2, 3, and 4—the long-standing "potential" versus "resonance" controversy of ALAS in favor of the potential interpretation. More generally, it gives the strongest experimental evidence to date for a surface transparent potential.

It is a pleasure to thank H. Bohn and S. Landowne for helpful discussions.

---

[1] See, e.g., J. S. Eck *et al.*, Nucl. Phys. A255, 157 (1975), and literature therein; P. Braun-Munzinger *et al.*, Phys. Rev. Lett. 38, 944 (1977).

[2] T. Delbar *et al.*, Phys. Rev. C 18, 1237 (1978).

[3] H. P. Gubler *et al.*, Phys. Lett. 74B, 202 (1978).

[4] D. M. Brink and N. Takigawa, Nucl. Phys. A279, 159 (1977).

[5] A. E. Bisson, K. A. Eberhard, and R. H. Davis, Phys. Rev. C 1, 539 (1970).

[6] P. Sperr *et al.*, Phys. Rev. Lett. 36, 405 (1976), and 37, 321 (1976).

[7] D. Glas and U. Mosel, Nucl. Phys. A237, 429 (1975), and Phys. Rev. C 10, 2620 (1974).

[8] K. A. Eberhard, Phys. Lett. 33B, 343 (1970).

[9] K. A. Eberhard *et al.*, Phys. Rev. C 14, 548 (1976).

[10] We note that in Fig. 5 of Ref. 2 the scale of the function $W(r)r^2/(4A_T)$ is wrong by a factor of approximately 20.