Limitation of Heavy-Ion Fusion: Fusion of Aligned ^{23}Na with ^{23}Na

K. Blatt, K. Becker, B. Heck, H. Jänsch, H. Leucker, and D. Fick
Fachbereich Physik, Philipps-Universität, 3550 Marburg, West Germany

R. Čaplar
Rudjer Bošković Institute, 41001 Zagreb, Yugoslavia

and

R. Butsch, D. Krämer, K.-H. Möbius, Z. Moroz,[a] W. Ott, P. Paul,[b] E. Steffens, G. Tungate, Irena M. Turkiewicz,[a] and A. Weller
Max-Planck-Institut für Kernphysik, 6900 Heidelberg, West Germany
(Received 10 December 1985)

The excitation function for fusion of ^{23}Na with ^{23}Na was measured in the energy range $40 \leq E_{c.m.} \leq 88.5$ MeV. Additionally, the tensor analyzing power T_{20} was determined to be $T_{20} = -0.0060 \pm 0.0125$ at $E_{c.m.} = 85$ MeV. The results are discussed in terms of an entrance-channel versus a compound-nucleus model for the observed limitation of fusion. A typical entrance-channel model, the surface-friction model, which is able to describe all fusion excitation functions leading to ^{46}Ti, fails to reproduce the observed value of T_{20}. The data are consistent, on the other hand, with the compound-nucleus interpretation.

PACS numbers: 25.70.Jj, 24.70.+s

One of the open questions in present-day research on heavy-ion fusion is the limitation of complete fusion at high energies.[1] At low energies the fusion cross section is determined by the grazing angular momentum and exhausts a fair fraction of the total reaction cross section. At higher energies the fusion cross section starts rather suddenly to deviate from the reaction cross section and after reaching a maximum decreases again. Two completely different concepts have been proposed to explain this limitation of the fusion process: One is based on the entrance-channel properties, the other on the properties of the compound nucleus.

The conventional approach clarifying this situation is the comparison of various entrance channels leading to the same compound nucleus.[2,3] Here we present results for a new entrance channel (^{23}Na + ^{23}Na) leading to one of the most studied compound nuclei[4–8]: ^{46}Ti (Fig. 1). In addition we use a new tool: the measurement of the second-rank tensor analyzing power T_{20} for fusion of ^{23}Na with ^{23}Na. This experiment provides new, independent information by testing the sensitivity of the fusion cross section to the alignment of one of the deformed reaction partners. It clearly points to a compound-nucleus explanation for the limitation of the fusion cross section in the system under investigation.

At low energies, near and below the fusion barrier, it is well known experimentally that the alignment of deformed nuclei influences the fusion cross section considerably.[9–12] Among other calculations those[13] within the surface-friction model,[14] an entrance-channel model, reproduce the data around the barrier, received with aligned ^{7}Li and ^{23}Na beams, very well. This model also predicts small but nonvanishing values of the analyzing power T_{20} for the fusion of ^{23}Na with ^{23}Na at high energies.[13] On the other hand, any (simple) interpretation of the limitation of the fusion cross section within a compound-nucleus model has to predict no dependence of the fusion cross section on the alignment, and therefore a vanishing second-rank tensor analyzing power T_{20}. This prediction is based on the general argument that any kind of entrance-channel variables, among them various orientations of the alignment axes of the deformed projectile, cannot affect the fusion cross section if it is determined exclusively by the properties of the compound nucleus. (A more sophisticated analysis is found below.)

The experiment, which will be described in greater detail in a forthcoming paper,[15] was performed at the Heidelberg MP-tandem–postaccelerator facility using unpolarized and polarized (aligned) ^{23}Na beams from recently installed atomic-beam sources.[16,17] The energies of the unpolarized beams ranged from 80 to 177 MeV. The measurement with the aligned beam was performed at a beam energy of $E = 170$ MeV only.

A time-of-flight spectrometer[18] was used to detect the reaction products at up to eighteen angles ranging from $\theta_{lab} = 2°$ to $\theta_{lab} = 30°$. The achieved time resolution of 70 to 100 ps, with an energy spread of 1 MeV, allowed for the separation of individual masses in the region of interest ($A < 45$). The targets consisted of 100 to 150 μg/cm^2 NaBr on 10–15-μg/cm^2 ^{12}C backings. The separation of the evaporation residues resulting from the $^{23}Na+^{12}C$ fusion on the carbon backing from those of the $^{23}Na+^{23}Na$ fusion was achieved by analysis of the velocity spectra for each mass. The uncertainty in this separation is important for the determination of the cross section for the low-mass evaporation-residue-like fragments from $^{23}Na+^{23}Na$ fusion. But because of the small contribution of these masses, the integrated fusion cross section is affected only slightly by this uncertainty. The values for the total fusion cross section were obtained by integrating the measured differential cross sections $d\sigma/d\theta$ for the evaporation-residue-like fragments over $d\theta$. Absolute values of these cross sections were obtained by normalization to the Rutherford cross section.

The contribution of the incomplete fusion process to the total $^{23}Na+^{23}Na$ fusion cross section, which for symmetric systems cannot be deduced from the difference between the compound-nucleus velocity and the mean velocities of the evaporation-residue-like fragments, was estimated to be small. This estimate was based on the general dependence of the threshold energy for the onset of incomplete fusion on the mass asymmetry in the entrance channel.[19]

The tensor analyzing power T_{20} for the fusion of ^{23}Na with ^{23}Na was obtained by comparing the fusion cross section σ_{al} for an aligned beam with the cross section σ for an unpolarized beam and normalizing with the alignment t_{20} of the beam,[20] according to $T_{20}=(\sigma_{al}/\sigma-1)/t_{20}$. In order to reduce systematic errors, the beam was switched between different polarization states at intervals of approximately 2 s. The reaction $^1H(^{23}Na,\alpha)^{20}Ne_{g.s.}$ at 0° has an energy-independent analyzing power $T_{20}=-1$,[21] and was used to determine the alignment $t_{20}=0.23\pm0.05$ of the accelerated 170-MeV ^{23}Na beam. At this energy the analyzing power for fusion of ^{23}Na with ^{23}Na turned out to be $T_{20}=-0.0060\pm0.0125$, which is consistent with zero. The error includes both statistical and estimated systematic contributions.

Figure 1 shows the excitation function for fusion of ^{23}Na with ^{23}Na together with data for four other entrance channels leading to the same compound nucleus ^{46}Ti.[4–8] Also plotted in this figure is the value for the tensor analyzing power T_{20} measured at $E_{c.m.}=85$ MeV. The limitation of the fusion cross section is obvious in the $^{20}Ne+^{26}Mg$ and in the $^{23}Na+^{23}Na$ data which extend to sufficient high energies. The formula

$$\sigma(E)=\pi\lambda\!\!\!^{-2}(l_{crit}+1)^2, \tag{1}$$

which gives the fusion cross section $\sigma(E)$ in terms of a critical angular momentum l_{crit}, is often used to relate the fusion cross section to the properties of the compound nucleus. Figure 2 displays all data points of Fig. 1 in form of an l_{crit}-E^* plot, E^* being the excitation energy of the compound nucleus. This plot indicates that, for sufficient high excitation energies ($E^*>70$ MeV), all data points converge towards one curve. This points to the properties of the compound nucleus as a reason for the observed limitation of the fusion cross section. Figure 2 displays also the yrast line $E^*_{yrast}(l)$ and the statistical yrast line $E^*_{SYL}(l)$,[23]

$$E^*_{SYL}(l)=E^*_{yrast}(l)+\Delta Q = (\hbar^2/2\theta)\,l(l+1)+\Delta Q, \tag{2}$$

calculated with a moment of inertia for a rigid sphere $[\theta=(2/5)MR^2]$ with $R=1.2A_{CN}^{1/3}$ fm for the compound nucleus ^{46}Ti. According to the systematics of Lee, Matsuse, and Arima,[22] ΔQ was chosen as $\Delta Q=10$ MeV.

Like the compound-nucleus yrast-line concept, entrance-channel models are also able to explain the limitation of the fusion process. Moreover, some of the entrance-channel models describe excitation functions of the fusion cross section successfully in a wide energy range. Calculations within the surface-friction model,[14,23] which is able to describe a large variety of

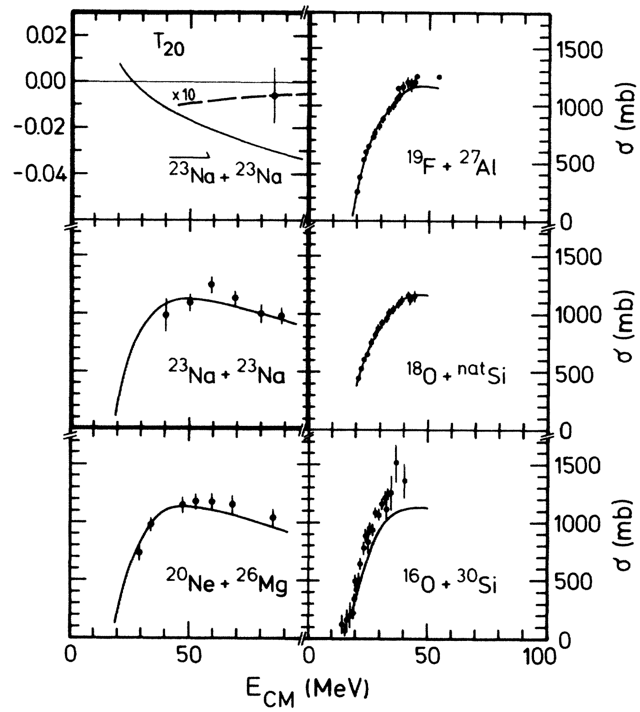

FIG. 1. Excitation functions of the fusion cross section for different entrance channels $^{16}O+^{30}Si$ (Ref. 4), $^{18}O+^{nat}Si$ (Ref. 5), $^{19}F+^{27}Al$ (Refs. 6 and 7), $^{20}Ne+^{26}Mg$ (Ref. 8), and $^{23}Na+^{23}Na$ (this work), all leading to the same compound nucleus ^{46}Ti. Also plotted is the tensor analyzing power T_{20} for fusion of the aligned deformed ^{23}Na projectile with the ^{23}Na target. The solid lines display calculations within the surface-friction model (Refs. 14 and 23). The dashed curve in the T_{20} plot represents the prediction of the compound-nucleus model (multiplied by a factor of 10).

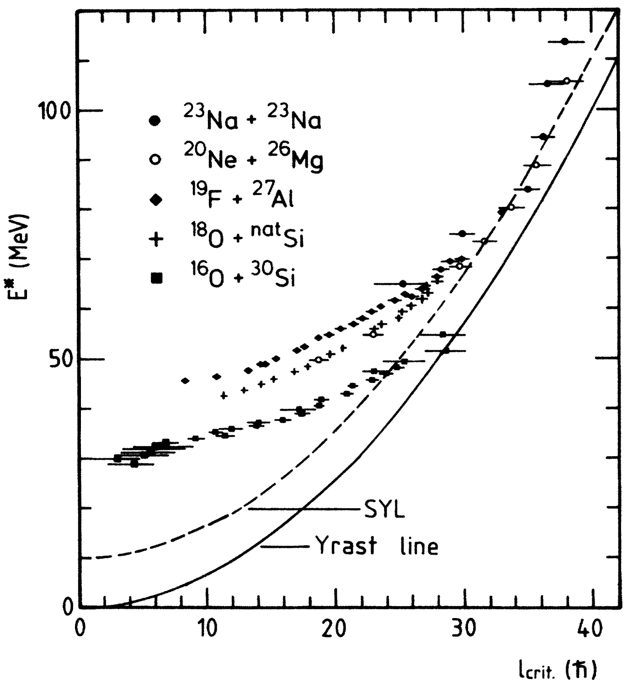

FIG. 2. Excitation energy of ^{46}Ti vs critical angular momentum l_{crit}. The data points of the different entrance channels leading to the compound nucleus ^{46}Ti are deduced from the experimental cross sections of Fig. 1 by use of the sharp cutoff procedure. The yrast and statistical yrast lines (SYL) are also plotted.

systems, are plotted in Fig. 1 as solid lines. They reproduce the five excitation functions of the cross section for fusion leading to ^{46}Ti reasonably well. Obviously, both the entrance-channel and the compound-nucleus concepts are able to reproduce the limitation of fusion as far as excitation functions are concerned.

In order to predict second-rank-tensor analyzing powers T_{20} within the surface-friction model, trajectories for aligned nuclei have to be calculated. For this, conservative and friction forces depending additionally on the alignment of the symmetry axes of the deformed projectile have to be introduced as well. The T_{20} plot in Fig. 1 shows the result of such a calculation as a solid line.[13] In the energy range $40 \leq E_{c.m.} \leq 100$ MeV the calculated tensor analyzing power T_{20} for fusion of ^{23}Na with ^{23}Na is negative (because of the positive quadrupole moment of ^{23}Na) and increases with energy to a few percent. Despite its relatively large error bar, the experimental value clearly disagrees with the prediction of the surface-friction model. This might point either to a failure of this model or to a need to refine it.

On the other hand, and also within the statistical yrast-line model, an estimate for T_{20} can be obtained. Within this model l_{crit} is interpreted as the maximum angular momentum which can be stood by the compound nucleus. Taking the spin s of the projectile into account, l_{crit} is replaced by a critical total angular momentum J_{crit}. Then for a polarized beam, in a single substate m, the fusion cross can be calculated to be[24]

$$\sigma_m = \pi \lambda\!\!\!^{-2} \sum_{J}^{J_{crit}} \left[\sum_{l=|J-s|}^{J+s} \langle sml0|Jm\rangle^2 (2l+1) \right], \qquad (3)$$

whereby the orbital angular momentum l and the spin s of the projectile couple to the total angular momentum J. This leads to

$$\sigma = \pi \lambda\!\!\!^{-2} (J_{crit}^2 + 2J_{crit} - \tfrac{1}{4}) \qquad (4)$$

and

$$T_{20} = -\pi \lambda\!\!\!^{-2} / \sigma. \qquad (5)$$

The prediction of the compound-nucleus model (multiplied by a factor 10) is shown as dashed curve in the T_{20} plot of Fig. 1. At $E_{c.m.} = 85$ MeV $T_{20} = -5 \times 10^{-4}$ is in good agreement with the data.

Another hint that compound-nucleus properties explain the limitation of fusion at high energies is the fact that the experimental values of T_{20} for the individual evaporation-residue-like masses are also in agreement with zero and show no mass dependence.[15] Since evaporation residues with different masses are correlated with different parts of the angular momentum distribution, this experimental result indicates the insensitivity of the fusion cross section at this energy to entrance channel angular momenta.

In summary, this experiment on the ^{23}Na + ^{23}Na fusion has added to the investigation of the fusion to the compound nucleus ^{46}Ti via a new heavy-ion entrance channel. The T_{20} datum point for fusion of ^{23}Na with the aligned ^{23}Na projectile is the first one of this type measured for heavy-ion fusion at high energies. It demonstrates that the second-rank-tensor analyzing power T_{20} represents a sensitive test for the heavy-ion fusion mechanism at high energies. The results obtained for the fusion cross section and T_{20} are consistent with a compound-nucleus explanation of the limitation of fusion. An entrance-channel model, the surface-friction model, is able to describe in detail the fusion excitation functions of different entrance channels leading to the compound nucleus ^{46}Ti. However, this model fails to reproduce the value of the tensor analyzing power for the ^{23}Na + ^{23}Na fusion at high energy. Future work, both experimental and theoretical, on this problem has to investigate whether this failure is one of a fundamental character or whether it merely reflects the incompleteness of the model.

We thankfully recognize contributions of Dr. H. Gemmeke, Kernforschungszentrum Karlsruhe, during the planning stage of this experiment. This work was supported in part by the Bundesministerium für Forschung und Technologie, Bonn, and the "Internationales Büro" der Kernforschungsanlage Jülich GmbH. One of (P.P.) is an Alexander-von-Humboldt awardee.

[(a)]On leave of absence from Institute of Nuclear Studies, Swierk, Poland.

[(b)]On leave of absence from Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794.

[1]U. Mosel, in *Treatise on Heavy-Ion Science,* edited by D. A. Bromley (Plenum, New York, 1984), Vol. 2.

[2]D. E. di Gregorio, J. Gomez del Campo, Y. D. Chan, J. L. C. Ford, Jr., D. Shapira, and M. E. Ortiz, Phys. Rev. C **26**, 1490 (1982).

[3]R. Novotny, D. Shapira, Y.-D. Chan, D. E. di Gregorio, J. L. C. Ford, Jr., J. Gomez del Campo, M. F. Ortiz, and F. Pougheon, Phys. Rev. C **26**, 2664 (1982).

[4]W. J. Jordan, J. V. Maher, and J. C. Peng, Phys. Lett. **87B**, 38 (1979).

[5]R. Rascher, W. F. J. Müller, and K. P. Lieb, Phys. Rev. C **20**, 1028 (1979).

[6]F. Pühlhofer, Nucl. Phys. **A280**, 267 (1977).

[8]H. Lehr, W. Bohne, H. Grabisch, H. Morgenstern, and W. von Oertzen, Nucl. Phys. **A415**, 149 (1984).

[9]K.-H. Möbius *et al.,* Z. Phys. A **306**, 335 (1982).

[10]K.-H. Möbius *et al.,* Phys. Rev. Lett. **46**, 1064 (1981), and Z. Phys. **A310**, 159 (1983).

[11]K.-H. Möbius and G. Grawert, in *Proceedings of the International Conference on Fusion Reactions Below the Coulomb Barrier,* edited by S. G. Skadman, Lecture Notes in Physics Vol. 219 (Springer, Berlin, 1985).

[12]R. Butsch, *et al.,* in Proceedings of the Sixth International Symposium on Polarization Phenomena in Nuclear Physics, Osaka, 1985, J. Phys. Soc. Jpn. Suppl. **55**, 74 (1986).

[13]P. Fröbrich and G. Grawert, Nucl. Phys. **A451**, 338 (1986).

[14]P. Fröbrich, Phys. Rep. **116**, 337 (1984).

[15]K. Blatt, Ph.D. thesis, University of Marburg, 1985 (unpublished), and to be published.

[16]K.-H. Möbius and K. Blatt, Nucl. Instrum. Methods **225**, 293 (1984).

[17]D. Krämer *et al.,* Nucl. Instrum. Methods **220**, 123 (1984).

[18]B. Kolb, G. Hlawatsch, G. Rosner, Th. Walcher, H. Ingwersen, E. Jaeschke, and R. Repnow, Nucl. Instrum. Methods **188**, 555 (1981).

[19]H. Morgenstern, W. Bohne, W. Galster, K. Grabisch, and A. Kyanowsky, Phys. Rev. Lett. **52**, 1104 (1984).

[20]The alignment t_{20} of a spin $-\frac{3}{2}$ beam is defined by the occupation probabilities $N(m)$ of the magnetic substate m according to $t_{20}=\{N(\frac{3}{2})+N(-\frac{3}{2})\}-\{N(\frac{1}{2})+N(-\frac{1}{2})\}$.

[21]P. Zupranski *et al.,* Nucl. Instrum. Methods **167**, 193 (1979).

[22]S. M. Lee, T. Matsuse, and A. Arima, Phys. Rev. Lett. **45**, 165 (1980).

[23]P. Fröbrich, private communication.

[24]H. Nishioka, private communication.