operating staff. We also thank Professor L. Grodzins and Dr. P. Wurm for helpful discussions.

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

†Supported by Undergraduate Research Opportunities Program.

‡Permanent address: Niels Bohr Institute, Copenhagen, Denmark.

[1]A. G. Artukh, G. F. Gridnev, V. L. Mikheev, V. V. Volkov, and J. Wilczynski, Nucl. Phys. A215, 91 (1973).

[2]F. Hanappe, M. Lefort, C. Ngô, J. Peter, and B. Tamain, Phys. Rev. Lett. 32, 738 (1974).

[3]R. Albrecht, W. Dünnweber, G. Graw, H. Ho, S. G. Steadman, and J. P. Wurm, Phys. Rev. Lett. 34, 1400 (1975).

[4]T. M. Cormier, A. J. Lazzarini, M. A. Neuhausen, A. Sperduto, K. Van Bibber, F. Videbæk, G. Young, E. B. Blum, L. Herreid, and W. Thoms, Phys. Rev. C 13, 682 (1976). R. Eggers, M. N. Namboodiri, P. Gonthier, K. Geoffrey, and J. B. Natowitz, Phys. Rev. Lett. 37, 324 (1976).

[5]R. Y. Cusson, R. K. Smith, and J. A. Maruhn, Phys. Rev. Lett. 36, 1166 (1976).

[6]R. A. Broglia, C. H. Dasso, and Aa. Winther, Phys. Lett. 61B, 113 (1976).

[7]L. G. Moretto and J. S. Sventek, Phys. Lett. 58B, 26 (1975).

[8]M. Ishihara, T. Numao, T. Fukuda, K. Tanaka, and I. Inamura, in Proceedings of the Symposium on Macroscopic Features of Heavy-Ion Collisions, Argonne, Illinois, 1976, edited by D. G. Kovar, ANL Report. No. ANL/PHY-76-2 (to be published), p. 617.

[9]R. G. Markham, S. M. Austen, and H. Laumer, Nucl. Instrum. Methods 129, 141 (1975).

[10]J. W. Harris, T. M. Cormier, D. F. Geesaman, L. L. Lee, R. L. McGrath and J. P. Wurm, in Proceedings of the Symposium on Macroscopic Features of Heavy-Ion Collisions, Argonne, Illinois, 1976, edited by D. G. Kovar, ANL Report No. ANL/PHY-76-2 (to be published), p. 609; R. Albrecht *et al.*, Max Planck Institut für Kernphysik, Heidelberg, Jahresbericht, 1975 (unpublished), p. 72.

[11]G. Young, E. Blum, A. J. Lazzarini, M. A. Neuhausen, S. G. Steadman, and N. Tsoupas, in Proceedings of the Symposium on Macroscopic Features of Heavy-Ion Collisions, Argonne, Illinois, 1976, edited by D. G. Kovar, ANL Report No. ANL/PHY-76-2 (to be published), p. 849.

[12]F. Ajzenberg-Selove, Nucl. Phys. A190, 1 (1972).

Study of the Fusion Reaction $^{12}C + ^{12}C$ below the Coulomb Barrier*

K.-U. Kettner, H. Lorenz-Wirzba, and C. Rolfs
Institut für Kernphysik, Universität Münster, Münster, Germany

and

H. Winkler†
Niels-Bohr-Institutet, Copenhagen, Denmark, and Institut für Kernphysik, Universität Münster, Münster, Germany

(Received 4 October 1976)

The reaction $^{12}C + ^{12}C$ has been studied at $E_{c.m.} = 2.5$ to 6.2 MeV by γ-ray spectroscopy. New resonances were found below 4 MeV. When the influence of the Coulomb barrier is removed, these resonances are superimposed on a flat background, which does not show a strong increase at low energies, in contrast to previous work.

The fusion cross section of $^{12}C + ^{12}C$ has been determined previously[1-3] at beam energies as low as $E_{c.m.} = 2.45$ MeV (Ref. 3) by observation of the light charged particles emitted in the $^{23}Na + p$ and $^{20}Ne + \alpha$ exit channels. For astrophysical purposes, the fusion cross section has been extrapolated[4-6] to even lower energies. The extrapolation of Michaud and Vogt,[5] known as "absorption under the barrier," leads to high fusion cross sections in this region. This extrapolation is supported by the measurements of Ref. 3 in the energy range $E_{c.m.} = 2.45$–3.20 MeV. However, the reported fusion cross sections are rather uncertain at these low energies.

In the present work, the $^{12}C + ^{12}C$ process at $E_{c.m.} = 2.5$–6.2 MeV has been studied by γ-ray spectroscopy with a Ge (Li) detector. γ-ray transitions from a large number of excited states in ^{20}Ne and ^{23}Na were observed, which show strong and rapid yield variations. Only the results for the γ-ray transitions from the first excited state in ^{20}Ne ($E_\gamma = 1634$ keV) and ^{23}Na ($E_\gamma = 440$ keV) are reported here. These states are populated directly as well as by γ cascades from higher excited states and the γ-rays "γ_{1634}" and "γ_{440}" are the most intense lines in the spectra. Their yields as function of beam energy represent a somewhat varying but sizable fraction of the total fusion yield [mean value ≈68(45)% of the $\alpha(p)$ channel, according to Ref. 3]. Most of the fusion yield not accounted for by these two γ rays consists of production of ^{20}Ne + α_0, α_5, or α_6, and ^{23}Na + p_0, p_4, p_9, p_{10}, or p_{15}.

The presence of ^{1}H and ^{2}H in the targets seriously hampers the measurement of the ^{12}C + ^{12}C process at low energies both in the charged-particle and γ-ray spectroscopy. For the charged-particle method, elastic ^{1}H and ^{2}H recoils mask the low-energy part of the spectrum and the reaction ^{2}H(^{12}C, p)^{13}C gives rise to high-energy protons. γ-ray measurements suffer under an intense background with the $E_\gamma \approx 2.36$ MeV from ^{1}H(^{12}C, γ)^{13}N and the $E_\gamma = 3.09$ MeV from ^{2}H(^{12}C, $p_1\gamma$)^{13}C. Therefore, targets with low hydrogen content were used in the present work.

The ^{12}C beam (up to 15 particle μA) was supplied by the Bochum Dynamitron Tandem Accelerator. A 1-μA ^{19}F beam was used to investigate the hydrogen distribution in the target[7] and to provide a check on the energy calibration of the accelerator. Both measurements were carried out at the well-known $E_p = 340.5$-keV resonance of ^{19}F(p, $\alpha\gamma$)^{16}O by using the inverse reaction ^{1}H(^{19}F, $\alpha\gamma$)^{16}O at $E(^{19}\mathrm{F}) = 6.418$ MeV. This energy corresponds to a magnetic field of the analyzing magnet equivalent to that required for a ^{12}C^{2+} beam of $E(^{12}\mathrm{C}) = 5.05$ MeV. Tantalum targets homogeneously loaded with 1–4% ^{1}H were used. The energy calibration was found to be correct and constant in time within ± 0.1%.

Carbon targets (9 to 55 μg/cm^2) were evaporated on 0.3-mm-thick Ta backings from pure graphite (supplied by Ringsdorf-Werke) with an electron gun in a bell jar with a large internal liquid-nitrogen–cooled surface. The hydrogen profile in the targets was investigated with the ^{19}F beam. The best targets contained no greater than 0.1 at.% of hydrogen, located mainly on top but sometimes also on the bottom of the carbon layer. The target thicknesses were determined at the Münster 350-kV accelerator to better than 20% accuracy from the observed energy spread of the γ rays in ^{12}C(p, γ)^{13}N.

All targets were cooled to 100°C by oil flow behind the backing. A liquid-nitrogen–cooled copper tube (30-cm length) extended to within 2 mm of the target, together they formed the Faraday cup for beam integration. With this tube and two more liquid-nitrogen traps, additional hydrogen contamination was kept below 0.02 at.% for a 14-μg/cm^2-thick target after 48 hours of bombardment. By running the target at an elevated temperature with the liquid-nitrogen–cooled surface close by, hydrogen from the outer surface of the carbon layer was removed during the first hour in vacuum. The target thickness stayed constant to better than ± 1 μg/cm^2 for a 20-particle Coulomb deposition. The 76-cm^3 Ge(Li) detector was positioned at 0° with 1.4 cm between the crystal front face and the target. A 7-cm-thick lead shield surrounded both the target and the detector.

The ^{12}C + ^{12}C measurements were taken in steps of 25–100 keV (c.m.) for a range of target thicknesses. Figure 1 shows a sample γ-ray spectrum obtained in the energy range where the γ-ray background from reactions on the H contamination in the target is most intense relative to γ_{1634} and γ_{440}. At $E_{\mathrm{c.m.}} = 3.5$–6.2-MeV measurements of γ-ray angular distributions have been carried out.[8]

For a comparison of the present results with previous work, only the data of Ref. 3 were used. In Ref. 2, only p and α production cross sections are given. The original data[12] of Ref. 2, going down to $E_{\mathrm{c.m.}} = 3.23$ MeV, contain much less information than Ref. 3 on individual exit channels (because of the lower resolution in the counter telescope used), especially below 3.73 MeV. Above this energy, however, the total cross section of Refs. 2 and 3 are in fair agreement and our measurements basically agree with the data of Ref. 3, except for details in the cross sections and a possible energy discrepancy (to be dis-

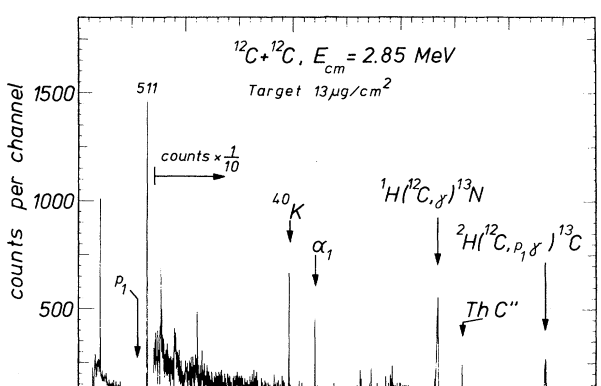

FIG. 1. Sample γ-ray spectrum obtained with Ge(Li) detector in close geometry and a tight lead shielding. The well-known $E_p = 457$ keV resonances ($\Gamma = 39$ keV) in ^{12}C(p, γ)^{13}N [$\sigma_{\mathrm{res}} = 120$ μb] corresponds in the inverse reaction ^{1}H(^{12}C, γ)^{13}N to an energy of $E_{\mathrm{c.m.}}(^{12}\mathrm{C} + ^{12}\mathrm{C}) = 2.74$ MeV.

cussed later). The partial cross sections for individual exit channels[3] have been used to calculate the fraction of all ^{20}Ne + α and ^{23}Na + p decays that lead to the emission of γ_{1634} and γ_{440}, respectively. The cross section σ_{1634} for the production of γ_{1634} was calculated from the expression

$$\sigma_{1634} = 1.0\sigma_1 + 0.94\sigma_2 + 0.94\sigma_3 + 0.42\sigma_{4+5} + 0.87\sigma_7,$$

where σ_i are the reported partial cross sections (Table I of Ref. 3) for production of ^{20}Ne in the ith excited state and the numerical factors are deduced from the known decay schemes of these states.[9] A similar expression was obtained for the production cross sections σ_{440} of γ_{440}. In some cases, partial cross sections are given[3] only for a group of two nearby states, where one member does not γ decay through the first excited state. For these cases[3] (α_{4+5}, p_{4+5}, and p_{8+9}) it was assumed that, for all energies, the quoted partial cross sections are shared equally by both states. Furthermore, photo-peak-count losses due to summing (~ 5–10%) were taken into account in the numerical factors. Whenever the second or a higher excited state contributes to γ_{1634} or γ_{440}, at least one other γ ray is emitted in cascade. The loss of counts is constant for a particular excited state and is not a function of energy.

The cross sections drop strongly with decreasing beam energy mainly due to the Coulomb barrier. For an easier comparison of the present results with previous work, these cross sections were converted to $\tilde{S}(E)$ values through the relation[3]

$$\sigma(E) = \tilde{S}(E)E^{-1}\exp(-2\pi\eta - gE)$$
$$= \tilde{S}(E)E^{-1}\exp(-87.21E^{1/2} - 0.46E),$$

with $E_{\mathrm{c.m.}}$ given in units of MeV. By applying this expression to σ_{1634} and σ_{440} of Ref. 3, values for $\tilde{S}_{1634}$ and $\tilde{S}_{440}$ were obtained as given in Figs. 2(a) and 2(b), respectively.

The values for $\tilde{S}_{1634}$ and $\tilde{S}_{440}$ from the present work are also shown in Fig. 2. These results were obtained by the following procedures: Since the γ-ray angular distributions were found to be nearly isotropic, the observed yields for γ_{1634} and γ_{440} represent total reaction rates. With the stopping powers of Northcliffe and Schilling,[10] a calculation of the integrated yields for γ_{1634} and γ_{440} [assuming in a first approximation a $\sigma(E)$ dependence over the *target* thickness as generated by $\tilde{S}(E)$ = constant] for all targets was used to obtain the mean bombarding energies. This procedure was sufficiently accurate for all thin targets,

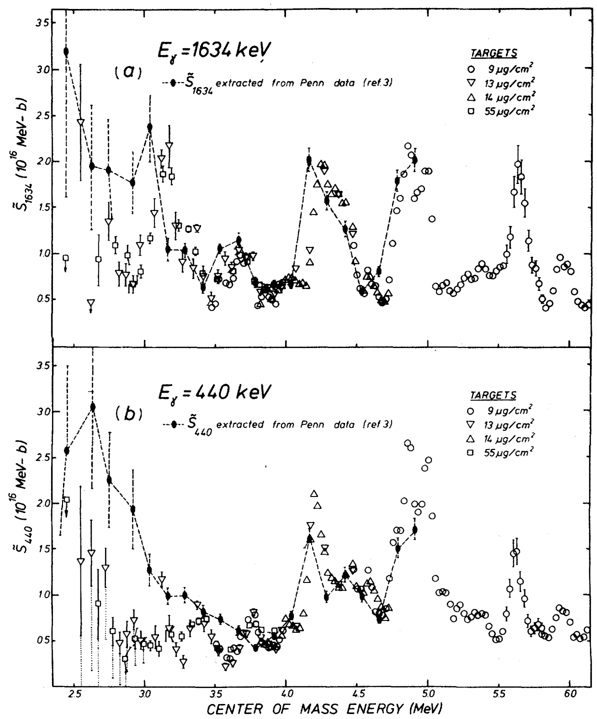

FIG. 2. Results of the fusion process ^{12}C + ^{12}C for (a) $\tilde{S}_{1634}$ and (b) $\tilde{S}_{440}$ are compared with previous work. The points connected by dashed lines correspond to Ref. 3. The present results for different targets are indicated by different symbols, where the statistical errors for many points are equal or smaller than the size of the symbols. If the γ_{440} data points at $E_{\mathrm{c.m.}}$ = 2.45 and 2.55 MeV for the 55- and 14-μg/cm^2-thick targets, respectively, are identified entirely with Coulomb excitation of a ^{23}Na contamination in the targets (dotted error bars), only the values in the neighborhood will be uncertain to a limited amount. This is due to the different energy dependence of Coulomb excitation.

even in the energy regions with sizable changes of $\tilde{S}(E)$. For the 55-μg/cm^2-thick target, however, the actual observed yield curve had to be numerically integrated in order to give reliable mean energies, especially near the 3.2-MeV resonance. The results for the different targets agree in the overlapping energy regions to within the experimental errors. This result is significant because at low energies, where the cross sections rise very rapidly with energy, the calculated $\tilde{S}$ values are extremely sensitive to the c.m. energy. Energy determination in this region becomes as important as the yield measurements. For this reason, both a thin (13-μg/cm^2) and a thick (55-μg/cm^2) target were used in the low-energy region. The $\tilde{S}(E)$ values from all targets were normalized to the absolute values of Ref. 3 for 3.80 to 4.05 MeV (Fig. 2).

The results for $\tilde{S}_{1634}$ [Fig. 2(a)] agree fairly well with those of Ref. 3 with two exceptions: (i) Below 3.25 MeV, the present data indicate resonance structures similar to those found at higher energies, with a minimum at 2.95 MeV and perhaps at 2.60 MeV. (ii) A difference in energies seems to be indicated around 3.2, 3.5, and 4.2 MeV. The difference of ~100 keV is about twice as large as the full energy loss in the thin targets used in the present work in this energy region. A conservative estimate of the error of the mean c.m. energy, calculated for these targets in this energy region, is ±15 keV. The work of Ref. 3 used a 30-μg/cm^2 target for this region.

For $\tilde{S}_{440}$ [Fig. 2(b)], the discrepancies above 4.8 MeV could be caused by the limited partial-cross-section data of Ref. 3. At the narrow peak around 4.2 MeV, the energy scales seem to agree, in contrast to $\tilde{S}_{1634}$. However, this agreement could be accidental in view of the wide energy step size in Ref. 3 and the fact that the peaks in $\tilde{S}_{1634}$ and $\tilde{S}_{440}$ around 4.2 MeV do not occur in our data at the same energy. The four $\tilde{S}_{440}$ points from Ref. 3 between 4.0 and 4.5 MeV would fall right on our data if shifted up by about 90 keV. Since the energies used in Ref. 2 bisect the steps of Ref. 3, an estimate of $\tilde{S}_{440}$ from the original proton data of Ref. 2 was also obtained for this region.[12] These additional $\tilde{S}_{440}$ data indicate a narrow peak at 4.23 MeV, about 30 keV higher than in our data. From 2.7 to 3.8 MeV, the present results do not indicate a strong increase in $\tilde{S}_{440}$.

The present measurements below 3.2 MeV do not support the reported partial cross sections[3] used for the calculation[3] of the total fusion cross section. In view of this disagreement in the partial cross sections, it is not meaningful to use the reported relative yields[3] in order to deduce total fusion cross sections from our measurements. There is some evidence, however, that the disagreement is all or in part in the energy values, in which case the reported yield *ratios*[3] could probably be used, with some corrections, to derive new values of σ_α in this energy range from the results presented here. The same procedure applied to the proton channel would be subject to very large uncertainties, because of (i) the smaller fraction σ_p that σ_{440} represents, (ii) the ^{23}Na Coulomb-excitation problem in our work, and (iii) the difficulty in interpreting the more complex proton particle spectra (see Fig. 1 of Ref. 3) in the presence of proton backgrounds.

The fast and strong fluctuations in the fusion cross sections of $^{12}C+^{12}C$, observed previously at higher beam energies, persist down to low energies.[11] In addition to the observed fine structures, the previously known 4.9-MeV resonance appears as a doublet.

*Supported in part by the Deutsche Forschungsgemeinschaft [Mu 40/39].

†On sabbatical leave from California State University, Los Angeles, Calif. 90053.

[1]E. Almquist, D. A. Bromley, and J. A. Kuehner, Phys. Rev. Lett. 10, 515 (1960).

[2]J. R. Patterson, H. Winkler, and C. S. Zaidins, Astrophys. J. 157, 367 (1969).

[3]M. G. Mazarakis and W. E. Stephens, Phys. Rev. C 7, 1280 (1973).

[4]H. Reeves, Astrophys. J. 146, 447 (1966).

[5]G. Michaud and E. Vogt, Phys. Rev. C 5, 350 (1972).

[6]W. A. Fowler, G. R. Caughlan, and B. A. Zimmerman, Annu. Rev. Astron. Astrophys. 13, 69 (1975).

[7]D. A. Leich and T. A. Trombrello, Nucl. Instrum. Methods 108, 67 (1973).

[8]K.-U. Kettner, H. Lorenz-Wirzba, C. Poppensieker, and C. Rolfs, to be published.

[9]F. Ajzenberg-Selove, Nucl. Phys. A190, 1 (1972); P. M. Endt and C. van der Leun, Nucl. Phys. A214, 1 (1973).

[10]L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables 7, 233 (1970).

[11]A report by M. High and B. Cujek [Bull. Am. Phys. Soc. 21, 656 (1976)] indicates similar experimental results.

[12]H. Winkler, unpublished.