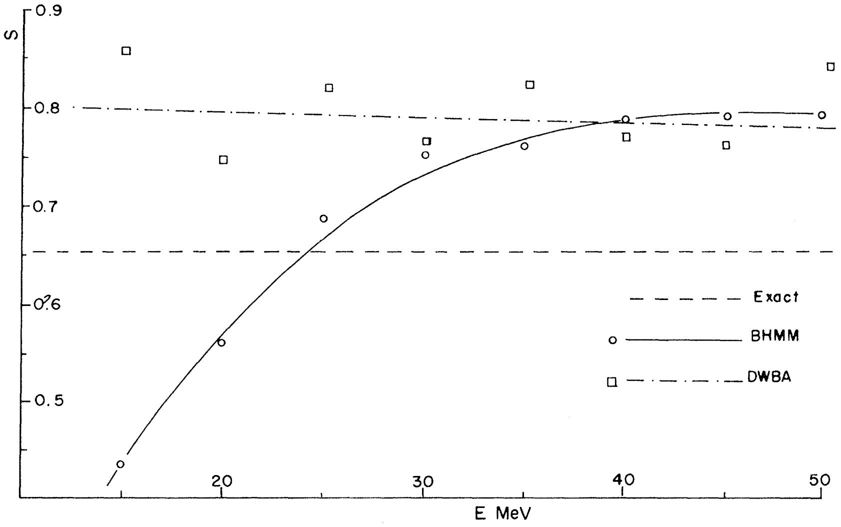

FIG. 2. Energy dependence of the spectroscopic factor extracted by BHMM and DWBA theories.

yield incorrect spectroscopic factors when applied to our model, and the values they give when applied to real nuclei should be regarded with due suspicion. The curious fact that both theories give the same incorrect S at large energies remains unexplained. Further details of the model, with additional applications to the study of the behavior of the BHMM theory near $S=1$, and two-step (d,p) reactions, will be published elsewhere.

This work was supported in part by the Science Foundation for Physics within the University of Sydney, and the authors are grateful to the Director of the Foundation, Professor H. Messel, for this support.

[1] H. A. Bethe and S. T. Butler, Phys. Rev. 85, 1045 (1952); M. H. MacFarlane and J. B. French, Rev. Mod. Phys. 32, 567 (1960).

[2] G. E. Brown, Comments Nucl. Particle Phys. 3, 136 (1969).

[3] P. E. Shanley and R. Aaron, Ann. Phys. (New York) 44, 363 (1967).

[4] P. Beregi, I. Lovas, and J. Revai, Ann. Phys. (New York) 61, 57 (1970).

[5] Y. Yamaguchi, Phys. Rev. 95, 1628 (1954).

[6] S. T. Butler, R. G. L. Hewitt, B. H. J. McKellar, and R. M. May, Ann. Phys. (New York) 43, 282 (1967).

[7] D. P. Bouldin and F. S. Levin, Nucl. Phys. A189, 449 (1972).

[8] K. King and B. H. J. McKellar, Phys. Rev. C 1, 1538 (1970).

[9] T. F. Baker and L. J. B. Goldfarb, Nucl. Phys. A146, 577 (1970).

Experimental Evidence for α-Particle Doorway States in the $^{12}C + {}^{12}C$ Reaction

H. Voit, G. Ischenko, and F. Siller
Physikalisches Institut der Universität Erlangen-Nürnberg, Erlangen, Germany

(Received 29 December 1972)

Quartet states in ^{20}Ne are preferentially populated in the reaction $^{12}C(^{12}C,\alpha)^{20}Ne$ at $E_{c.m.}=5.7$, 6.0, and 6.3 MeV. This may be due to α-particle doorway states having a large overlap with quartet states in ^{20}Ne. The interpretation of the correlated resonances in the $^{12}C+{}^{12}C$ system as intermediate structure resulting from α-particle doorway states is supported by the results of the measurement reported.

Twelve years ago three marked resonances were found in the excitation functions of the α, p, n, and γ yields of the reaction $^{12}C+{}^{12}C$ just below the Coulomb barrier.[1] The resonances at $E_{c.m.}=5.7$, 6.0, and 6.3 MeV were correlated among all angles and exit channels. These experimental results have inspired a great number of experimental and especially theoretical activities. The first interpretation of these resonances was based on the formation of a quasibound ^{12}C-^{12}C molecule. This interpretation was supported by the large reduced carbon width γ_C compared with the single-particle width γ_s ($\gamma_C/\gamma_s = 14\%$).[2] The ^{12}C-^{12}C molecule was considered to be an intermediate step in the reaction mechanism lying between entrance channel and compound nucleus formation, being able to decay either into the compound nucleus or back into the entrance channel. For the formation of the ^{12}C-^{12}C molecule, different mechanisms were reported by several authors.[3-5]

Against this molecular hypothesis the following objections, resulting from later experimental investigations, can be made: (i) The continuation of the resonance structure down to $E_{\text{c.m.}} = 4$ MeV[6,7] with a spacing of less than 0.5 MeV excludes the interpretation in terms of single-particle states for any optical potential with a reasonable radius; (ii) no resonance structure exists in the $^{12}C + ^{13}C$ system,[8,9] although resonances could exist within the molecular hypothesis.

Michaud and Vogt[10] summarize some of the objections to the molecular hypothesis. In that paper they came to the conclusion that $^{12}C + ^{12}C$ resonances are due to α-particle doorway states. This interpretation is supported by the fact that, besides the $^{12}C + ^{12}C$ system, only the $^{16}O + ^{12}C$ system exhibits such correlated resonance structure,[11,12] i.e., only systems with $4n$ nuclei (disregarding the single bump in the γ yield of the $^{14}N + ^{14}N$ system[13]). Furthermore, this interpretation accounts, at least qualitatively, for the right spacing of the resonances observed in the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ systems.

The present paper gives tentative evidence that the α-particle doorway-state hypothesis is correct. The idea is that in the reactions $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$, exited states of the residual nuclei with rather pure α-particle configuration should be preferentially populated at the resonance energies if α-particle doorway states exist as assumed by Michaud and Vogt. There are many indications for the existence of excited states with rather pure α-particle configuration (quartet states) in light $4n$ nuclei, both theoretically[14,15] and experimentally.[16,17,18]

The reaction examined was $^{12}C(^{12}C,\alpha)^{20}Ne$. The measurement was performed in the energy range of the three resonances reported in Ref. 1. The population of quartet states in the residual nucleus ^{20}Ne was compared with the population of nonquartet states having the same angular momentum and parity. As quartet states we assumed both the 7.20-MeV 0^+ and the 7.84-MeV 2^+ states, and the 6.72-MeV 0^+ and the 7.43-MeV 2^+ states. Whereas the configuration of the two former states as two α particles outside a ^{12}C core is well established,[16,19] the interpretation of the two latter states in terms of quartet states, as in the work of Satpathy, Schmid, and Faessler,[14] is not so obvious. These states are usually interpreted as shell-model states with $(sd)^4$ configuration on account of their large cross sections in single-nucleon[20] and two-nucleon[21] transfer reactions. This interpretation is contradicted by the anomalous large α reduced width[22] of these states compared with shell-model calculations.[23] In a recent Letter a significant admixture of $(fp)^4$ configuration has been suggested by Fortune, Middleton, and Betts[24] to account for this large reduced α width. This explanation supports the assumption of a $^{16}O + \alpha$ parentage for the ^{20}Ne states in question, a configuration resulting in large α reduced widths.

The measurement was performed at the Erlangen EN tandem. α spectra of the reaction $^{12}C(^{12}C,\alpha)\,^{20}Ne$ were measured for several angles in the energy range $E_{\text{c.m.}} = 5.5$-6.5 MeV (see Fig. 1). The $\theta_{\text{lab}} = 6°$ spectra were measured with a surface barrier detector covered with a 12-μm Al foil (to absorb the elastically scattered ^{12}C ions). The depletion depth was chosen so that the protons gave only a small energy signal. α particles emitted at $\theta_{\text{lab}} = 25°$ and $65°$ had to be detected with a ΔE-E telescope (gas-flow proportional counter with surface barrier detector) on account of the relatively low energy of those α particles belonging to the high-lying ^{20}Ne quartet states. The comparison between quartet and nonquartet states should be made for about the same c.m. angles. In the case of the $\theta_{\text{lab}} = 6°$ measurements, the comparison can be made using the same spectrum because the c.m. angles are nearly equal for all transitions in question. For the $\theta_{\text{lab}} = 65°$ spectra, the c.m. angles of the nonquartet and the quartet states are symmetric to $\theta_{\text{c.m.}} = 90°$. The comparison of these states is possible because of the 90° symmetry of the cross section of the ^{12}C-^{12}C reaction. To compare the quartet states measured at $\theta_{\text{lab}} = 25°$ with the corresponding nonquartet states, an additional measurement at $\theta_{\text{lab}} = 29.5°$ was made.

The self-supporting ^{12}C targets were about 10 to 15 $\mu g/cm^2$ thick. The linear solid angle of the detectors was about $\pm 1.5°$. Special care was taken concerning the carbon contamination of the

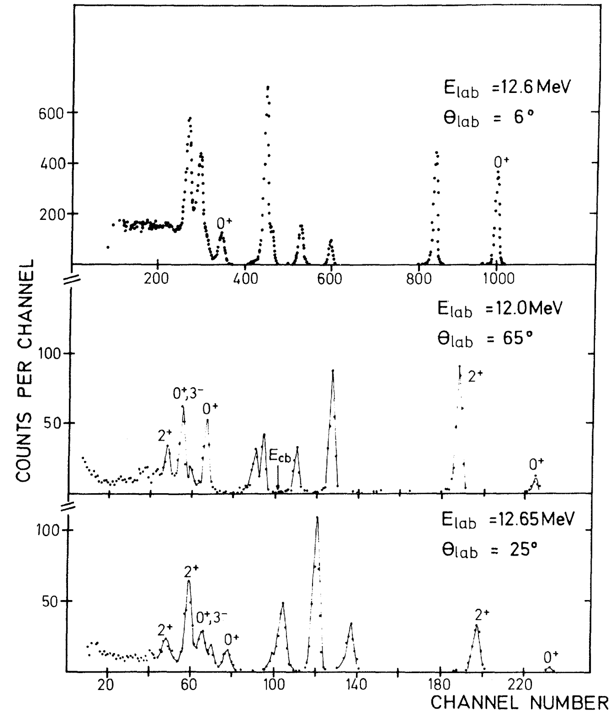

FIG. 1. α-particle spectra from the reaction $^{12}C(^{12}C,\alpha)^{20}Ne$. The peaks on the left side of the spectra, labeled with the J^π values, correspond to transitions to the quartet states in the residual nucleus ^{20}Ne (the 3^- state excepted). From right to left: the 6.72-MeV 0^+, 7.20-MeV 0^+ (together with the unresolved 7.17-MeV 3^- state), 7.43-MeV 2^+, and 7.84-MeV 2^+ states.

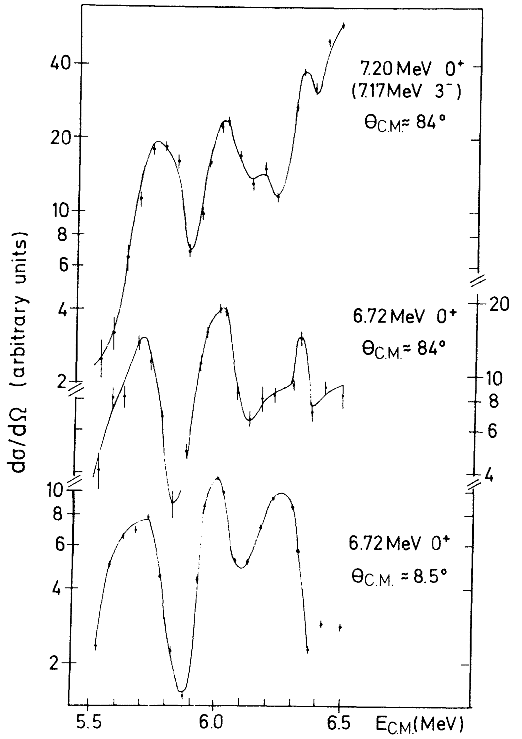

FIG. 2. Excitation functions for transitions to some of the assumed quartet states in ^{20}Ne measured in the energy range, where resonances are reported in Ref. 1. The excitation function for the transition to the 7.20-MeV 0^+ state includes contributions from the unresolved transition to the 7.17-MeV 3^- state.

targets by measuring simultaneously the $^{12}C + ^{12}C$ elastic scattering.

Figure 2 shows some of the excitation functions for transitions to the assumed quartet states in ^{20}Ne. All excitation functions show resonances at the resonance energies reported in Ref. 1. These resonances could, in principle, be explained as statistical fluctuations, because the compound nucleus ^{24}Mg is highly excited in the region of overlapping states ($E_x = 20$ MeV). The width of these states[25] is comparable to the width of the measured resonances. Large deviations from a mean cross section are also not inconceivable on account of the small damping coefficients involved. A strong hint against this interpretation, however, is the cross correlation observed in the excitation functions measured. In order to have further arguments against the statistical interpretation of the resonances, we have compared the c.m. yields for the transitions to the quartet states assumed with those of nonquartet states having the same $J\pi$ assignment. The statistical model predicts that the cross sections for any two excited states of the same spin and parity (comparable excitation energies) should fluctuate in a random way, with the result that, on the average, their cross sections should be comparable. In Fig. 3 cross-section ratios are shown for the transitions to the quartet states compared with transitions to the 0^+ ground state (g.s.) and the 2^+ first excited state of ^{20}Ne. These ratios obviously show marked resonances at the resonance energies of Ref. 1, demonstrating that the selective population of the quartet states in ^{20}Ne must be explained in another way, not by the statistical model.

We believe that the following interpretation of the experimental results could be made: In the $^{12}C + ^{12}C$ reaction α-particle doorway states arise at the resonance energies $E_{c.m.} = 5.7$, 6.0, and 6.3 MeV. These doorway states are built up of $^{16}O + 2\alpha$ and $^{12}C + 3\alpha$ and have a large overlap with the quartet states in ^{20}Ne having $^{16}O + \alpha$ and $^{12}C + 2\alpha$ parentages, respectively. From this overlap, the selective population of the quartet states in ^{20}Ne at the corresponding energies is

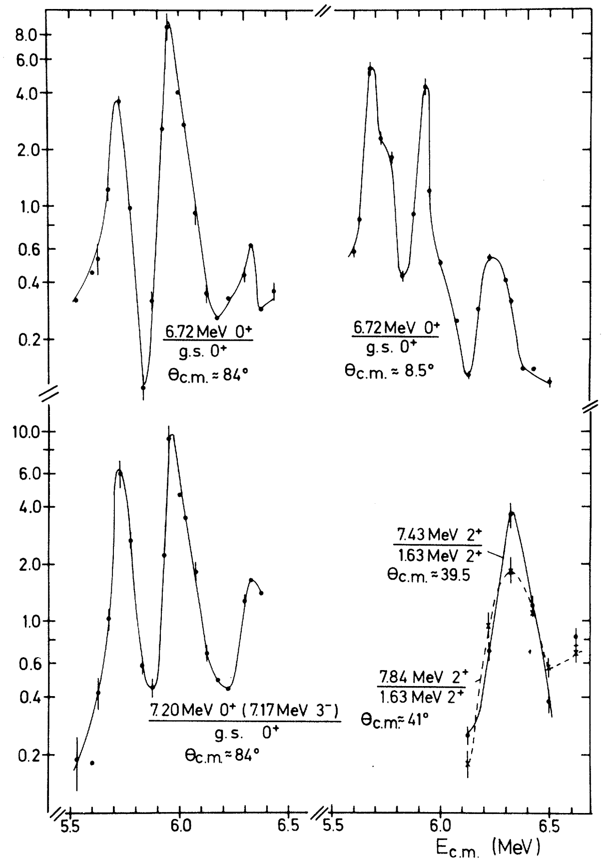

FIG. 3. Cross-section ratios for the transitions to quartet states in ^{20}Ne compared with transitions to non-quartet states.

understandable. The α-particle doorway states are identical with states in ^{24}Mg having ^{16}O + 2α and ^{12}C + 3α parentages, respectively. In Ref. 14 the excitation energy of the ^{12}C + 3α configuration (one quartet hole in the *p* shell, three quartets in the *sd* shell) in ^{24}Mg is calculated at 19.22 MeV. In Ref. 15 the excitation energy for the ^{16}O + 2α configuration (two quartets in the *fp* shell) is calculated at about 20 MeV. These energies agree with the excitation energy of about 20 MeV in ^{24}Mg, which is obtained in the reaction ^{12}C + ^{12}C for projectile energies in the region of the Coulomb barrier.

We believe that our measurements support the interpretation of the ^{12}C + ^{12}C resonances as intermediate structure resulting from α-particle doorway states.

This work was supported by the Bundesministerium für Bildung und Wissenschaft, Bonn, Germany.

---

[1] E. Almqvist, D. A. Bromley, and J. A. Kuehner, Phys. Rev. Lett. 4, 515 (1960).

[2] E. Almqvist, D. A. Bromley, J. A. Kuehner, and B. Whalen, Phys. Rev. 130, 1140 (1963).

[3] E. Vogt and H. McManus, Phys. Rev. Lett. 4, 518 (1960).

[4] R. H. Davis, Phys. Rev. Lett. 4, 521 (1960).

[5] B. Imanishi, Nucl. Phys. A125, 33 (1968).

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

[7] M. G. Mazarakis, and W. E. Stephens, Astrophys. J. 171, L97 (1972).

[8] H. Voit, G. Ischenko, F. Siller, and H.-D. Helb, Nucl. Phys. A179, 23 (1972).

[9] M. L. Halbert and K. Nagatani, Bull. Amer. Phys. Soc. 17, 530 (1972).

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

[11] J. R. Patterson, B. N. Nagorcka, G. D. Symons, and W. M. Zuk, Nucl. Phys. A165, 545 (1971).

[12] H. Voit, G. Hartmann, H.-D. Helb, G. Ischenko, and F. Siller, Z. Phys. 255, 425 (1972).

[13] E. Almqvist, D. A. Bromley, and J. A. Kuehner, in *Proceedings of the International Conference on Nuclear Structure, Kingston, Canada,* edited by D. A. Bromley and E. W. Vogt (North-Holland, Amsterdam, 1960).

[14] L. Satpathy, K. W. Schmid, and A. Faessler, Phys. Rev. Lett. 28, 832 (1972).

[15] A. Arima, V. Gillet, and J. Ginocchio, Phys. Rev. Lett. 25, 1043 (1970).

[16] R. Middleton, J. D. Garrett, and H. T. Fortune, Phys. Rev. Lett. 27, 950 (1971).

[17] R. Middleton, J. D. Garrett, and H. T. Fortune, Phys. Lett. 39B, 339 (1972).

[18] K. Nagatani, M. J. LeVine, T. A. Belote, and A. Arima, Phys. Rev. Lett. 27, 1071 (1971).

[19] E. Vogt, Phys. Lett. 40B, 345 (1972).

[20] R. H. Siemssen, L. L. Lee, Jr., and D. Cline, Phys. Rev. 140, B1258 (1965).

[21] W. R. Falk, P. Kulisic, and A. McDonald, Nucl. Phys. A167, 157 (1971).

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

[23] E. C. Halbert, J. B. McGrory, D. H. Wildenthal, and S. P. Pandya, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1971), Vol. 4.

[24] H. T. Fortune, R. Middleton, and R. R. Betts, Phys. Rev. Lett. 29, 738 (1972).

[25] H. McManus and E. Vogt, in *Proceedings of the Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, 1960,* edited by A. Zucker, F. T. Howard, and E. C. Halbert (Wiley, New York, 1960).