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Spins and Partial Widths of Quasimolecular Resonances in $C^{12}+C^{12}$ Interactions

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Angular distributions for the reaction $C^{12}(C^{12},\alpha)Ne^{20}$ to levels in Ne^{20} at 0, 1.63, 4.25, and 4.97 MeV and an unresolved doublet at 5.63–5.80 MeV have been studied at incident energies near 6 MeV in the center-of-mass system. The results strongly suggest spins 2 and 4 for the "quasimolecular" states at 19.5- and 19.9-MeV excitation in Mg^{24}. The partial widths of these states reduced to units of $\hbar^2/MR^2$ appropriate to each channel are given; in these units the C^{12} width is more than ten times the average width for α-particle emission and one hundred times the average nucleon width. The nature of these states, which are prominent in the total reaction cross section, is discussed.

A. INTRODUCTION

WITH heavy-ion beams of precisely defined energy from tandem accelerators it has been possible to examine a number of hitherto inaccessible aspects of heavy-ion interaction mechanisms. In particular, as has been reported previously, evidence has been found for the existence of sharp resonance phenomena in the total reaction cross section[1] as well as in elastic scattering[2,3] and individual reaction channels. Of the systems examined to date only C^{12} on C^{12} near 6 MeV center-of-mass energy has shown prominent and fairly well-resolved resonance structure in the total reaction cross section. Other systems have resonances in selected reaction channels but in these cases, when the sum is taken over all channels, the resulting total cross section shows a fairly smooth energy dependence.

Since all the particles in the $C^{12}(C^{12},\alpha)Ne^{20}$ ground-state reaction have spin zero it was hoped that measurements of the α-particle angular distributions might allow unambiguous assignments of the incident orbital angular momentum involved in each of the sharp resonances observed in the C^{12} on C^{12} interactions near 6-MeV incident channel energy[1,2] in the center-of-mass system. A knowledge of this angular momentum is of interest in connection with the suggested quasimolecular nature of these states which was postulated in order to explain the surprisingly large width observed for reemission of C^{12} nuclei from the compound system. In the "molecular" states the C^{12} nuclei are envisaged to be bonded together by surface interactions while Coulomb repulsion, the angular momentum barrier, and rearrangement energy (Pauli exclusion principle) inhibit immediate collapse into a compound nucleus of small radius. A similar structure was also suggested for sharp states observed in $C^{12}-C^{12}$ elastic scattering at higher energies.[3] On the other hand, no such resonance structure has been observed in the $O^{16}-O^{16}$ system in either the total reaction yield or in the elastic scattering yield although individual reaction channels do show resonance fluctuations.

The possible nature of the quasimolecular states and reasons for their occurrence only in some cases have been discussed by a number of authors.[4] Vogt and McManus suggested a physical mechanism in which collective oscillations and easy deformability of the C^{12} nuclei together with the Pauli exclusion principle play crucial parts. Wildermuth and Carovillano discuss these states from the point of view of the cluster model and also emphasize the role of the Pauli exclusion principle in permitting the C^{12} nuclei to retain their identity when their surfaces interpenetrate in the molecular state. If it is accepted that two carbon nuclei can interpenetrate without losing their identity then the interaction can be represented by a real potential; using a plausible form of real potential, Davis has computed energies of excited states of molecular systems and obtains level spacings similar to those observed. Kompaneets discusses a model where a molecular bond is provided by sharing of neutrons between the interacting pair of nuclei but as he points out this is an unlikely process for the resonances in question here. Some of these models are discussed further in connection with the experimental results that are presented in the following sections.

In view of the interest in the nature of these resonant states, both as a manifestation of a new type of interaction between complex nuclei and because of possible insight which study of these states may provide into the fission mechanism in particularly simple and controllable situations, a program of investigation of the properties of these resonant states has been undertaken. The studies of α-particle angular distributions and elas-

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[1] (a) E. Almqvist, D. A. Bromley, and J. A. Kuehner, Phys. Rev. Letters 4, 515 (1960); in *Proceedings of the Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, 1960*, edited by A. Zucker, E. C. Halbert, and F. T. Howard (John Wiley & Sons, Inc., New York, 1960), p. 282; (b) in *Proceedings of the International Conference on Nuclear Structure, Kingston, Canada, 1960*, edited by D. A. Bromley and E. Vogt (University of Toronto Press, Toronto, 1960), pp. 258 and 922.

[2] J. A. Kuehner, B. Whalen, E. Almqvist, and D. A. Bromley, see reference 1(b), p. 261.

[3] D. A. Bromley, J. A. Kuehner, and E. Almqvist, Phys. Rev. Letters 4, 365 (1960); Phys. Rev. **123**, 878 (1961); reference 1(a), p. 151; and in reference 1(b), p. 255.

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tic scattering reported herein were undertaken as part of a program of investigation of properties of the low-energy resonances in the C^{12} on C^{12} interaction with the specific aim of determining the angular momenta of the resonant states and partial widths for different modes of de-excitation.

The ground-state $C^{12}(C^{12},\alpha_0)Ne^{20}$ reaction which was expected to yield unambiguous angular momentum assignments unfortunately did not resonate for the two resonances near 6 MeV center-of-mass energy in question here. However, the α-particle measurements include angular distributions of the α-particle groups feeding the first five excited states of Ne^{20} and from one of these information concerning the angular momentum of the compound state can be deduced. The angular distributions and the spin assignments obtained from them are discussed in Sec. D. The fourth ($E^*=5.63$ MeV) and recently reported fifth[5] ($E^*=5.80$ MeV) states were not resolved.

An alternative method employed in an attempt to determine the spins of the resonant states involved examination of the energy dependence of the elastic scattering cross section at selected angles. The elastic-scattering differential cross section for identical spin-zero bosons in the region of an isolated resonance may be written as[6]

$$\frac{d\sigma}{d\Omega}=\left(\frac{Z^2e^2}{4E}\right)^2\left|\frac{e^{-i\eta\ln\sin^2(\theta/2)}}{\sin^2(\theta/2)}+\frac{e^{-i\eta\ln\cos^2(\theta/2)}}{\cos^2(\theta/2)}\right.$$
$$+\sum_l\frac{2}{i\eta}(2l+1)P_l(\cos\theta)$$
$$\left.\times e^{2i\delta_l}\left(1-e^{2i\phi_l}\left[1-\frac{i\Gamma_C\delta_{ll'}}{(E-E_0)+i\Gamma/2}\right]\right)\right|^2, \quad (1)$$

where E and θ are the center-of-mass energy and angle and where the angle δ_l is the Coulomb phase shift defined in such a way that $\delta_0=0$, and ϕ_l is the nuclear phase shift. The parameter η is given by

$$\eta=0.1574Z^2(m/E)^{1/2},$$

where m is the reduced mass. The Kronecker delta, $\delta_{ll'}$, in the last term expresses the fact that only a single isolated resonance is considered. Γ_C and Γ are the carbon width and the total width, respectively, of the resonance. In the present work, the nuclear phase shift was assumed to be the hard-sphere value given by $\phi_l=-\tan^{-1}(F_l/G_l)$, where F_l and G_l are the usual regular and irregular Coulomb functions. At energies below the Coulomb barrier such as used here, ϕ_l is always small.

To evaluate Eq. (1) numerically it is necessary to know the widths Γ_C and Γ. The energy resolution of the tandem accelerator is sufficiently good to obtain the latter directly from the measured width of the resonances in the reaction yield[1,2] and Γ_C can be deduced using the Breit-Wigner relations:

$$\sigma_R=4\pi\lambda\!\!\!^{-2}(2l+1)\Gamma_C\Gamma_R/\Gamma^2 \quad (2a)$$
$$=\text{total reaction cross section at resonance.}$$

and

$$\Gamma_R=\Gamma-\Gamma_C=\text{total reaction width,} \quad (2b)$$

where l is the orbital angular momentum of the $C^{12}+C^{12}$ system and necessarily equals the spin, J, of the resonant state. The measurements of the total reaction cross sections are not reported in detail here but are the subject of a separate paper that is being prepared.

The scattering cross section evaluated by Eq. (1) depends on the assumed value of resonant spin through the l-dependent factors in the summation term. In particular, the value of Γ_C deduced from the measured reaction cross section depends on the spin assumed for the resonant state through the $(2l+1)$ factor in Eq. (2a). It follows that a careful comparison of measured scattering cross sections with those computed using a variety of l values can, in principle, determine the angular momentum, l, and hence the spin, J, of an isolated resonance and this method has been used in an attempt to determine the resonant spins. These measurements are discussed in Sec. D on spin assignments.

Recently Gove, Litherland, and Clark[7] and Kuehner[8] have used the $C^{12}(C^{12},\alpha)Ne^{20}$ reaction to produce excited states of Ne^{20} and to measure their properties by employing the special 0° geometry suggested by Litherland and Ferguson[9] to align the Ne^{20*} nuclei. In the course of this work it was realized that the cross section for the reaction $C^{12}(C^{12},\alpha)Ne^{20*}$ necessarily goes to zero at 0° and 180° to the incident beam if the parity of the corresponding Ne^{20*} state does not have the value $\pi=(-1)^J$, where J is its spin.[10] This feature arises from the facts that the incident channel spin is zero and final channel spin equals the spin J of the Ne^{20} state involved; under these circumstances the amplitude for emission of a particle along the direction of the incident beam (0° or 180°) contains the vector addition coefficient $(l_1l_200|J0)$ which is zero unless the sum (l_1+l_2+J) is even. l_1 and l_2 are the initial and final orbital angular momenta, respectively. Since both C^{12} and He^4 have even intrinsic parities, the parity of the resultant Ne^{20*} state found in the $C^{12}(C^{12},\alpha)Ne^{20}$ reaction is necessarily $(-1)^{l_1+l_2}$, which, because of the above restriction, is equal to $(-1)^J$ when the reaction is observed at 0° or 180° to the beam.

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[9] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961).

[10] A. E. Litherland, Can. J. Phys. **39**, 1245 (1961).

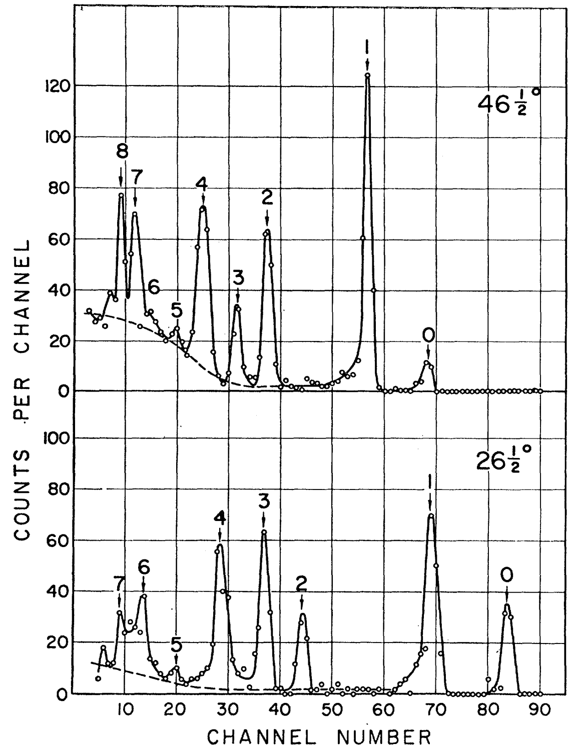

FIG. 1. Particle spectra from C^{12} on C^{12} at 12 MeV incident energy in the laboratory system. The present work concerns groups 0, 1, 2, 3, and 4 which, respectively, correspond to levels in Ne^{20} at excitations of 0, 1.63, 4.25, and 4.97 MeV, and an unresolved doublet 5.63–5.80 MeV. Groups 5, 6, 7, and 8 were not identified and may be protons.

From the selection rule just discussed, it follows that finite α-particle yield at 0° determines the spin-parity combination of the Ne^{20*} state formed in the $C^{12}(C^{12},\alpha)Ne^{20*}$ reaction. Conversely, no matter what reaction mechanism is involved, the α-particle angular distribution must go to zero intensity at 0° if the associated Ne^{20*} state has unnatural parity $[\pi\neq(-1)^J]$. A striking example of the operation of this rule is illustrated among the results discussed in Sec. I.

B. EXPERIMENTAL METHOD

The measurements were carried out using the variable energy C^{12} beam from the Chalk River tandem accelerator. The preparation of the carbon targets and the scattering chamber were described in an earlier report of elastic scattering studies involving spin-zero nuclei.[3] Si *p-n* diffused junction detectors fabricated and tested at Chalk River were used to detect the alpha particles and conventional electronics and a 100-channel pulse-height analyzer recorded the particle spectra.

Since both the energy dependence and absolute cross sections for elastic scattering are known from the earlier work the product of the number of carbon atoms/cm² in the target times the solid angle of the detector was calibrated by observing elastic scattering at 45° and 25° in the laboratory system. For the α-particle measurements, the counter was then covered by 2-mg/cm² Al foil to stop scattered beam; to make measurements near zero degrees the target was backed with 4-mg/cm² Al foil to prevent the beam from producing reactions in the detector window and the runs were normalized to a given integrated beam on the target. At larger angles the target backing was removed and the beam intensity monitored by observing elastic scattering at 19½° to the beam as well as by measuring the integrated beam arriving at the beam stopper. The two methods gave consistent results but the monitor had the advantage of

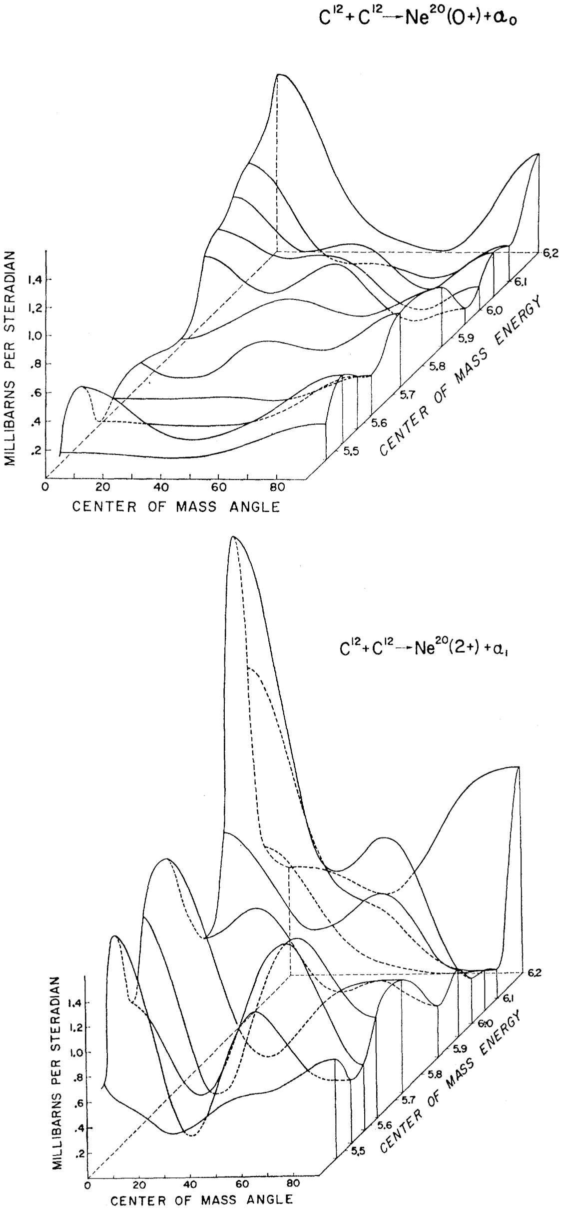

FIG. 2. Differential cross sections for the ground state and 1.63-MeV-level alpha particles from $C^{12}+C^{12}\rightarrow Ne^{20}+He^4$ as functions of the angle of emission and the incident kinetic energy.

automatically taking into account changes in target thickness caused by carbon build up with time.

The target thicknesses used were 10 to 15 $\mu g/cm^2$ which correspond to a beam energy loss of 60 to 90 keV in the laboratory system or 30 to 45 keV in the center-of-mass system at the resonance energies. The beam energy calibration was taken from earlier calibration work and is believed accurate to ±50 keV.

The angular resolution determined by the counter aperture and beam spot was ±2° and the solid angle of the counter 2.75×10^{-3} sr.

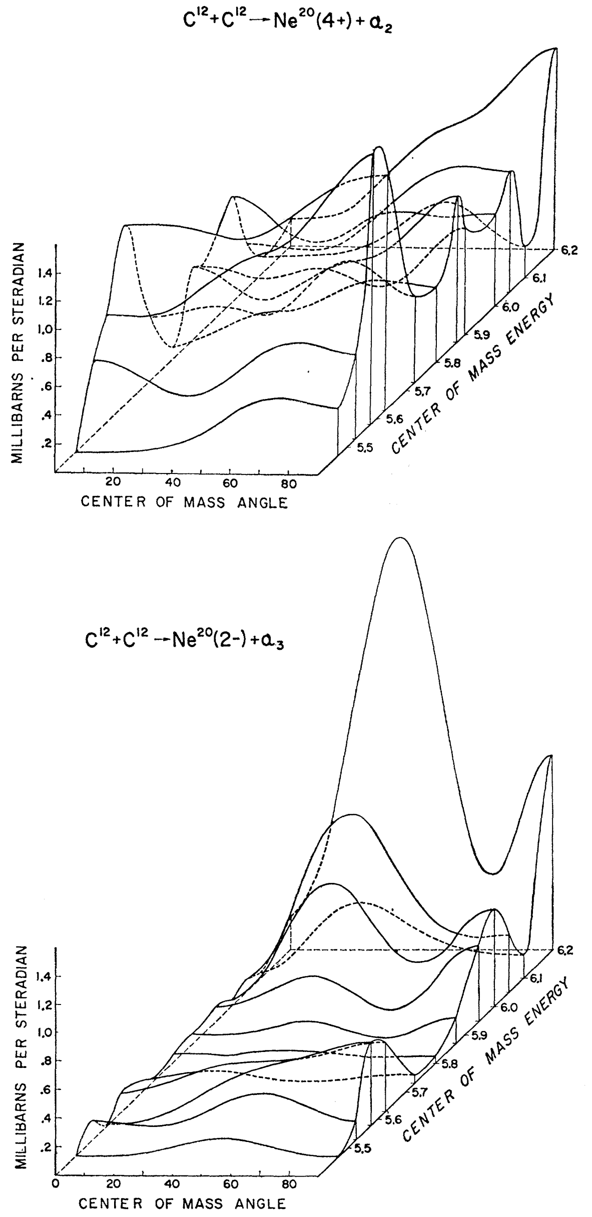

FIG. 3. Differential cross sections for the 4.25-MeV level and 4.97-MeV level alpha particles from $C^{12}+C^{12}\rightarrow Ne^{20}+He^4$ as functions of the angle of emission and the incident kinetic energy.

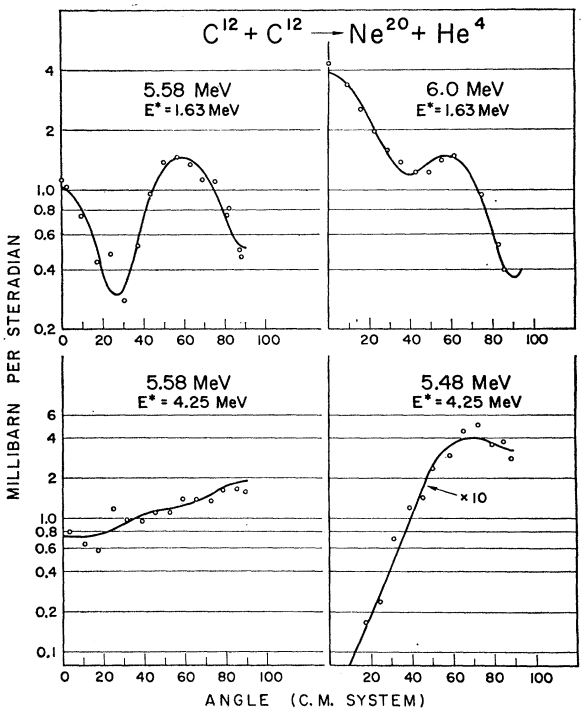

FIG. 4. Some typical angular distributions showing the experimental points and the least-squares fits (solid lines) by a Legendre polynomial series using only even terms up to order 8. Because the interaction is between identical particles odd terms cannot occur.

Typical α-particle spectra are shown in Fig. 1. The total counts in each peak were added and then an estimated contribution from the underlying continuum subtracted when necessary. The estimate was made by drawing a smooth curve through the background between the peaks. An available computer program[11] was used to transform the results to the center-of-mass system and to fit Legendre polynomial expansions to the data; only even polynomial terms were used since symmetry about 90° in the center-of-mass system is required for reactions between identical particles.

C. EXPERIMENTAL RESULTS

The angular distributions of the α-particle groups to the ground, 1.63, 4.25, and 4.97 MeV states are summarized in the isometric plots shown in Figs. 2 and 3. The curves shown are the Legendre polynomial fits to the experimental points for a number of different bombarding energies. Even polynomial terms up to P_6, P_8, and P_{10} were successively tried but in no case did inclusion of P_{10} result in a significant improvement of the fit.

Representative angular distributions showing the experimental points and the fitted curves are illustrated in Fig. 4. In Fig. 5 the polynomial coefficients obtained

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[11] The authors are indebted to J. M. Kennedy and the computing staff for making the programs available.

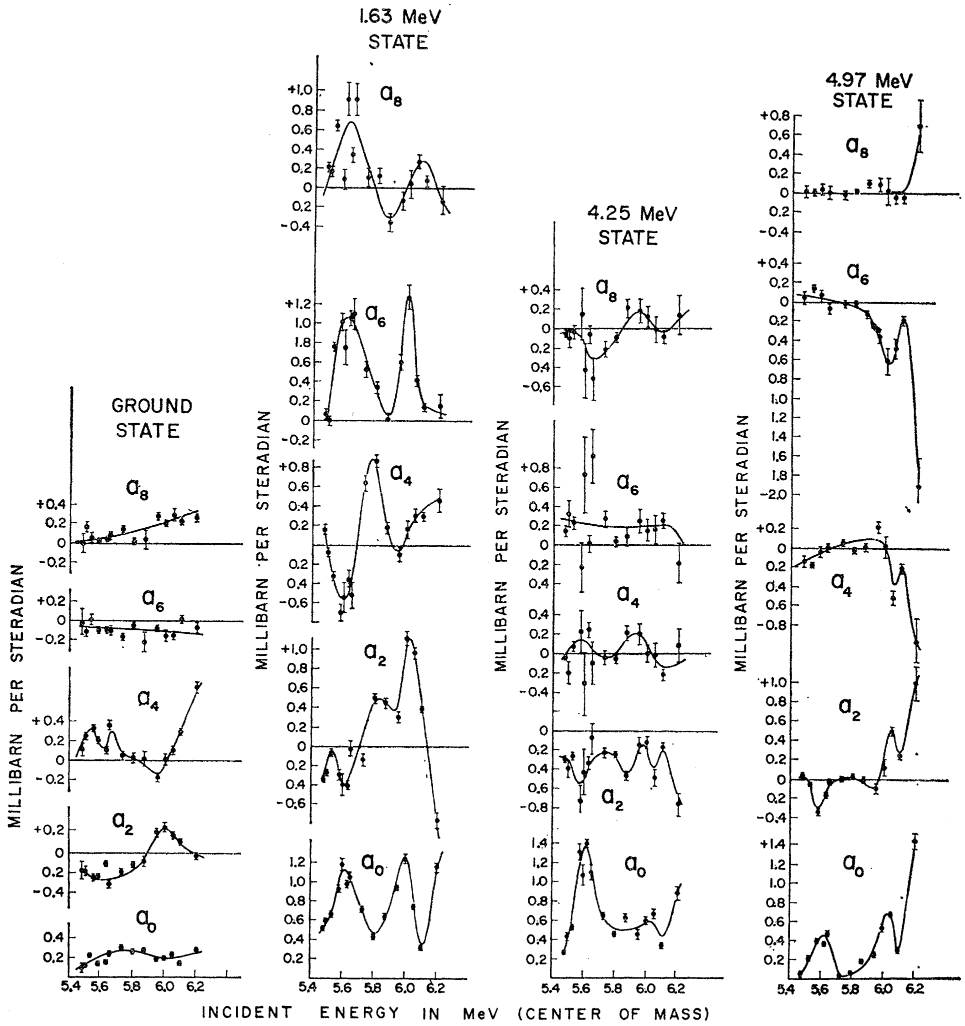

FIG. 5. The values of the coefficients, a_k, in the Legendre polynomial series, $\Sigma_k a_k P_k$, obtained by least-squares fits to the angular distributions are shown as functions of the incident energy.

from all the experimental data using terms up to P_8 are shown as functions of the bombarding energy and in Fig. 6 the total cross section for each α-particle group studied is plotted as a function of beam energy, including the unresolved doublet corresponding to the levels at 5.63 and 5.80 MeV in Ne^{20}. These total cross sections are of course just 4π times the coefficient of the P_0 term of the Legendre series. They are here displayed together to permit comparison of the resonance structure in each α-particle channel. The absolute cross sections are estimated to be accurate to $\pm 20\%$ in all cases. Also shown in this figure are some angular distributions for the α-group feeding the 4.97-MeV (2−) level in Ne^{20}.

In Fig. 7(a) are shown the ratios of the measured scattering cross section to the Coulomb (Mott) scattering cross section plotted as a function of energy. There appear sharp fluctuations superimposed on a broad slowly varying cross section which deviate slightly from Mott scattering. The latter is assumed to be associated with tails of distant resonances giving rise to the smooth continuum reaction yield which underlies the sharp resonances. When this smooth background is normalized to a constant value the fluctuations appear as shown by the open circles in Figs. 7(b), (c), and (d). The solid curves are theoretical expressions computed using expressions (1) and (2) together with measured values of the resonant reaction cross section and widths at each resonance. The values used were resonant cross sections of 50 mb and 45 mb and widths of 130 and 100 keV for the 5.6- and 6.0-MeV resonances, respectively. These values agree within the experimental errors with those reported previously[1,2] but are more precise in that they encompass additional measurements. They are lower limits obtained by subtracting a background given by joining points in the valleys between peaks by smooth curves. An extreme upper limit would be twice these values.

Equation (1), of course, is an oversimplification which assumes that we have completely isolated resonances and does not take into account the "continuum" scattering which appears to change only slowly with energy. For this reason the calculated curves are compared only

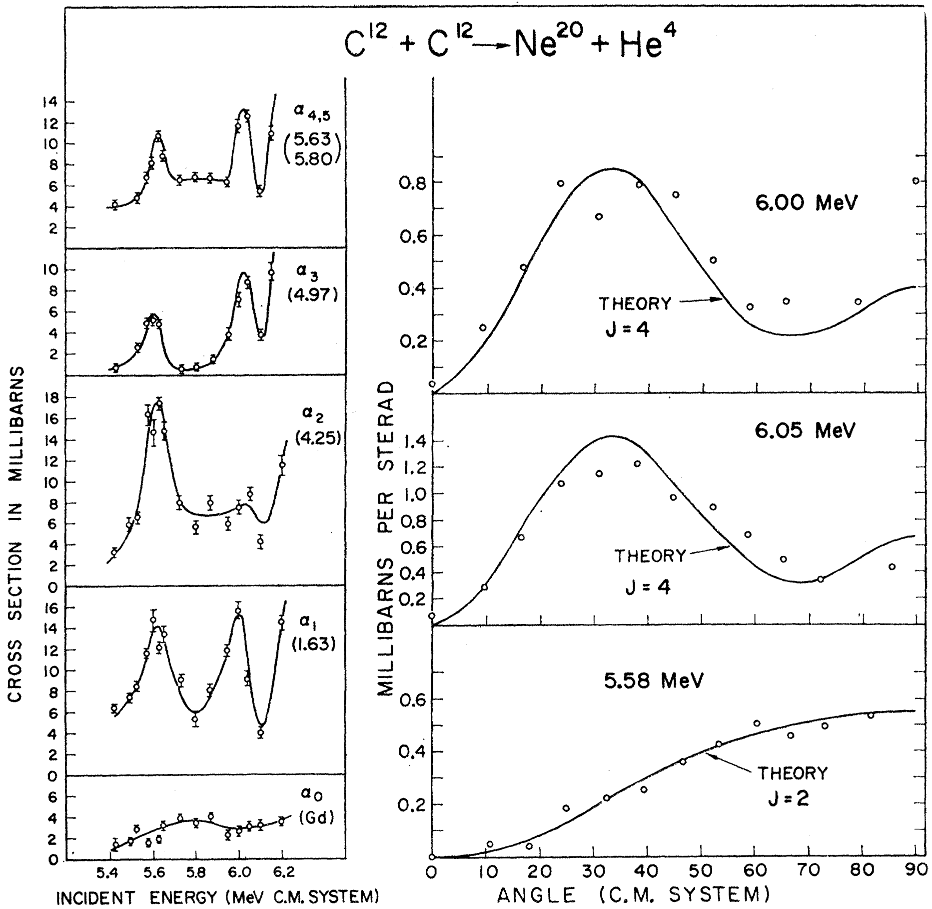

FIG. 6. On the left is shown the energy dependence of the cross sections obtained by integrating each angular distribution. On the right are three angular distribution for the 4.97-MeV (2−) state at energies near the resonant values. The solid lines were computed from theory using the indicated spin assignments as discussed in the text.

with the fluctuations away from the smooth background. The theoretical curves have been computed for spin values of 2, 4, 6, and 8 for the 5.6-MeV resonance and only spins 2 and 4 for the 6.0-MeV resonance; three examples are given in Fig. 7.

D. SPIN ASSIGNMENTS

The primary motivation for undertaking the α-particle measurements was to obtain information about the angular momenta of the C^{12} on C^{12} resonances near 6 MeV by study of the $C^{12}(C^{12},\alpha)Ne^{20}$ ground-state reaction which is, in principle, particularly simple to interpret since it involves only spin-zero particles. However, the results illustrated in Fig. 6 show that the resonance contribution to this reaction, if present at all, is too small to be useful for this purpose. However, it is possible to obtain information from the angular distributions of the reactions to excited states. In particular, the reaction to the 2− (4.97-MeV) unnatural parity state is a favorable case both because experimentally it appears to show a very well isolated resonance at 5.6 MeV, and because conservation of spin and parity restricts the outgoing orbital angular momenta to only two values for any given resonance spin as discussed. The following are some well-known general features of reactions of the type $(0+)+(0+)\rightarrow(J\pi)+(0+)$; l_1 and l_2 refer to the incident and exit orbital angular momenta, respectively.

(i) If l_1 is zero then the 2− (4.97-MeV) state of Ne^{20} cannot be formed without violating the requirement of conservation of angular momentum and parity in nuclear reactions.

(ii) The angular distribution of the 2− state must necessarily go to zero at 0°, as discussed in the Introduction (Sec. A), if angular momentum and parity are conserved.

(iii) For 2− (or 1−) states l_2 must be odd to conserve parity and is restricted to the values $l_2=l_1\pm1$.

(iv) For 0+ (or 1+) states, $l_1=l_2$.

(v) If we expand the distribution as a Legendre polynomial series of the form $\sum a_kP_k$, then the maximum value of k cannot exceed the smaller of either $2l_1$ or $2l_2$, where l_1 and l_2 are the largest participating orbital angular momenta in the entrance and exit channels, respectively. The spin of the compound state is of course equal to l_1.

The selection rules combined with the fact that the 2− state resonates both at 5.6 and 6.0 MeV rules out spin 0 for both resonances. In Fig. 5, the lower energy

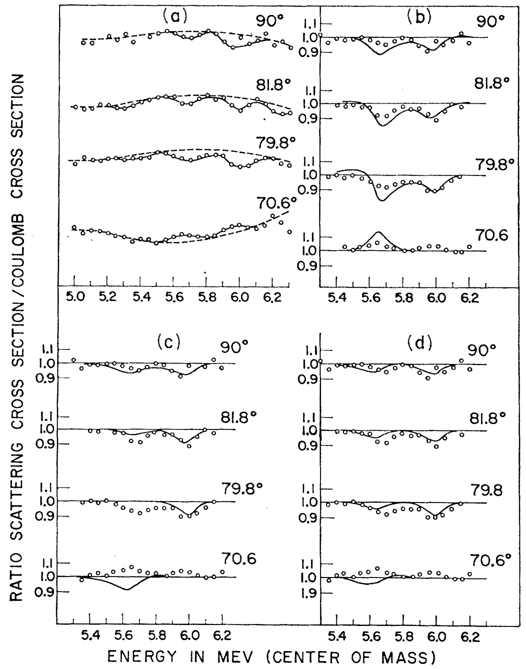

FIG. 7. (a) Shows the measured ratio of the scattering cross section to the Coulomb (Mott) value plotted as a function of energy. The dashed curves represent an assumed smooth background as discussed in the text. Figures (b), (c), and (d) show the resonance fluctuations that remain when the smooth background is normalized to unity. The points are experimental; the solid lines are calculated using Eq. (1). The spin values assumed for the 5.6- and 6.0-MeV resonances, respectively, are (b) 2 and 4, (c) 8 and 4, and (d) 6 and 4.

resonance shows no significant P_6 or P_8 terms, suggesting an angular momentum less than 3 quantum units for the resonant state. Since the values 0, 1, and 3 are forbidden, this implies a spin of 2 for the compound state; taking this value, a good fit is obtained to the angular distribution for the 2− level (see Fig. 6) by choosing the ratio (amplitude $l_2=3$):(amplitude $l_2=1$) in the exit channel to be either 0.077 or −1.56. It should be noted that in this case there are two parameters, a_2 and a_4 coefficients determined by experiment which have to be simultaneously fitted by varying a single parameter, namely the amplitude mixing of the two allowed l values in the exit channel. For higher spins such as discussed below there are even more coefficients determined experimentally which makes an accidental fit even less likely.

A comparison of the theoretical Legendre polynomial coefficients shown in Fig. 8 with the measured values in Fig. 5 makes it apparent that a spin-4 assignment cannot produce coefficient values that have any resemblance to those observed at the 5.6-MeV resonance. The latter show a negative a_2 coefficient combined with simultaneous near-zero values of P_6 and P_8; neither of these features can arise with spin 4. Similar comparisons for higher spin values of 6 and 8 have shown that only spin 2 yields a fit to experiment.

A comparison of the experimental values in Fig. 5 for the 6.0-MeV resonance with the curves of Fig. 8 indicates that good fits to the experimental data with a spin-4 assignment can be obtained in this case by choosing the amplitude mixing ratio $(l=5/l=3)$ to be either 0 or −2.8 in the exit channel. In this case, four measured parameters, a_2,a_4,a_6, and a_8 coefficients, are fitted by varying the single amplitude mixing parameter that is available. The theoretical angular distributions are compared with the measured points in Fig. 6. Again, similar comparisons for spin 6 and spin 8 show that no similarity to the measured coefficient values can be obtained for any value of amplitude mixture in the exit channel with these spins.

The possiblity that some other values of resonant spin interfering with the underlying continuum from tails of nearby levels should accidentally yield the observed angular distributions seems unlikely, particularly since this continuum appears to be absent in the total cross section of the alpha group just discussed. The smaller intensity of the continuum under the 2− level compared with that under other states almost certainly, in part,

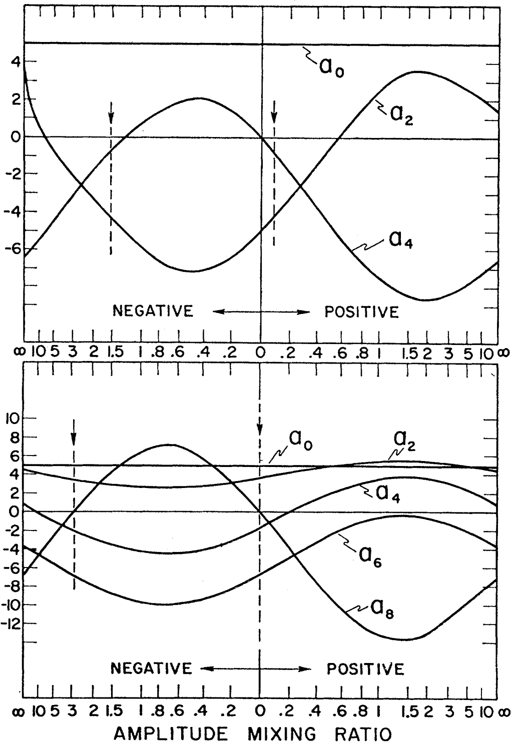

FIG. 8. The theoretical values of the coefficients, a_k, in the Legendre polynomial series, $\Sigma_k a_k P_k$, which is used to represent the angular distributions for the reaction $C^{12}+C^{12}\rightarrow Ne^{20}(2-)+He^4$. a_0 has been normalized to 5 mb/sr to correspond to the resonant value for the 5.6-MeV state. The upper curve is for a compound state of spin 2 and the lower for a state of spin 4. Only even values of k are obtained because of the identity of the incident particles. The abscissa gives the ratio of the amplitudes of the two possible outgoing orbital momenta, $(l_1+1)/(l_1-1)$. The arrows indicate values which give fits to the measured results at 5.58 MeV (top) and 6.00 and 6.05 MeV (bottom).

reflects the fact that s-wave collisions are forbidden for the 2− state so that only contributions from higher spins can be seen; even these appear small.

The selection rules that apply to the other residual states allow three or more l values in the associated α-particle channel so that almost any form of angular distribution within restriction, v, above can be accommodated by choosing suitable amplitude mixing parameters and only some qualitative remarks can be made. Obviously the resonant P_6 term for the 2+ level (Fig. 5) at 5.6 MeV cannot arise from an $l=2$ resonance by itself but requires interference between the resonant amplitude and some spin-4 component in the underlying continuum arising from tails of nearby levels. The intensity of this continuum for the 2+ level is about 50% of the resonant peak in the total cross section, so that strong interference effects are to be expected in the angular distribution.

The spin value 8 for the 5.6-MeV resonance which was suggested by a preliminary analysis of the elastic scattering measurements[2] is not supported by the more complete data shown in Fig. 7. In this figure a comparison is made between computed and observed resonance fluctuations for a number of assumed spin values. It now seems probable that the situation is too complicated for the simple expression of Eq. (1) to be applicable directly and as was already discussed in Sec. C an *ad hoc* normalization of the continuum background to a constant value has been made. With this assumption the remaining sharp fluctuations show qualitative resemblence to the computed curves for spin 2 and 4 for the 5.6- and 6.0-MeV states, respectively. On the other hand, the results at 70.6° disagree in sign as well as in magnitude with a resonant spin of either 6 or 8 units of $\hbar$ and the 79.8° results also show opposite sign to that given by spin 8. To this extent, therefore, the scattering results are in accord with the spin assignments based on the α-particle angular distributions for the 2− state but in themselves they do not provide any convincing evidence on which to base spin assignments.

The α-particle angular distributions strongly suggest that the most likely assignments are spin 2 and spin 4, respectively, to the 5.6- and 6.0-MeV resonances. The rapid increase in P_8 and P_6 terms at energies above 6 MeV suggest that higher spin states are coming into play at still higher energies.

E. PARTIAL WIDTHS

The comparison in Fig. 7 does not permit any convincing choice among the spin possibilities but it does show that the resonant carbon widths[12] deduced from the total reaction cross-section measurements lead to fluctuations of the right magnitude in the elastic scattering.

TABLE I. Widths for the emission of α particles into specific channels and of C^{12} (ground state) from resonances in the $C^{12}-C^{12}$ system. The C^{12} widths assume spin 2 and spin 4, respectively, as indicated in brackets; the α-particle widths are nearly independent of assumed spin (see text).

Emitted particle	Excitation of residual nucleus (MeV)	Resonance widths (c.m.) in keV 5.6 MeV	 6.0 MeV
α_0	0	$\sim<1$	$\sim<1$
α_1	1.63	18.3	20.1
α_2	4.25	25.5	$\sim<2$
α_3	4.97	11.5	13.4
α_{45}	5.6–5.8	11.5	13.4
C^{12} (2)	0	19.5	15
C^{12} (4)	0	9.8	7.5

This fact confirms the earlier conclusion[1] that the resonant width for carbon emission even at low energy is a surprisingly large fraction of the total width and in fact Γ_C/Γ is of the order 0.1 for the resonant states. The exact numerical values computed by inserting the measured reaction cross sections and widths of the 5.6- and 6.0-MeV states in Eq. (2) are dependent on the spin of the corresponding state through the $(2l+1)$ factor; for the 5.6-MeV resonance a value of Γ_C/Γ of $0.15(\pm 0.04)$ results from the spin assignment of 2. Assignment of spin 4 yields Γ_C/Γ to be $0.075(\pm 0.02)$ for the 6.0-MeV state.

The alternate solutions of the quadratic equation (2) yield values of Γ_C/Γ that are too large to be in accord with the elastic scattering results; e.g., Γ_C/Γ of 0.85 and 0.93 for spin 2 and 4 assignments. These very implausible values are ruled out by the scattering measurements.

The resonant widths for α-particle emission into particular channels were computed using the relation:

$$\Gamma_\alpha = (\sigma_\alpha/\sigma_R)\Gamma_R \approx (\sigma_\alpha/\sigma_R)\Gamma, \qquad (3)$$

which shows that the α-particle width, Γ_α, that is derived from the measured cross section σ_α, is independent of assumptions about the spin of the resonant state provided that the total reaction width, Γ_R [Eq. (2b)], is not very different from the total width Γ. This approximation is true to better than 15% in this case as can be shown by substituting the measured value $\Gamma_C \gtrsim 0.15\Gamma$ in Eq. (2b). The α-particle widths are given in Table I together with the carbon widths computed for spin values of 2 and 4 for the resonant states.

F. REDUCED WIDTHS

The measured widths[12] reduced to percent of single-particle units $(\hbar^2/MR^2)$ are shown in Table II for spin 2 and spin 4 for the resonant states, respectively, and for radii of 5F and 7F for the Mg^{24} compound state. The reduction was carried out using the relation:

$$\frac{\gamma_\alpha{}^2}{\hbar^2/(MR^2)} = \frac{\Gamma_\alpha}{\sum_l 2P_l}\,\frac{1}{\hbar^2/(MR^2)}, \qquad (4)$$

where γ^2 is the reduced width which is assumed to be

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[12] *Note added in proof*. For reactions between identical particles the resonance cross section given by Eq. 2(a) should read $\sigma_R = 8\pi\lambda\!\!\!^{-}(2l+1)\Gamma_c\Gamma_R/\Gamma^2$, i.e., the tabulated values of carbon widths throughout the paper should be reduced by a factor of 2. The conclusions are not affected.

TABLE II. Reduced widths in percent of $\hbar^2/MR^2$ for emission of α particles and of C^{12} (ground state) from resonances in C^{12}+C^{12} system.

Emitted particle	Excitation of residual nucleus (MeV)	Reduced widths (%) 5.6 MeV (2+)	6.0 MeV (4+)
	Radius = 5 fermis		
C^{12}	0	400	1800
α_0	0	~0.03	~0.04
α_1	1.63	0.24	0.42
α_2	4.25	1.9	~0.05
α_3	4.97	0.82	2.4
α_{45}	5.6–5.8	0.87	0.92
	Radius = 7 fermis		
C^{12}	0	14	11
α_0	0	~0.03	~0.03
α_1	1.63	0.23	0.30
α_2	4.25	0.90	~0.40
α_3	4.97	0.46	0.80
α_{45}	5.6–5.8	0.31	0.39

independent of the orbital angular momentum, l, of the emitted α particle. A computer program[11] for Coulomb functions gave values of the penetration factor

$$2P_l = 2KR/(F_l^2+G_l^2),$$

where K is the reduced wave number, R the radius, and F_l and G_l the regular and irregular Coulomb functions.

In addition to studies of individual α-particle channels measurements also have been made of the total integrated yields of α particles, of protons, and of neutrons[1] and from these data the mean widths for emission of α particles, protons, and neutrons shown in Table III were computed. The average reduced widths again were obtained by relation (4), but in this case the sum was carried out over all known accessible levels in the residual nuclei. In the cases of emission of protons to Na^{23} and neutrons to Mg^{23} it was necessary to assume spin and parities of some residual states for which no measured values are available but the results do not depend significantly ($<\pm 50\%$) on these assumptions. Experimentally the neutron yield was estimated from measurements at a single angle (30°) and within the experimental uncertainty the neutron widths are not significantly different from the proton widths but both are a factor of ten less than the α-particle width.

The striking feature that emerges from Tables II and III is the surprisingly large value of the reduced C^{12} width obtained in each case. The carbon widths exceed the α-particle widths by a factor of 200 or more with a radius of 5F for both and of more than 10 with a larger radius of 7F. The smaller radius corresponds to the commonly used value $R=(1.4A^{1/3}+1.2)$F for the radius of interaction between an α particle and the residual nucleus of mass A and the larger value is close to that suggested for the C$^{12}-$C^{12} system by elastic scattering studies and corresponds to $1.5(A^{1/3}+A^{1/3})$. The α-particle widths are of the magnitude[13] usually found in light nuclei, i.e., about 1% of a single-particle unit for a radius of 5F, whereas the carbon widths are exceedingly large and even for a radius of 7F amount to 14% and 11% of $\hbar^2/MR^2$ for the 5.6- and 6.0-MeV resonances, respectively. The average reduced nucleon width in the same units is a factor of 10 smaller than the average α-particle width and is less than 1% of the C^{12} widths. These facts strongly suggest that clustering and collective motions of clusters play important roles in these highly excited states of Mg^{24}($E^*\approx 20$ MeV); otherwise it is surprising that the emission of a complicated structure such as C^{12} is favored over simpler subunits such as α particles or nucleons.

TABLE III. Widths for the emission of various particles each summed over all open channels and the corresponding mean reduced width per channel. The measured widths Γ are in keV. The average reduced widths per channel, $\langle\gamma^2\rangle$, are in % of $\hbar^2/MR^2$, with $R=5$F for the light particles and $R=7$F for the C^{12} case.

Resonance (MeV)	Γ_C	$\Sigma\Gamma_\alpha$	$\Sigma\Gamma_p$	$\Sigma\Gamma_n$	$\langle\gamma_C^2\rangle$ (%)	$\langle\gamma_\alpha^2\rangle$ (%)	$\langle\gamma_p^2\rangle$ (%)	$\langle\gamma_n^2\rangle$ (%)
5.6	20	78	22	4	14	0.5	0.03	0.02
6.0	7.5	65	19	4	11	0.6	0.04	0.05

The previously reported elastic-scattering studies[3] showed similarly sharp resonances at energies well above the Coulomb barrier value with measured peak intensities that suggested the C^{12} widths to be 15% of the total widths which in turn averaged about 200 keV. The corresponding reduced C^{12} width cannot be determined uniquely without spin determinations but, assuming the value $J=8$ as suggested by the recent work of Lassen[14] on the inverse reaction and a collision energy of 12.5 MeV (c.m. system), an estimate can be made. The results are reduced C^{12} widths of 29% and 2.5% of $\hbar^2/MR^2$ for radii of 5 and 7F, respectively. Table IV summarizes the results for assumptions of resonant angular momenta between 2 and 10 units of $\hbar$. These elastic scattering results suggest that the higher energy resonances also have large reduced C^{12} widths and are similar in character to those observed near 6 MeV.

An approximate value of the total reaction width [defined in Eq. 2(b)] at the higher energies is given by the observed widths of the resonances seen in the elastic scattering, i.e., about 200 keV. Measurements on the reaction cross sections,[1] which will be described more fully in a forthcoming paper, suggest that most of the reaction width at high energy is α width as was also found for the resonances reported here. From these facts an estimate can be made of the mean reduced α-particle width in single-particle units ($\hbar^2/MR^2$). Again relation (4) was used but the sum was taken over all open α-particle channels assuming a bombarding energy of 12.5 MeV (c.m. system) and a radius of 5F. The result-

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[13] D. H. Wilkinson, *Proceedings of the Rehovoth Conference on Nuclear Structure* (North-Holland Publishing Company, Amsterdam, 1958), Chap. IV. R. L. Clarke, E. Almqvist, and E. B. Paul, Nucl. Phys. **14**, 472 (1960).

[14] N. O. Lassen, Phys. Letters **1**, 65 (1962); **1**, 161 (1962).

TABLE IV. Level properties derived from elastic scattering data near 12.5 MeV (c.m.) energy, i.e., at about 26-MeV excitation in Mg^{24}.

J	2	4	6	8	10	$\hbar$
Γ_C	52	40	32	28	26	keV
γ_C^2	2.2	1.9	1.9	2.5	5.4	% of $\hbar^2/MR_1^2$ [a]
γ_C^2	2.2	2.6	5.5	29	380	% of $\hbar^2/MR_2^2$ [a]
γ_α^2	0.18	0.19	0.35	0.83	3.3	% of $\hbar^2/MR_2^2$

[a] The last column shows the units used; R_1 is 7F and R_2 is 5F. The values in row J are the assumed spin of the resonant states and the rows Γ_C and γ_C^2 show the corresponding C^{12} width and its reduced value for two different radii. The row γ_α^2 is the mean alpha width obtained by averaging over all open channels for alpha emission.

ing mean values of the reduced α-particle widths are given in Table IV for a number of assumed spins of the resonant state. These estimates are of the same magnitude as those adduced for the 5.6- and 6.0-MeV resonances.

In summary, all the experimental data indicate that the sharp resonances in the $C^{12}+C^{12}$ interaction both below and above the Coulomb barrier have very large reduced C^{12} widths, about normal α-particle widths, and small nucleon widths. These facts suggest that clustering and collective excitation play important roles in these states. The evidence for the surface nature of the collisions involved in the resonance interaction is discussed in the following section. Together, these facts suggest that we are dealing with a highly deformed system in which C^{12} clusters form or remain with high probability for times as long as 5×10^{-21} sec ($\Gamma\approx100$ keV).

G. GRAZING NATURE OF RESONANT COLLISIONS

The fact that the sharp resonances are most prominent in the total reaction yield at collision energies below the Coulomb barrier and then at higher energies become relatively much weaker with respect to the compound-nucleus continuum of reactions[1] suggests that the former are associated with surface or grazing collisions. At the higher energies, the Coulomb barrier no longer prevents the nuclei from coming together in collisions involving low angular momenta to form the usual compound nucleus. Intense reaction yield from this mechanism is then expected to appear in addition to reactions of different character arising from grazing collisions involving larger angular momenta. Nevertheless, there should be selected channels in which grazing collisions are favored by the barrier penetration factor. For example, the high angular momenta in grazing collisions at high-energy yield barrier penetration factors that certainly favor breakup into heavy fragments and into channels with high Q value or high spin. If some of these also happen to have large reduced width then the resonance will be very prominent in that channel. As already discussed, the elastic scattering[3] channel (heavy fragments) shows strong resonances and similar strong structure is observed in selected α-particle channels at energies well above the Coulomb barrier in accord with the expectations of a grazing surface interaction for the resonant states. The total reaction yield, which in large part is from the usual compound nucleus de-excitation at the higher bombarding energies, shows very little resonance fluctuation.

Support for the above suggestion that the resonant states are connected with distant or grazing collisions is obtained from estimates of the closest approach of the classical orbits of the colliding C^{12} nuclei at the resonance energies and angular momenta. These estimates for the low-energy resonances at 5.6 MeV ($l=2$) and 6.0 MeV ($l=4$) are 9.5 and 9.8F, respectively. At higher energies near 11 MeV and using the spin value $l=8$ suggested by Lassen,[14] a closest approach of 7.7F is obtained. Thus, the existing evidence indicates the sharp resonances to be connected with grazing collisions in which the interpenetration of the nuclear surfaces is small. Under these conditions it seems likely that Coulomb excitation, electric polarization effects, and deformation leading to extensions of the nuclei beyond the usually assumed 7F spherical diameter will play important roles.

H. QUASIMOLECULAR STATES

The experimental results described above show that in Mg^{24} there are states of low angular momentum ($J=2$ and 4) which have a structure that favors symmetric fission into two C^{12} nuclei by a factor of 10 or more over any one of the competing de-excitation channels and which are most probably formed in grazing collisions. These facts form the most compelling arguments for the quasimolecular model[1-4] of these states, which assumes that the C^{12} nuclei can bond together by surface interactions while retaining their identity to some extent for periods as long as $\approx5\times10^{-21}$ sec in a state which is reminiscent of the saddle point in fission. The molecular state is postulated to terminate either by reemission of the C^{12} nuclei, or by collapse of the system into the usual compound nucleus followed by α-particle and nucleon emission. This model raises questions as to why collapse to a small radius takes as long as 5×10^{-21} sec when nucleons can travel five to ten nuclear diameters in this length of time and why similar states are not observed in the $O^{16}-O^{16}$ system which also involves a pair of spin-zero bosons.

Before discussing the questions raised above, it is of interest to make some order of mangitude estimates of the effects of angular momentum. When a pair of C^{12} nuclei come within range of nuclear forces, it does not appear likely that angular momentum forces by themselves are a strong factor in preventing immediate collapse of the initial system to a compound nucleus of radius of about 5F. An estimate of the radius at which angular momentum forces become important in inhibiting further collapse after the Coulomb barrier has been penetrated can be made using the approximation

$$R=[l(l+1)\hbar^2/(2ME)]^{1/2}, \qquad (5)$$

where R is the radius corresponding to the angular momentum l for a system of reduced mass M and energy E. The kinetic energy, E, attained under the influence of the attractive nuclear potential is expected to exceed the incident energy so that use of the latter leads to an upper limit of R. For the $C^{12}-C^{12}$ system with an energy of 6 MeV and l values of 2 and 4, respectively, the limiting radii obtained are 1.9F and 3.4F, respectively. These are much smaller than the surface contact separation of about 7F for the $C^{12}-C^{12}$ system and suggest that angular momentum forces by themselves cannot be important in preventing coalescence once the strongly attractive nuclear forces come into play, at least for the cases in question here.

At higher energies it may well be that angular momentum forces become of greater importance in inhibiting collapse of the system. For example, with 12.5 MeV and $l=8$ in Eq. (5) a radius of 4.5 is obtained which is approaching the value, 5F, expected for Mg^{24}. Thus, the structure of the very high spin states that may be found at high bombarding energy probably favors extended or quasimolecular systems because angular momentum forces inhibit collapse, but this is not true for the states in question here at 5.6 and 6.0 MeV energy. It is possible, therefore, that the character of the sharp states that appear in the total reaction cross section below the Coulomb barrier energy is different from that of the sharp states seen in individual channels, e.g., elastic scattering and α-particle channels at high energy where angular momentum plays a much more important role in preventing coalescence of the incident nuclei.

Mechanisms[4] which are not dependent on angular momentum forces have been suggested by Vogt and McManus, by Wildermuth and Carovillano, and by Kompaneets. In the view of Vogt and McManus[4] the crucial feature that leads to formation of quasimolecular states is that the subunits, in this case, C^{12} nuclei, are deformable so that the potential energy released when they approach within range of nuclear forces sets each of the incident nuclei into collective modes of oscillation with the two centers of mass approaching and receding from one another along a line joining them. As the deformed C^{12} nuclei approach each other, the nuclear surfaces (where the nucleon density is low) can interpenetrate to some extent. However, if the nuclei are to coalesce the Pauli exclusion principle requires a rearrangement of the nucleon orbits to take place; this gives rise to an effective repulsion that inhibits the immediate collapse of the system and as the oscillation of the C^{12} nuclei continues, the centers of mass move apart again. The easy deformability of the C^{12} nuclei makes it energetically possible for the separation of the centers of mass to increase to about 10F while the nuclei are still bonded together by attractive nuclear forces in the region of surface interpenetration. At this range the configuration of two separate ground-state nuclei becomes energetically favored over the deformed system. However, the still higher energy required to pass through a point of scission constitutes a barrier that inhibits the nuclei from snapping into their ground-state shapes. This barrier may reflect the nuclei inward again and thus the oscillations continue until the system either collapses or breaks the bond. If the incident energy is sufficiently high the nuclei can, of course, break the bond while still in excited states (inelastic scattering). Vogt and McManus show that the properties of C^{12} make it plausible that such a system would exist for five oscillations or about 5×10^{-21} sec corresponding to the observed widths. On this view it is the greater rigidity of the closed-shell O^{16} nucleus which precludes the formation of quasimolecular states in the $O^{16}-O^{16}$ case.

Since on this model the energy gained from nuclear interaction is put into collective excitation of the incident C^{12} nuclei, it would seem likely that the resonant emission of C^{12} in excited states should have a large width. Measurements[15] of inelastic scattering of C^{12} by heavy ions support this expectation. In particular, the studies of inelastic scattering in the $C^{12}-C^{12}$ system by Garvey *et al.*,[15] at Yale University has shown levels at 4.43 and 14.6 MeV in C^{12} to be strongly excited and suggest a quadrupole deformation of C^{12} corresponding to a β of 0.17; the sign is undetermined.

Inglis[4] has suggested that C^{12} nuclei are perhaps disk shaped (e.g., three α particles form a plane) and a disk of uncertain orientation or spinning about a diameter appears as a high-density core with a relatively low-density region around it. The low-density regions of the two C^{12} nuclei can interpenetrate to form an attractive bond and lead to states similar to those suggested by Vogt and McManus.

Wildermuth and Carovillano[4] also emphasize the important role played by the Pauli exclusion principle in allowing two C^{12} nuclei to interpenetrate to some extent without losing their ground-state C^{12} cluster identity. They make rough qualitative estimates to suggest that at energies near the Coulomb barrier value the two nuclei can be trapped within the Coulomb barrier and undergo several reflections inside the nucleus without destroying the clusters. In the first respect their view is very similar to that of Vogt and McManus. The two views differ, however, in that Vogt and McManus picture the molecular system to be highly deformed so that part of the time the C^{12} nuclei are 9 to 10F apart (i.e., outside the Coulomb barrier) whereas Wildermuth and Carovillano suggest that the C^{12} nuclei are trapped within the Coulomb barrier and, therefore, the type of state discussed by them can only be sharp near the barrier energy and is not relevant to the sharp resonances seen in elastic scattering at higher energy. The

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[15] E. Almqvist and J. A. Kuehner, Bull. Am. Phys. Soc. **6**, 287 (1961); M. L. Halbert and A. Zucker, Phys. Rev. **121**, 236 (1961); G. T. Garvey, A. M. Smith, J. C. Hiebert, and F. E. Steigert, Phys. Rev. Letters **8**, 25 (1962); G. T. Garvey, International Symposium on Direct Interactions, Padua September 3, 1962 (unpublished); and (private communication) from G. T. Garvey.

two views also appear to differ on the reasons for the absence of "molecular" states in the $O^{16}-O^{16}$ system; Vogt and McManus attribute this to the greater rigidity of O^{16} leading to a very short lifetime for any molecular states while Wildermuth and Carovillano suggest that the closed-shell O^{16} structures cannot interpenetrate without breaking up (internally exciting) the clusters.

If it is accepted that two carbon nuclei can interpenetrate without losing their identity, then the interaction can be represented by a real potential. Using a plausible form of potential, Davis[4] has computed excitation energies of vibrational states of the system, including corrections for vibration-rotation interaction, and obtains level spacings similar to those observed. This calculation, of course, does not yield any insight into the physical mechanism responsible for the "molecular" potential in the way that is attempted by Vogt and McManus who similarly show that a square well of appropriate dimensions leads to reasonable level spacings.

Studies of some other systems where the colliding nuclei are not identical and also have spin will be reported in a forthcoming publication. None of these systems have shown prominent resonant structure in the total reaction cross section such as found in the $C^{12}-C^{12}$ system. In these cases where the compound states are not restricted to even parity and even spin, a greater density of levels can be excited, and the chance of observing isolated resonances is correspondingly reduced even though quasimolecular states may exist.

Another essential point about the $C^{12}-C^{12}$ system as compared with others is the fact that nuclear transfer reactions, for example going to C^{11} and C^{13}, are energetically impossible near the Coulomb barrier energy where the prominent sharp resonances in total cross section occur. In other reactions where such transfers are energetically allowed they provide an alternate mode of breakup of molecular states and may thus contribute to their width. The energy dependence of nucleon transfer reaction has not yet been studied with sufficiently good resolution to see whether resonance effects are apparent such as are seen, for example, in (d,p) reactions on light nuclei.

In summary, therefore, the current views of the sharp resonances in the $C^{12}-C^{12}$ interaction suggest that the Pauli principle plays a crucial role in permitting carbon nuclei to interpenetrate to some extent without complete loss of their C^{12} structure to form a very special type of Mg^{24} state. One model suggests such states to be intimately connected with the deformability of C^{12} nuclei—the lack of structure in the $O^{16}-O^{16}$ observations is then attributed to the rigidity of O^{16}. The closed-shell structure of O^{16} also reduces the probability of the nuclei interpenetrating to form a molecular bond since this interpenetration requires promotion of nucleons from the closed p shell to the d or higher shells. No model yet proposed has permitted any quantitative predictions to be tested by experiment.

I. PARITY RULE

The parity rule discussed in the Introduction requires that the α-particle angular distribution goes to zero intensity at 0° and 180° for the $2-$ (4.97-MeV) state of Ne^{20} no matter what reaction mechanism is involved. In Figs. 2 and 3 we see that there is a striking drop in the α-particle yield at forward angles for this state compared to the other levels; the small residual yield can be accounted for by finite solid angle and uncertainties in background subtraction. The strong intensity at forward angles for all the other states studied unambiguously shows that they each have natural parity $[\pi=(-1)^J]$.

In applying this rule, it is important that measurements be done at several bombarding energies if unnatural parity is indicated, because accidental cancellations can lead to low intensity at 0°. An example is the angular distribution of the Ne^{20} $4+$ (4.25-MeV) state in Fig. 4 which at one particular energy drops to zero intensity at 0° although it has natural parity.

J. SUMMARY AND DISCUSSION

It has been shown that the sharp resonances ($\Gamma\sim 120$ keV) in the $C^{12}+C^{12}$ reaction at 5.6- and 6.0-MeV carbon energy (c.m.) almost certainly have spins 2 and 4, respectively. Their reduced widths for emission of C^{12} are 14% and 11% of the single particle unit, $\hbar^2/MR^2$, appropriate to the $C^{12}-C^{12}$ system. These values are more than ten times the measured average reduced width for α-particle emission and over one hundred times the observed nucleon widths expressed in the same way, which suggests that important effects arise from carbon clusters forming in the compound state.

It should be noted that the carbon widths are based on resonant cross sections[1,2] obtained by subtracting a background given by drawing a smooth curve through the points in the valleys between peaks. This gives a lower limit. An upper limit would be twice the carbon widths given here. These measurements are described in a paper to be published shortly. The same remarks apply to the estimates of the α-particle widths.

Evidence has been presented which indicates that both these resonances and similar sharp resonances observed at higher energies are formed in grazing collisions. For the two low-energy resonances the angular momenta involved do not appear great enough to be a significant factor in inhibiting coalescence of the carbon nuclei once they come within the range of nuclear forces. Consequently, the large reduced C^{12} width must result from the particular structure of the corresponding Mg^{24} states.

Additional measurements on other systems, to be published, have shown that resonances of a few hundred keV width appear in selected channels, e.g., in elastic scattering for $C^{12}+O^{16}$ at energies well above the Coulomb barrier and in α-particle channels with high Q value in $O^{16}+O^{16}$. The latter resonances have about twice the width of those seen in the $C^{12}+C^{12}$ system. They differ also in that no prominent resonances are seen at energies near the Coulomb barrier value in either the total reaction cross section or in elastic scattering such as appear in the $C^{12}+C^{12}$ system. As discussed below, these observations suggest that the widths for the incident channel (elastic scattering) are a relatively smaller fraction of the total width for $C^{12}+O^{16}$ as compared with $C^{12}+C^{12}$ and are still smaller for O^{16} on O^{16}.

At energies below the Coulomb barrier value the penetrability factor inhibits re-emission into the incident channel and resonant elastic scattering will only be observed if the reduced width is very large in this channel. The absence of resonant elastic scattering effects at low energies in C^{12} on O^{16} and their appearance at higher energies where the penetrability factor is more favorable indicate the reduced scattering width in this case to be a smaller fraction of the total resonant width than for C^{12} on C^{12}. The complete absence of resonant elastic effects even at higher energies in O^{16} on O^{16} similarly indicates that the resonances observed in selected α-particle channels have even smaller relative reduced widths for elastic scattering than those in the $C^{12}+O^{16}$ system and much smaller than C^{12} on C^{12}.

The observation of large carbon widths in the $C^{12}+C^{12}$ reaction led to the suggestion of the quasimolecular model in which the Mg^{24} state is assumed to exist for some time ($\sim 5\times 10^{-21}$ sec) as two C^{12} nuclei bonded together in a fashion reminiscent of the saddle point in fission. This state de-excites either by re-emission of the C^{12} nuclei or by collapse into a normal compound nucleus from which α particles and nucleons are emitted. A number of authors[4] have recently suggested mechanisms that make the existence of such states plausible and these have been discussed in Sec. H. None of these views provide a basis for quantitative predictions to be tested by experiment; however, they do suggest that the absence of resonances in the $O^{16}-O^{16}$ system is connected with the closed-shell nature of this nucleus.

It should be noted that the absence of resonances in the O^{16} on O^{16} elastic scattering does not exclude the possibility that quasimolecular states of S^{32} exist. On the view of Vogt and McManus that deformability plays a crucial role, such states would favor the pair $Ne^{20}-C^{12}$ and a detailed examination of the elastic scattering of the latter system would be an interesting test to see whether resonances with a large width for this pair of nuclei exist. It is known from the C^{12} on C^{12} studies that elastic scattering at higher energies shows resonances much more prominently and is thus a more sensitive test than the total reaction yield which has already been shown to be smooth for the $Ne^{20}-C^{12}$ system.[1] Since individual channels in reactions among heavy ions usually show resonances when examined with good energy resolution it would be of interest to see whether this is also true for nuclear transfer reactions. It is well known, for example, that resonant effects are clearly apparent in (d,p) reactions among light nuclei and seriously affect detailed interpretation of many results in terms of direct interaction theory. A similar situation may exist, at least at low energies, for nucleon transfer reactions between heavier ions such as C, N, and O which all show resonant behavior in individual reaction channels.

When a detailed understanding of these resonance phenomena in interactions between complex nuclei is found, it seems very probable that an important role will be played by deformation of the colliding nuclei arising from both Coulomb effects (excitation and polarization) as well as nuclear interactions. The fact that the emission of complicated structures such as C^{12} in some cases is favored over that of simpler subunits such as alpha particles and nucleons suggests that clustering and collective motions of clusters more complicated than α particles are important in the nuclear structure of highly excited states.

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