PHYSICAL REVIEW C VOLUME 9, NUMBER 5 MAY 1974

Systematics of "quasimolecular" resonances: A search for sub-Coulomb resonant structure in the reactions $^{14}N + {}^{14}N$ and $^{9}Be + {}^{12}C$†

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(Received 11 February 1974)

A correlation between the absence of nonstatistical sub-Coulomb resonant structure in many reactions previously studied and the density of levels in the associated compound (or precompound) nucleus is noted and discussed in terms of the intermediate structure model of nuclear reactions. Such a correlation would predict the absence of structure in the $^{14}N + {}^{14}N$ system, in disagreement with a previous measurement of excitation functions for the production of γ radiation. Excitation functions for the reactions $^{14}N(^{14}N,p)^{27}Al$, $^{14}N(^{14}N,d)^{26}Al$, $^{14}N(^{14}N,\alpha)^{24}Mg$, $^{9}Be(^{12}C,\alpha)^{17}O$, and $^{9}Be(^{12}C,p)^{20}F$ have been measured in the region of the Coulomb barrier in a search for resonance structure of the "quasimolecular" type observed in $^{12}C + {}^{12}C$ scattering. The present measurements of excitation functions for charged-particle production in $^{14}N + {}^{14}N$ do not exhibit any correlated resonances. The $^{9}Be + {}^{12}C$ system at the Coulomb-barrier energy produces ^{21}Ne in a region of excitation where the level density is relatively low and hence could be a reaction in which intermediate structure might be observed. The excitation functions measured for α-particle production show fluctuations, but with no apparent correlations.

NUCLEAR REACTIONS $^{14}N(^{14}N,\alpha)$, $^{14}N(^{14}N,p)$, $^{14}N(^{14}N,d)$, $E_{c.m.} = 7.0-10.0$ MeV; measured $\sigma_{\alpha+p+d}(E)$, $\sigma_p(E)$, $\sigma_d(E)$; $^{9}Be(^{12}C,\alpha)$, $^{9}Be(^{12}C,p)$, $E_{c.m.} = 2.40-6.34$ MeV; measured $\sigma_{\alpha+p}(E)$; searched for nonstatistical resonances in Coulomb barrier region; discussed systematics of "quasimolecular" resonances.

I. INTRODUCTION

One of the most striking early results of heavy-ion research with tandem accelerators was the observation of "quasimolecular" resonances in $^{12}C + {}^{12}C$ scattering at energies below the Coulomb barrier.[1] One of the distinctive features of such resonances is their clearly nonstatistical origin. All observed exit channels ($p, n, \alpha, {}^{12}C$)[1] and ^{8}Be[2] exhibit strongly correlated resonances in their summed reaction cross sections, whereas uncorrelated fluctuations arising from statistical compound-nucleus formation would be damped out by summation over the final states in the residual nuclei. The possibility that the resonances correspond to isolated states or random fluctuations in level density in the compound nucleus, as might be realized in lighter systems[3] such as $\alpha + \alpha$, $^{6}Li + \alpha$, and $^{6}Li + {}^{6}Li$, is unlikely because of the higher density of levels in the ^{24}Mg compound nucleus in the region of 18 MeV excitation. The nonstatistical character of these resonances then suggests that they involve only relatively few degrees of freedom and represent simple structure in the continuum, easily excited in the entrance channel of a heavy-ion reaction.[4]

Similar, although broader, resonances have also been observed in the $^{12}C + {}^{16}O$,[5] and possibly in the $^{12}C + {}^{14}C$[6] reaction cross sections, and recent theoretical efforts have met with some success in explaining their energies, widths, and spins. However, the microscopic nuclear structure underlying these resonances is still not well understood. Early explanations of the three $^{12}C + {}^{12}C$ resonances above 5.5 MeV observed at Chalk River attributed the long lifetime ($\sim 10^{-20}$ sec) and large reduced width for the decay of the resonances into two ^{12}C ions to the formation of a quasibound molecular state of two ^{12}C ions. In this case, the motion of the ^{12}C ions is governed by a "single-particle" potential well[7-9] produced by the combined effects of Coulomb repulsion, the centrifugal barrier, and the Pauli exclusion principle.[7,8]

While Davis[9] was able to show that a standard optical model can produce a resonant condition for the grazing partial wave, Vogt and McManus[7] used the deformability of the ^{12}C ions to justify a potential well of large radius, an approach which could both reproduce approximately the close level spacings and spins for the observed resonances and explain the lack of resonances in the more rigid $^{16}O + {}^{16}O$ system. Imanishi[10] was able to obtain excellent agreement with the spins and level spacing of the three Chalk River resonances by assuming that, at certain bombarding energies where an energy-matching condition is satisfied, one of the highly deformable ^{12}C nuclei is virtually excited and the resulting change in

TABLE I. Information on sub-Coulomb resonance structure in heavy-ion reactions.

Compound system	Reaction	E_x^{cn} [c] (MeV)	Relative [b] level density	Relative [a] number of open channels	Exit channels observed	Lowest E_x^{cn} (MeV) reached in measurements	Resonances [d] observed	Reference
^{20}Ne	^{10}B + ^{10}B	36.1	37	160			Not reported	
^{21}Ne	^{9}Be + ^{12}C	21.7	3.3	7	p, α	19.6	No	20, Present work
^{22}Na	^{10}B + ^{12}C	23.0	15	14	γ	20.2	No	22
^{23}Na	^{11}B + ^{12}C	23.8	11	14	γ	21.2	No	22
^{24}Mg	^{10}B + ^{14}N	35.4	100	350	$\alpha, {}^{12}$C	34.0	No	17
	^{12}C + ^{12}C	20.6	1	1	$\gamma, p, n, \alpha, {}^{8}$Be, ^{12}C	17.1	$\Gamma \sim$ 100–250 keV	1, 2, 11, 12, 15
^{25}Mg	^{12}C + ^{13}C	22.9	7.1	13	γ, p, α	21.4	No	17, 18
^{26}Mg	^{13}C + ^{13}C	28.9	36	48	γ	27.7	No	18
	^{12}C + ^{14}C	25.7	13	12	d, t, α	24.6	$\Gamma \sim$ 270–400 keV	6
^{26}Al	^{12}C + ^{14}N	22.6	23	13	p, α, γ	18.4	No	16, 22, e
^{27}Mg	^{13}C + ^{14}C	27.2	44	170			Not reported	
^{27}Al	^{13}C + ^{14}N	30.7	98	440			Not reported	
^{28}Mg	^{14}C + ^{14}C	27.4	27	100			Not reported	
^{28}Si	^{12}C + ^{16}O	25.2	3.8	3.9	p, α	21.3	$\Gamma \sim$ 220–350 keV	5
	^{14}N + ^{14}N	35.8	110	300	γ, p, d, α	31.0	No	20, 28, 30, 31, Present work
^{29}Si	^{13}C + ^{16}O	28.6	59	125			Not reported	
^{30}Si	^{12}C + ^{18}O	31.9	130	340			Not reported	
	^{14}C + ^{16}O	31.0	98	220			Not reported	
^{31}P	^{12}C + ^{19}F	32.1	350	1.8×10^{3}	γ	30.2	No	16
^{32}S	^{12}C + ^{20}Ne	29.1	43	75	γ	27.9	No	16
	^{16}O + ^{16}O	27.3	22	34	γ, p, n, d, α	23.3	No	1, 15
^{36}Ar	^{12}C + ^{24}Mg	28.1	130	300			Not reported	
	^{16}O + ^{20}Ne	31.4	450	1.5×10^{3}	γ	30.2	No	16
^{40}Ca	^{12}C + ^{28}Si	26.7	185	170			Not reported	
	^{16}O + ^{24}Mg	31.2	1.0×10^{3}	$2\ \times10^{3}$			Not reported	
	^{20}Ne + ^{20}Ne	36.4	7.9×10^{3}	2.4×10^{4}			Not reported	
^{44}Ti	^{20}Ne + ^{24}Mg	34.8	4.2×10^{4}	$8\ \times10^{4}$			Not reported	
^{48}Cr	^{24}Mg + ^{24}Mg	36.4	2.8×10^{5}	2.9×10^{5}			Not reported	

[a] Relative number of channels open for the decay of compound-nucleus levels of spin 0, evaluated using the code STATIS (Ref. 26) and pairing energies and single-particle level densities for the residual nuclei given by A. Gilbert and A. G. W. Cameron [Can. J. Phys. 43, 1446 (1965)] and by U. Facchini and E. Saetta-Menichella [Energia Nucl. 15, 54 (1968)], respectively.

[b] The level-density expression of D. W. Lang [Nucl. Phys. 42, 353 (1963)] has been evaluated using $\mathscr{I} = \mathscr{I}_r$ with $r_0 = 1.40$ fm, pairing energies of A. Gilbert and A. G. W. Cameron [Can. J. Phys. 43, 1446 (1965)], and level-density parameter a determined by linear interpolation between the values given by U. Facchini and E. Saetta-Menichella [Energia Nucl. 15, 54 (1968)] for low excitation energies and the common value $a = A/7$ approached at $E_x = 100$ MeV by all nuclei in this mass region. Where the level-density parameter for a particular nucleus of mass A was not available from Facchini and Saetta-Menichella (see footnote a), the value adopted was that for the nearest nucleus (mass A') of similar structure (e.g., even even), corrected for the ratio of masses A/A'. The relative level densities are for spin 0, but the qualitative conclusions are not altered if, for example, the ratios are obtained for spin-4 states.

[c] Excitation energy in the compound nucleus when the bombarding energy is equal to the Coulomb barrier as given by $R_c = 1.7(A_1^{1/3} + A_2^{1/3})$.

[d] The designation "No" is somewhat arbitrary. For example, a slight structure in the ^{12}C + ^{14}N total reaction cross section at $E_{\mathrm{c.m.}} \sim 10$–$13$ MeV [see J. A. Kuehner and E. Almqvist, Phys. Rev. 134, B1229 (1964)] has not been included as an example of an intermediate resonance, because the structure is not sufficiently pronounced to reliably assign a characteristic width.

[e] J. A. Kuehner and E. Almquist, Phys. Rev. 134, B1229 (1964).

the potential produces a quasibound state. Michaud and Vogt,[4] however, pointed out that all single-particle models face the serious problem of being unable to reproduce, with a potential well of reasonable radius, the additional $^{12}C+^{12}C$ resonances discovered below 5.5 MeV c.m. by Patterson, Winkler, and Zaidins[11] and Mazarakis and Stephens.[12] They proposed to overcome this difficulty by replacing the concept of a doorway state involving two ^{12}C nuclei with a mechansim whereby one of the ^{12}C nuclei dissociates into three α-particle clusters. By introducing additional degrees of freedom into the system, the α-cluster model[4] is able to account qualitatively for the additional resonances in the $^{12}C+^{12}C$ system. It provides a natural explanation for an enhanced α-particle or ^{8}Be emission compared to statistical compound-nucleus predictions[2,13] for the relative strengths of α-particle and proton emission. The α-particle intermediate structure model has received much support from the recent measurements of Voit and collaborators who observed an enhanced α-particle decay to α-cluster states in ^{20}Ne when the compound system is at an intermediate resonance.[14]

We note that a fundamental difficulty with all of the models discussed is that they would apparently predict resonances in systems where none are observed. Table I lists the information available on heavy-ion systems in which sub-Coulomb resonances have been sought experimentally. In the single-particle model of Vogt and McManus,[7] any deformable heavy-ion pair should produce resonances. The coupled-channel model of Imanishi[10] would seem to predict the possibility of resonances in any system where strong coupling to low-lying excited states is possible, a feature common to many systems where resonances are not observed. The α-conjugate systems $^{16}O+^{16}O$,[1,15] $^{16}O+^{20}Ne$,[16] and $^{12}C+^{20}Ne$[16] would appear to be excellent candidates for α-particle intermediate structure, but again the results have been negative. An equally puzzling pattern has emerged from investigations of the $^{12}C+^{13}C$,[17,18] $^{13}C+^{13}C$,[18] and $^{12}C+^{14}C$[6] systems. Here the addition of a single extra neutron to either one or both ^{12}C cores would seem to completely suppress an effect of α-particle intermediate structure and eliminate the associated resonances while the addition of two paired neutrons to one of the cores apparently does not have such strong negative consequences.

Clearly, a systematic study of many reactions is a necessary prerequisite to an eventual understanding of the reaction mechanisms and nuclear structure responsible for the presence of resonances in some systems and absence in many others. In this paper, we examine the systematics[19] of previous experimental results and describe two new measurements[20] on the $^{14}N+^{14}N$ and $^{9}Be+^{12}C$ systems which were motivated by simple arguments emerging from this systematic study.

II. SYSTEMATICS

Until the present work, nonstatistical or "quasimolecular"[21] resonances had been sought in a total of 12 different nuclear reactions covering compound nuclei with $A=24$ to $A=36$. These reactions and the results obtained are listed in Table I. In only three cases, $^{12}C+^{12}C$, $^{12}C+^{14}C$, and $^{12}C+^{16}O$, were resonances observed, with $^{12}C+^{12}C$ displaying the most prominent structure. In cases where positive results were obtained, the typical width of the resonant structure is indicated in the table.

At present there are no theoretical predictions available for comparison with the data from all of these 12 cases. Theoretical work has naturally been directed more toward explaining positive results rather than negative results. As noted above, however, the negative results are also of importance. Given the absence of specific theoretical predictions, we approach the problem phenomenologically by examining the characteristics of the various systems to see whether a correlation exists between a given feature and the presence or absence of resonant structure. Several such correlations are evident, although not necessarily of obvious physical significance. For example, all cases where resonances are observed involve spin-zero even-even targets and projectiles, and include at least one ^{12}C nucleus in the system. Systems not possessing *both* of these features do not show resonances. However, an explicit correlation with the spin of the target or projectile would not seem physically significant in light of the theories which have been advanced thus far, since these quantities have not entered specifically into the theories based on the gross properties of the heavy ions. Although the importance of spin is not obvious apart from a geometrical average over magnetic substates, it nevertheless cannot be discounted since the present theories are generally inadequate in their explanation of the negative results.

The presence of ^{12}C in all reactions exhibiting intermediate structure, on the other hand, is of crucial significance in the α-particle model of Michaud and Vogt. Yet this model would apparently apply to reactions involving α-conjugate nuclei like ^{16}O and ^{20}Ne, and thus experiences difficulty with several of the negative experimental results.

Another characteristic which we may examine is the density of levels in the compound nucleus at the excitation energy determined by the Coulomb barrier in the entrance channel. This quantity, which is given for spin-0 states and normalized to unity for the case of $^{12}C+^{12}C$, is presented for all reactions listed in Table I. There is a limited and negative correlation between the relative level density in the compound nucleus and the observation of nonstatistical resonances. Of the systems for which data have been reported, none for which the relative level density is greater than ~15 exhibit molecular-type resonances. These include such systems as $^{16}O+^{16}O$, $^{12}C+^{20}Ne$, and $^{10}B+^{14}N$. (This ratio is reduced to ~5 if the $^{12}C+^{14}C$ result is excluded. The case of $^{14}N+^{14}N$ is discussed in a later section, the present experimental work revealing no evidence for a resonance.) When the relative level density is less than ~15 no correlation exists, since some systems with comparable relative densities exhibit resonances whereas others do not. The contrast between the $^{12}C+^{12}C$ system and the $^{12}C+^{13}C$[17,18] and $^{10,11}B+^{12}C$ systems,[22] all of which have comparable low level densities, is particularly striking. Of the three systems which show resonances, however, we note that those with higher level densities exhibit broader less-pronouned structure. Thus the most useful application of this correlation is in determining which systems would *not* be expected to show structure. A low level density does not ensure that structure will be observed in an experiment. But it can at least delineate those systems which might show structure and which therefore should be investigated.

Some insight into this correlation is given by the intermediate structure model which relates the width of the intermediate structure to the density of levels in the compound (or precompound) nucleus. Feshbach, Kerman, and Lemmer[23] discuss this dependence in their theoretical treatment of intermediate structure. The width Γ of the intermediate structure or doorway state is made up of two parts, the width Γ_1 for decay back into the entrance channel (or into other channels having a configuration similar to the intermediate resonance) and the width Γ_2 for decay into the compound nucleus. The "damping width" Γ_2 of the intermediate structure state is given by

$$\Gamma_2(J^\pi) \simeq 2\pi\rho(J^\pi)\,|\langle\Phi_{cn}(J^\pi,M)|H|\psi_i(J^\pi,M)\rangle|_{av}^2, \tag{1}$$

where $\rho(J^\pi)$ is the average density of the compound-nucleus states of spin and parity J^π in the interval ΔE over which the simple excitation is spread, and the square of the matrix element which gives the coupling to compound-nucleus states is averaged over this same interval.

Thus in this picture, the absence of resonant structure in, e.g., $^{16}O+^{16}O$ and $^{12}C+^{20}Ne$, need not arise from an absence of α-cluster configurations or doorway states. Indeed, in Michaud's and Vogt's model, the "escape width" Γ_1 should be roughly similar for $^{12}C+^{12}C$, $^{12}C+^{16}O$, and $^{16}O+^{16}O$, for example, since all of these nuclei have low thresholds for dissociation into α-cluster configurations. Rather, the negative results could be caused by a large spreading or damping width of these intermediate states associated with the high density of levels in the compound nucleus, i.e., the resonances are so broad that they are not observed. This discussion assumes, of course, that the average matrix element in Eq. (1) is smoothly varying from system to system. While this assumption is made more on the basis of ignorance than theoretical argument, it seems reasonable since we are only trying to make plausible a dependence of spreading width on level density.

It might be argued here that the density of levels in the statistical compound nucleus is not the important quantity determining the spreading width of the intermediate states. Rather, the precompound levels,[24] simpler in structure than the equilibrium levels yet more complex than the intermediate states (or the entrance channel states), should be the determining factor. The density of such levels, having fewer degrees of freedom than the compound states, might be estimated roughly by reducing the parameter a for the density of single-particle levels in the Fermi-gas formula for the level density. It is not clear how much the parameter a should be reduced for each system. At some point, as the number of degrees of freedom becomes smaller, one enters the regime of microscopic structure, shell effects become important, and these statistical arguments are no longer valid. To the extent that the density of precompound levels is still governed mainly by the number of nucleons in the system, however, approximately the same ordering of relative level densities as in Table I would be obtained.

It follows from the statistical model that a similar correlation will exist between the absence of structure and the number of channels open for the decay of the compound nucleus. This is a consequence of the statistical model relation

$$\rho^{J,\pi} = \frac{N^{J,\pi}}{2\pi\Gamma_{cn}^{J,\pi}}, \tag{2}$$

where $N^{J,\pi}$ is the number of channels open for the decay of a state of J^π, and $\Gamma_{cn}^{J,\pi}$ is the average width of these states. Experiments show that Γ_{cn} does not vary rapidly with excitation energy nor from system to system, with $\Gamma_{cn} \sim 50\text{–}110$ keV.[25] The quantity N has been calculated explicitly[26] using $N = \sum_{c,l,s} T_l^c$, where T_l^c is an optical-model transmission coefficient for exit channel c, and is also listed in Table I for comparison. However, such a correlation is not as well motivated physically in the case of sub-Coulomb resonances[27] as is the one involving the density of compound or precompound levels since the decay of the statistical compound nucleus is one step further removed from the decay of the intermediate state in the compound nucleus. Further discussion of the importance of level-density arguments and the role of microscopic nuclear structure in the origin and absence of quasimolecular resonances is given in Sec. IV.

Among the measurements performed on the systems listed in Table I there is one experimental observation which is in striking exception to the foregoing ideas on α-particle intermediate structure and level density in the compound nucleus. This exception is the single narrow resonance observed in the γ-radiation yield for $^{14}N + ^{14}N$ obtained in 1960 by Almqvist, Bromley, and Kuehner[28] and shown in Fig. 1. Although these authors emphasized the general lack of structure in this excitation function, the single bump appearing at $E_{c.m.} = 7.5$ MeV was measured a second time with a thinner target and found to persist. Because of the relatively high level density reached in the $^{14}N + ^{14}N$ reaction, one would expect any intermediate structure to be strongly damped. If a narrow resonance were present in the $^{14}N + ^{14}N$ reaction, it would then imply the operation of a strong selection rule inhibiting the decay of the intermediate state to the compound nucleus, a result of considerable interest.[19] It was this pos-

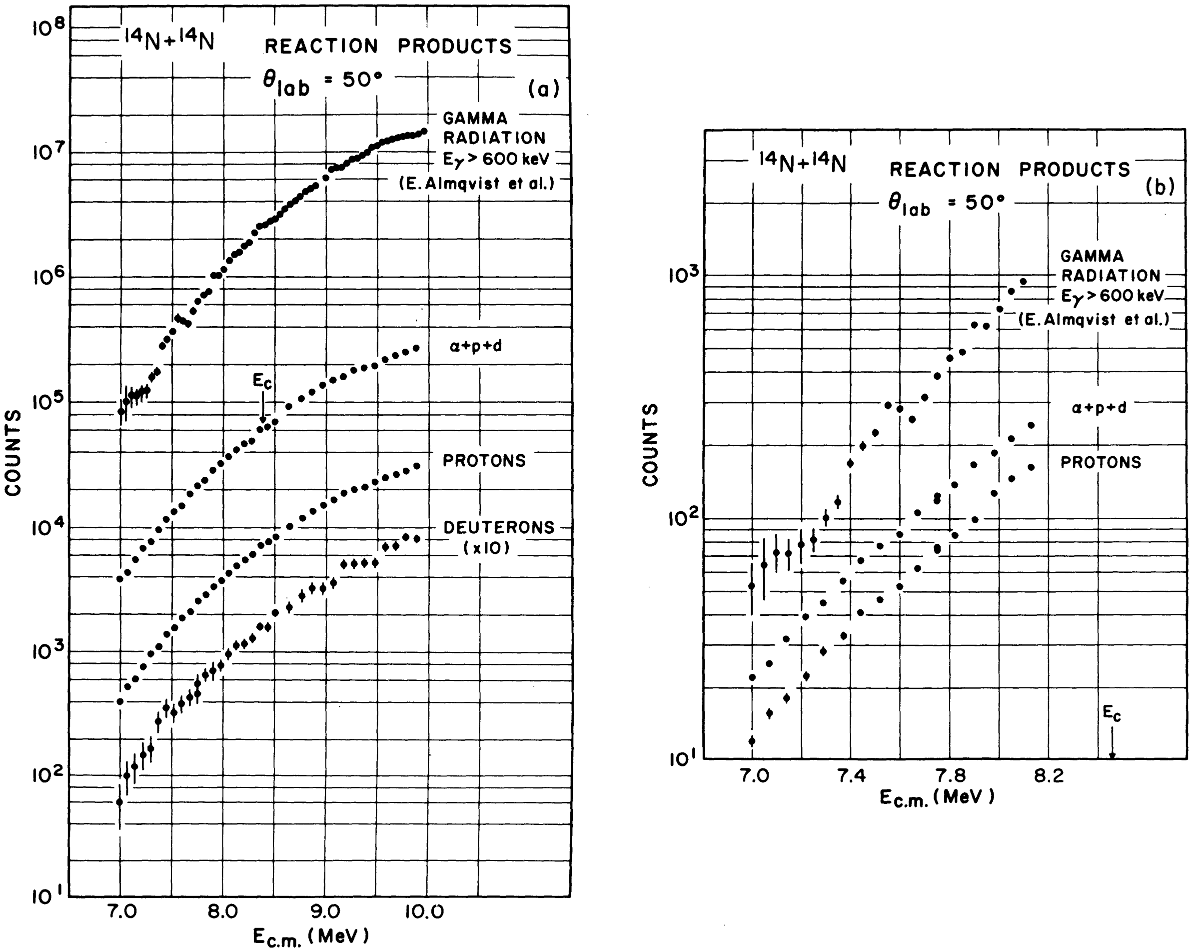

FIG. 1. (a) Excitation functions for $^{14}N + ^{14}N$ γ-radiation yield (E_γ >600 keV) from Almqvist, Bromley, and Kuehner (Ref. 28). The target thickness was ~100 keV c.m. and the normalization is arbitrary. Also shown are charged-particle yields for $^{14}N + ^{14}N$ reactions determined in the present work. (b) $^{14}N + ^{14}N$ charged-particle yields in the region of $E_{c.m.}$ ~ 7.5 MeV compared to the γ-ray yield (Ref. 28).

sibility which motivated our measurements of charged-particle yields for the $^{14}N+^{14}N$ reaction, to be described in Sec. III.

Since the negative predictions of level-density arguments seem to be confirmed in the overwhelming majority of cases investigated, it seems reasonable to use these arguments as a guide in deciding which reactions might be favorable cases for the observation of sub-Coulomb resonances. From among several systems of lighter ($A<24$) nuclei not yet studied, we chose to investigate the $^{9}Be+^{12}C$ system because the density of levels at the Coulomb-barrier excitation energy in the ^{21}Ne compound nucleus is about as low as that of the $^{12}C+^{12}C$ system. This reaction also appeared particularly attractive in light of recent results obtained by Middleton *et al.*[29] on the $^{12}C(^{13}C,\alpha)^{21}Ne^*$ reaction. The latter reaction suggests the presence of eight-particle–three-hole strength in ^{21}Ne. Such structure, if present at high excitation energies, might appear as intermediate structure in the compound system in the $^{9}Be+^{12}C$ reaction. The experimental procedure and results for this reaction are reported in Sec. III.

Of the other reactions in Table I involving lighter nuclei not yet reported, $^{10}B+^{10}B$ would seem to be the least likely candidate to exhibit resonance structure. Also included in Table I are reactions involving heavier systems such as $^{12}C+^{24}Mg$. Such reactions, while presenting new possibilities for ^{12}C and α-cluster configurations, in general go through a region of high relative level density in the compound nucleus at the Coulomb barrier, and thus do not seem to be as promising cases for the observation of sub-Coulomb resonances.

III. EXPERIMENTAL PROCEDURE AND RESULTS

A. $^{14}N+^{14}N$

Measurements were made using a $^{14}N^{3+}$ beam from the Yale MP tandem accelerator. The target consisted of a nitrogen-filled gas cell with a 0.22-mg/cm^2 nickel foil entrance window. The energy loss and straggling in this entrance window were determined in the energy range $E_{lab}=14-20$ MeV by measuring directly the energy loss of ^{14}N particles passing through a similar nickel foil. This measurement is illustrated in Fig. 2. Straggling in the entrance foil of the gas cell was thus measured to be 65 keV (c.m.) over this energy range.

Charged particles were detected in two ΔE-E silicon surface-barrier telescopes ($\Delta E\sim 500$ μm, $E\sim 2\times 2000$ μm) positioned at $\theta_{lab}=50$ and 85°. Each telescope was masked by a 3.15-mg/cm^2 nickel absorber to stop particles heavier than α particles, and the thickness of the ΔE detectors was chosen to stop all α particles while optimizing the energy loss in the ΔE detector for protons and deuterons. Data were taken on line with an IBM 360/44 computer and stored event by event on magnetic tape. Coincident E and ΔE signals were sorted into a ΔE by $E+\Delta E$ array to obtain proton yields for unresolved states up to 19 MeV excitation in ^{27}Al and deuteron yields for unresolved states up to 6 MeV excitation in ^{26}Al. Sums of the total α-particle yield and the yield for protons and deuterons stopped in the ΔE detector were then obtained from noncoincident ΔE singles events. These low-energy proton and deuteron yields are concentrated in the energy region corresponding to the Coulomb barrier for emission from the compound nucleus. The telescopes at 50, 85°_{lab} had angular acceptances of 5.7, 9.1°, subtended solid angles of 7.8, 20.1 msr, and viewed linear distances of 6.0, 3.7 mm in the gas cell. The effective center of the target was at a distance of 6 mm from the gas cell entrance window. The nitrogen gas pressure was typically 18 Torr corresponding to an approximate target thickness of 18 μg/cm^2 (~60 keV c.m.) for the 50° telescope and 11 μg/cm^2 (~40 keV c.m.) for the 85° telescope.

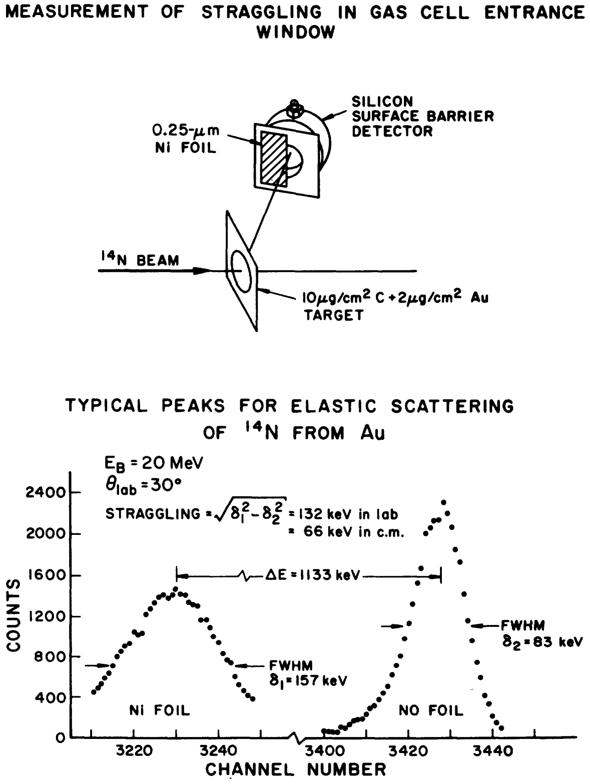

FIG. 2. Measurement of straggling in the nickel foil entrance window of the nitrogen gas cell.

The total spread in beam energy due to target thickness plus straggling in the entrance foil and approach gas was estimated to be 135 keV c.m. for the 50° telescope and 115 keV c.m. for the 85° telescope. Thus the energy resolution in the entrance channel is less than or equal to the width of the structure observed at $E_{c.m.} \sim 7.5$ MeV in Ref. 28.

Yields for protons, deuterons, and α particles were measured in 75-keV c.m. steps and normalized both to the integrated beam current and, at energies below the Coulomb barrier, to $^{14}N+^{14}N$ elastic scattering observed by a silicon surface-barrier detector at $\theta_{lab}=45°$. Figure 1(a) compares the measured charged-particle yields and the γ radiation yields from Almqvist, Bromley, and Kuehner.[28] In Fig. 1(b) which shows the same data expanded in the region of the resonance in the γ-radiation yields, it can be seen that no pronounced structure appears in the energy-integrated charged-particle yields. A very similar, smoothly increasing yield for α particles and protons was obtained at $\theta_{lab}=85°$ and is not shown.

B. $^9Be+^{12}C$

Measurements were made with a 23-μg/cm^2 ^{9}Be target on a 10-μg/cm^2 carbon backing, resulting in a 75-keV c.m. energy loss in the ^{9}Be target for an 11-MeV ^{12}C beam passing through the target at 37° to the normal. α particles, protons, and deuterons were detected in four separate silicon surface-barrier detectors positioned at $\theta_{lab}=23$, 37, 67, and 97°. Each detector was masked by a 4.5-mg/cm^2 nickel foil absorber to stop heavy ions and the detector thickness at each angle was chosen to completely stop α particles.

The Q values for reactions going through the ^{21}Ne compound nucleus make α particles the dominant decay product from the $^9Be+^{12}C$ reaction. Statistical model calculations[26] predict that over the range of energies studied, the total cross section for the $^9Be(^{12}C,\alpha)^{17}O$ reaction is larger than the corresponding total cross section for the $^9Be(^{12}C,p)^{20}F$ and $^9Be(^{12}C,d)^{19}F$ reactions by factors of ~3 and ~6, respectively. With regard to the α-particle yield from the carbon backing, a similar calculation at the same bombarding energy predicts a ratio of total cross sections for compound-nucleus decay producing light ($A \leq 4$) charged particles $[\sigma_T(^9Be+^{12}C)]/[\sigma_T(^{12}C+^{12}C)]$ of 17 at $E_{^{12}C}=10.0$ MeV and 1.4 at $E_{^{12}C}=14.8$ MeV lab. The difference in target thickness re-

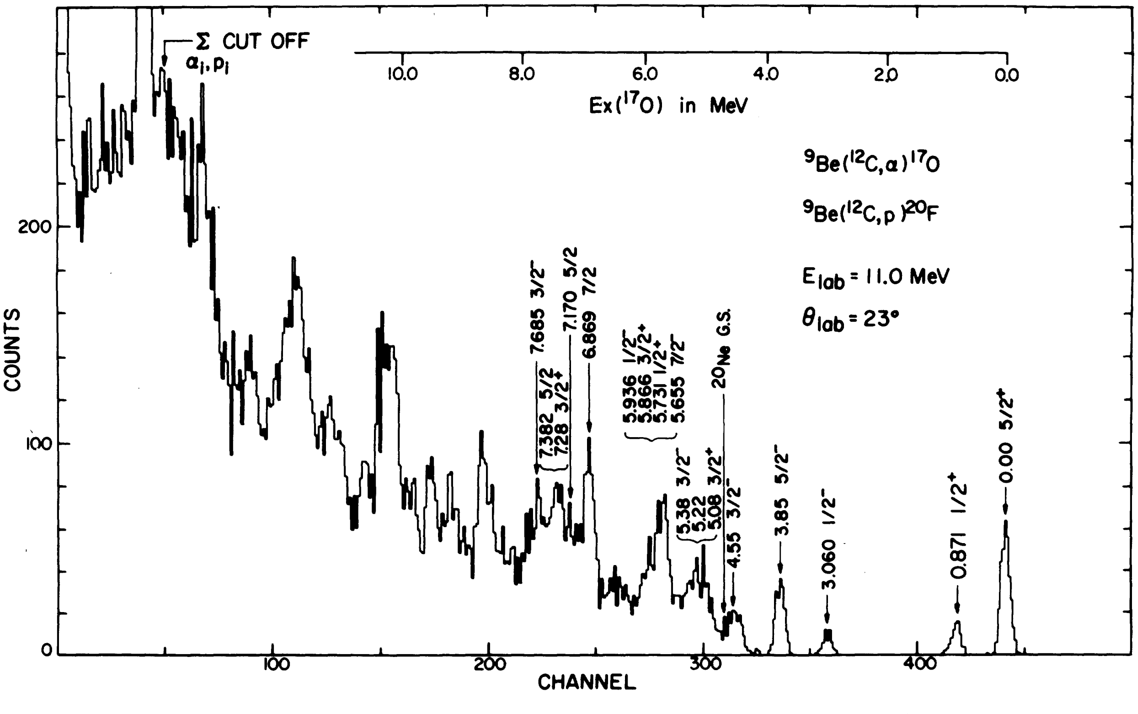

FIG. 3. Forward-angle spectrum for α particles and protons from the reactions $^9Be(^{12}C,\alpha)^{17}O$, $^9Be(^{12}C,p)^{20}F$, and $^{12}C(^{12}C,\alpha)^{20}Ne$. Energies, spins, and parities of ^{17}O levels populated in the dominant $^9Be(^{12}C,\alpha)^{17}O$ reaction are from K. Bethge *et al.*, Phys. Rev. C 2, 395 (1970) and H. Schmitt-Bocking *et al.*, Z. Phys. 246, 431 (1971). The highest-energy proton groups are folded back under the spectrum because of insufficient detector thickness. The background contribution at $E_B=11$ MeV (lab) from the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction on the carbon backing of the target is ~5% of the total $^9Be+^{12}C$ yield.

sults in a further factor of 2 reduction in the $^{12}C+^{12}C$ total reaction yield from the carbon backing relative to that of $^{9}Be+^{12}C$. Measurements with a separate 10-$\mu g/cm^2$ ^{12}C target at $\theta_{lab}=37°$ indicate that the total yield for the $^{12}C+^{12}C$ contaminant reaction is lower than that of the $^{9}Be+^{12}C$ reaction for our target by factors of 45 and 3.5 at $E_{^{12}C}=10.0$ and 14.8 MeV lab, respectively, in reasonable agreement with the statistical model predictions when the ratios of the target thicknesses are taken into account. Because of the low yields for $^{12}C+^{12}C$ reactions relative to $^{9}Be+^{12}C$ over the energy range considered, no attempt was made to measure the competing $^{12}C+^{12}C$ reaction at each energy with a ^{12}C target and to then subtract off this background in arriving at a total charged-particle yield. Resonances in the otherwise smoothly varying $^{12}C+^{12}C$ component of the total yield would have a small effect compared to possible resonances in $^{9}Be+^{12}C$ reaction. Also, the kinematics of the $^{9}Be(^{12}C, \alpha)^{17}O$ and $^{12}C(^{12}C, \alpha)^{20}Ne$ reactions give a clean separation of at least four states in ^{17}O from states in ^{20}Ne at the angles measured.

Figure 3 shows a typical spectrum obtained with the detector at $\theta_{lab}=23°$, for α-particle transitions to various levels in the ^{17}O residual nucleus. At the forward angles (23, 37°) charged-particle yields are summed from just above the large peak of elastically scattered ^{12}C ions (the presence of which arises from a nonuniform absorber) and include yields to approximately 75 states in ^{17}O, 75 states in ^{20}F, and from 1% ($E_B=9$ MeV) to 20% ($E_B=14.8$ MeV) background, depending on energy, from the competing $^{12}C+^{12}C$ reaction. The summation was over the entire spectrum at

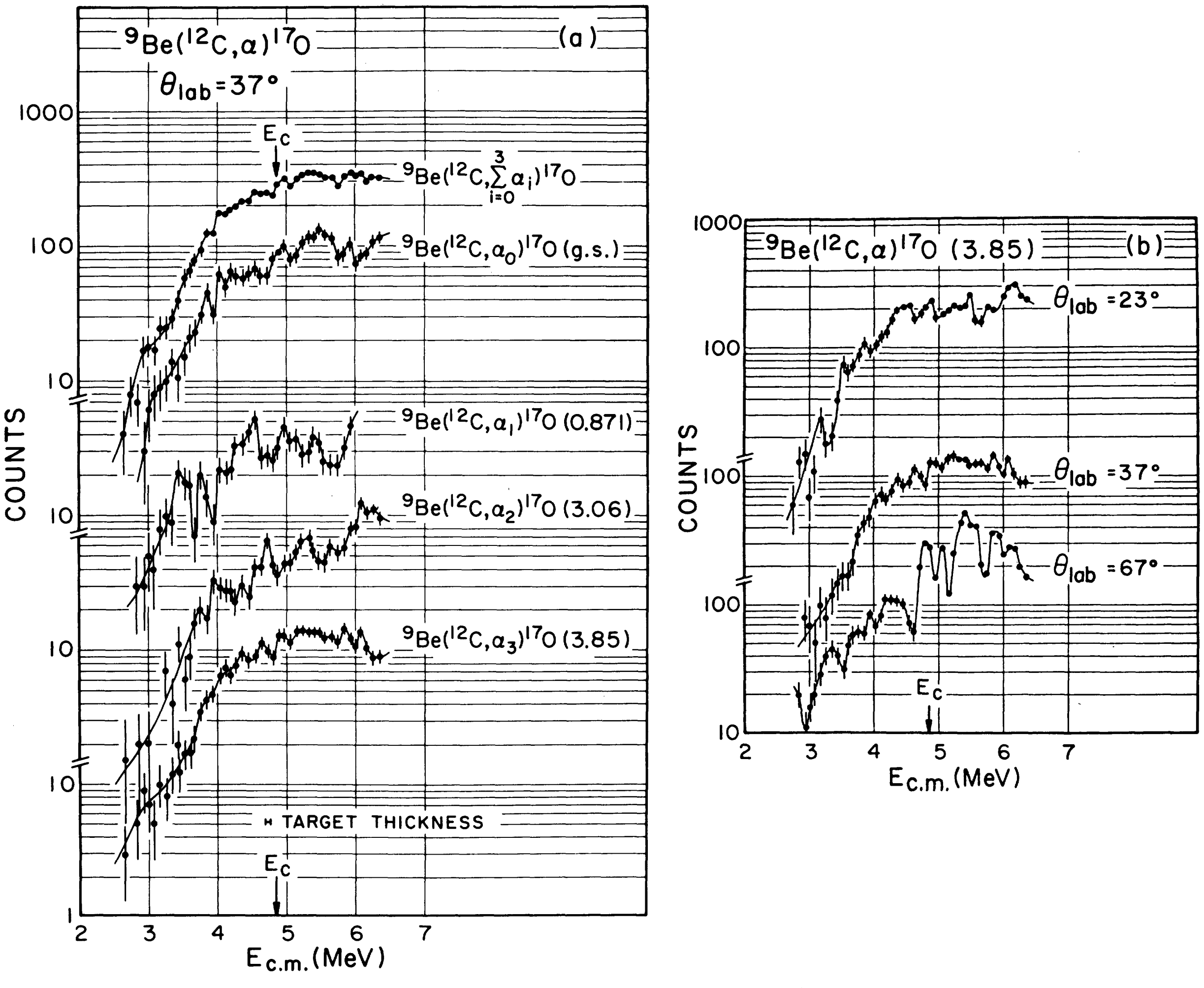

FIG. 4. Excitation functions for α- particle transitions to individual levels in ^{17}O. (a) Yields for α-particle transitions to the first four levels in ^{17}O and their sum at $\theta_{lab}=37°$. The scale is $d\sigma/d\Omega|_{lab}=0.95$ μb/sr count. (b) Yields for the 3.85-MeV state in ^{17}O at three different angles. The scale is $d\sigma/d\Omega|_{lab}=(0.95, 0.95, 0.43)$ μb/sr count for $\theta_{lab}=(23, 37, 67°)$.

the more backward angles where no heavy-ion penetration of the absorber was observed.

Excitation functions at $\theta_{\text{lab}} = 37°$ for α particles going to the first four states in ^{17}O are shown in Fig. 4(a). The pronounced structures on a steeply rising background for the individual channels show no obvious cross-channel correlations and are almost completely damped out after summing over only four residual states. Figure 4(b) shows the excitation function for a single state in ^{17}O at three different angles. Again, there is no apparent angular cross correlation of the resonances for this channel. Such uncorrelated resonances or fluctuations are characteristic of statistical compound-nucleus formation and a summation over many states must be made in order to reveal the presence of nonstatistical resonances. No such correlated resonant structure appears in the summed charged-particle yields of Fig. 5. The inset in Fig. 5 shows for comparison an excitation function for summed charged-particle yields taken across the 5.0-MeV resonance region of the ^{12}C + ^{12}C system with our same experimental arrangement and a carbon target. Here we observe a resonance with the same energy, width, and peak-to-valley ratio as in Refs. 1, 11, and 12.

IV. DISCUSSION

No evidence is found for a sub-Coulomb resonance in the ^{14}N + ^{14}N total cross section when light charged particles (p, d, α) are observed at $\theta_{\text{lab}} = 50$ or 85°. However, a single resonance is observed in the γ-radiation yield measured by Almqvist, Bromley, and Kuehner[28] using a differentially pumped windowless gas cell (Fig. 1). Two possible explanations for these results present themselves: (a) the γ-ray results are correct and there is a resonance which appears only in neutron exit channels (and not followed by charged-particle emission) or for heavy particles which are stopped in the absorbers in front of our detectors; or (b) a contaminant reaction is observed in the γ-ray measurement. The first possibility seems unlikely to produce a large resonance in the total cross section since compound-nucleus cross sections for single neutron emission not followed by charged-particle emission and for heavy-ion exit channels are much smaller than those for the dominant α, p, and d channels.

The second possibility may be tested by repeating the γ-ray measurement. Results of new γ-yield measurements[30,31] currently being carried out indicate no such structure.

Our charged-particle measurements and the recent γ-yield measurements[30,31] stimulated by them confirm the absence of sub-Coulomb resonances in the ^{14}N + ^{14}N reaction. While the ^{14}N + ^{14}N system goes through the same ^{28}Si compound nucleus as the ^{12}C + ^{16}O system which exhibits resonances, the higher excitation energy and the much larger level density and number of open channels for the ^{14}N + ^{14}N system apparently lead to strong damping of any intermediate structure.

For the ^{12}C + ^{16}O and ^{12}C + ^{14}C reactions, where resonances are observed, the relative level densities and number of open channels are less than 15 (Table I). Although the ^{12}C + ^{13}C and (especially) the ^{9}Be + ^{12}C reactions go through a region of excitation in the compound nucleus where the level densities and number of open channels are quite comparable to those for the ^{12}C + ^{12}C system, no resonances are observed in either case. The absence of sub-Coulomb resonant structure in the ^{9}Be + ^{12}C system further emphasizes the fact that, in those systems where relative level densities are low, nuclear structure on a microscopic scale must be the determining factor in the observation of resonances.

V. CONCLUSION

A study of the systematics of nonstatistical resonances in heavy-ion reactions at sub-Coulomb energies has led to a correlation between the absence of such structure and a high level density in the

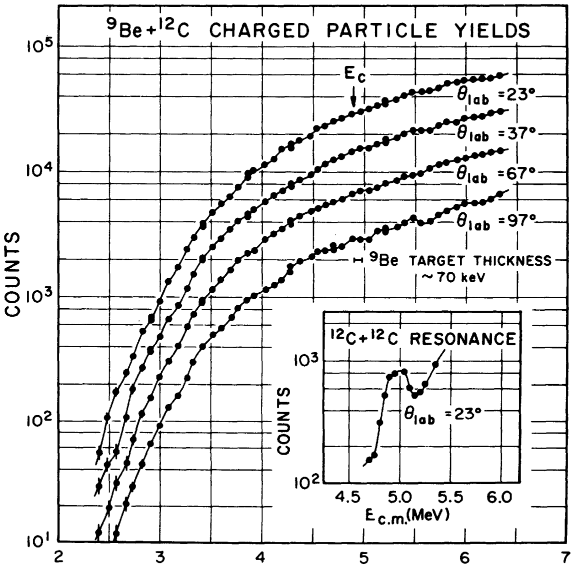

FIG. 5. Charged-particle yields for the ^{9}Be + ^{12}C reactions in the region of the Coulomb barrier. The inset shows a resonance in the ^{12}C + ^{12}C system measured with the same experimental arrangement and a 40-keV- (c.m.) thick ^{12}C target.

compound nucleus. Such a correlation could be explained within the framework of an intermediate structure model by the dependence of the spreading width on the density of levels in the compound nucleus. Of the few systems which exhibit intermediate structure, all involve at least one ^{12}C nucleus as target or projectile.

Experimental studies of the $^{14}N+^{14}N$ system have shown that a previously observed resonance is in fact not present, a finding which supports the validity of the level density arguments. An experimental study of $^{9}Be+^{12}C$ induced reactions did not reveal any intermediate structure. The explanation of the presence or absence of intermediate structure in compound systems with comparable level densities but differing in only one nucleon clearly must involve nuclear structure on a microscopic scale. The theoretical explanation of these phenomena remains as one of the most interesting challenges in nuclear structure.

ACKNOWLEDGMENTS

The authors wish to thank R. Dayras, Z. Switkowski, and R. Wieland for communicating their results on the reactions $^{10}B+^{12}C$ and $^{11}B+^{12}C$ before publication. We also gratefully acknowledge the technical assistance provided by Dr. Edith Fehr, Kenzo Sato, C. E. L. Gingell, Mrs. Hana Novak, and Mrs. Harriet Comen.

[†] Work supported under U. S. Atomic Energy Commission Contract No. AT(11-1)-3074.

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