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$^{12}C + ^{12}C$ resonances between $E_{c.m.} = 11$ and 15 MeV

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The reaction $^{12}C(^{12}C,\alpha)^{20}Ne$ has been investigated in the energy range $E_{c.m.} = 11–15$ MeV. Evidence has been found for two resonances at $E_{c.m.} = 13.12$ and 13.43 MeV besides the well-known resonance at $E_{c.m.} = 11.4$ MeV. This result is in contrast to other investigations which did not yield the first two resonances but many other resonances not seen in the present experiment.

[NUCLEAR REACTIONS $^{12}C(^{12}C, \alpha)$, E=11–15 MeV (c.m.), measured $\sigma(\Theta, E)$. Resonances observed at $E_{c.m.}$=11.4, 13.12, and 13.43 MeV.]

I. INTRODUCTION

The most pronounced evidence for the existence of resonances of the quasimolecular type has been found in the reaction $^{12}C+^{12}C$. This evidence is, in particular, very clear for energies below and around the Coulomb barrier. In this energy range resonances show up in γ-yield measurements[1,2] and in angle integrated excitation functions for different reaction channels which include many transitions to final states in the residual nuclei[3-6]; in addition they are correlated among different reaction channels. At higher energies, however, the evidence is not on the same sound footing. This is due to the fact that most high energy resonances have been deduced from excitation functions for only one particular exit channel measured at one or a few angles. Therefore one cannot determine whether observed structures are correlated among different reaction channels or excitation functions measured at different angles, i.e., if they are real resonances. On the other hand one has to exercise particular caution at high energies. The reason is that in addition to statistical effects (which are the main problem at lower energies), interference effects between direct and compound nuclear contributions and yrast effects in the compound nucleus and the residual nucleus tend to obscure resonant structures. We have carried out a thorough investigation of the reaction $^{12}C+^{12}C$ in order to determine resonances of the quasimolecular type at energies above the Coulomb barrier. The results are reported in this paper.

II. EXPERIMENT AND RESULTS

We have studied the reaction $^{12}C(^{12}C, \alpha)\,^{20}Ne$ in the energy range $E_{c.m.}$ =11–15 MeV. Angular distributions have been measured simultaneously at each energy for 23 angles between $\Theta_{c.m.} = 8°$ and 94° ($\Delta\Theta_{c.m.} \approx 3°–4°$). The energy steps were 50 keV (c.m.). Alpha particles were detected with solid state detectors. Discrimination against other reaction products could be achieved using suitable thicknesses for the depletion depth of the detectors and the Al absorbers in front of them. The ^{12}C targets used had a thickness of approximately 20μg/cm^2, which was determined from the elastic scattering at low energies. Two monitor counters were used in order to determine the carbon buildup on the target. The cross sections and energies given in this work contain corrections due to the carbon buildup and the energy loss in the target. The absolute values of the cross sections are correct within ±20%, the energies given are known within ± 25 keV.

Angle integrated cross sections have been deduced from the measured angular distributions. Figure 1 shows excitation functions for transitions to the first six states in ^{20}Ne. The sum of these excitation functions is given on top of the figure. Figure 2 shows excitation functions for the transitions $\alpha_6–\alpha_{10}$, α_{11}, and $\alpha_{12}–\alpha_{22}$. The sum of all excitation functions measured is shown on top of Fig. 2.

The criterion used to find resonances among the many structures shown in Figs. 1 and 2 was that resonances should survive in angle integrated excitation functions which include contributions from many transitions to the residual nucleus. In addition it was required that a substantial branching ratio to several of the single transitions exists at each resonance energy.[6] This criterion is obviously fulfilled for the well-known $J^{\pi}=8^+$ resonance at 11.38 MeV (Refs. 6 and 7) as can be seen in Figs. 1 and 2. The only additional structures which show a similar behavior are located at $E_{c.m.}$ =13.12 and 13.43 MeV. They show up strongly in the excitation function for the transitions to the first 23 states in ^{20}Ne (see Fig. 2) and exhibit, in addition, a fair amount

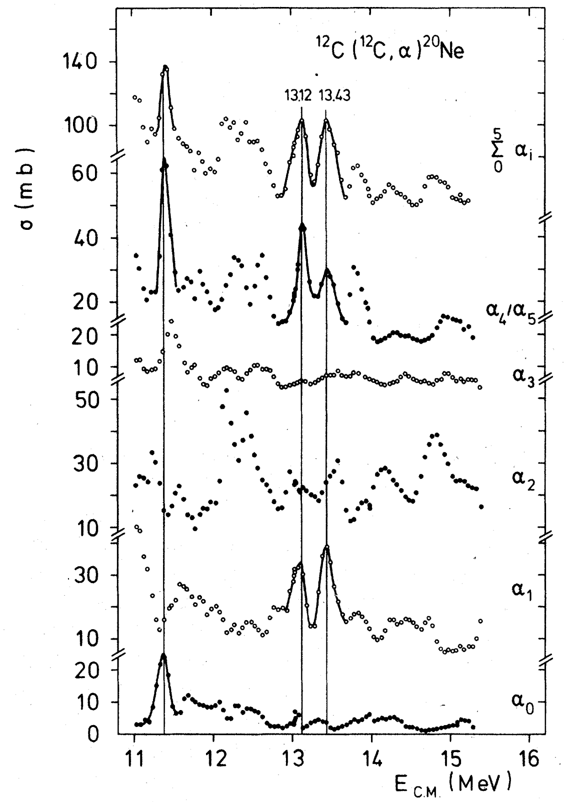

FIG. 1. Angle integrated cross sections of the reaction $^{12}C(^{12}C, \alpha)$ ^{20}Ne leading to the first six states in ^{20}Ne. The curve on top of the figure represents the sum of the curves underneath.

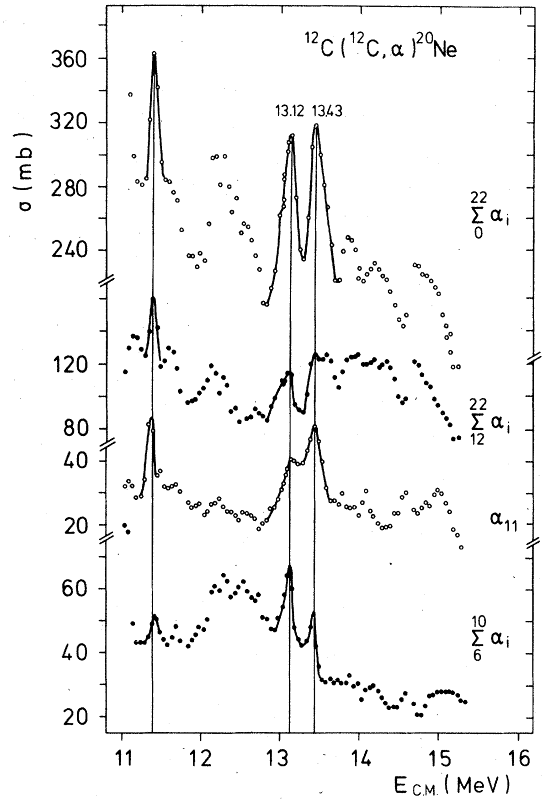

FIG. 2. Angle integrated cross sections of the reaction $^{12}C(^{12}C, \alpha)$ ^{20}Ne leading to the 2^+ state in ^{20}Ne at 7.83 MeV (α_{11}) and to the groups $\alpha_6-\alpha_{10}$ and $\alpha_{12}-\alpha_{22}$. The curve on top of the figure is the excitation function for all measured transitions.

of correlation. We conclude, therefore, that three resonances exist between $E_{c.m.}$ = 11 and 15 MeV with resonance energies $E_{c.m.}$ = 11.38, 13.12, and 13.43 MeV. The J^π value of the 11.38 MeV resonance has been determined already[6,7] ($J^\pi = 8^+$). The J^π values of the two remaining resonances could, unfortunately, not be determined since the excitation functions of the transitions α_0 and α_3 do not show resonance structures at the energies in question (the $\alpha_{0,3}$ angular distributions would allow an unambiguous determination of J^π).

III. DISCUSSION

The present investigation yields three $^{12}C+^{12}C$ resonances for energies between $E_{c.m.}$ = 11 and 15 MeV. This is in contrast to the fact that many more resonances or resonance anomalies are reported in the literature for this particular energy range. These resonances (or resonance anomalies) are summarized in Table I. The first two columns of Table I contain energies and reaction channels for which resonant features have been observed. Column 3 indicates if differential cross sections $\sigma(\theta)$ or angle integrated cross sections σ_t were used in order to determine resonances [the angle of observation is given in case $\sigma(\theta)$ was used].

Inspection of Table I shows that investigations of different reaction channels have yielded resonance anomalies at different energies. The only exceptions are the resonances at 11.4 and 14.3 MeV. The 11.4 MeV resonance has been found in the α-particle[6,7] and proton channel[8] and possibly in the ^8Be channel[9] (it should be pointed out that the evidence for a resonance in the ^8Be channel at approximately 11.4 MeV is very weak). The 14.3 MeV resonance shows up in the proton channel[8] and rather weakly in the ^8Be channel.[9] Moreover, investigations of the α-particle channel which have been carried out in Ref. 10 and in the present work lead to different results. The latter discrepancy is due to the fact that resonances have been deduced from differential cross sections in Ref. 10 (for the transitions $\alpha_0-\alpha_3$). The present investigation shows, however, that angle integrated excitation functions for the transitions α_0, α_1, and α_3 do not exhibit structures at the resonance energies reported in Ref. 10 ($E_{c.m.}$ = 11.2 and 13.751, see Fig.

TABLE I. $^{12}C + ^{12}C$ resonances and resonance anomalies reported for the energy range $11 \le E_{c.m.} \le 15$ MeV.

E (MeV)	Exit channel	$\sigma(\Theta)$ or σ_t	References
11.2	α_i, ^{20}Ne, $i = 0$–3	10°, 20°	10
11.4	α_i, ^{20}Ne, $i = 0$–22	σ_t	6,7 present work
	p, ^{23}Na* (9.81 MeV)	7.5°	8
11.43, 11.78, 12.00, 12.35, 12.85	^{8}Be g.s., ^{16}O g.s.	15°, 27.5°	9
13.12	α_i, ^{20}Ne, $i = 0$–22	σ_t	present work
13.35	^{8}Be g.s., ^{16}O g.s.	12.5°, 22.5°, 32.5°	9
13.43	α_i, ^{20}Ne, $i = 0$–22	σ_t	present work
13.5	d, ^{22}Na* (1.53 MeV)	10°, 20°	11
13.75	α_i, ^{20}Ne, $i = 0$–3	10°, 20°	10
13.85	^{8}Be g.s., ^{16}O g.s.	12.5°, 22.5°, 32.5°	9
14.1	d, ^{22}Na*(1.53 MeV)	10°, 20°	11
14.3	p, ^{23}Na*(9.04, 9.81 MeV)	7.5°	8
14.3	^{8}Be g.s., ^{16}O g.s.	12.5°, 22.5°, 32.5°	9
14.5	d, ^{22}Na*(1.53 MeV)	10°, 20°	11

1). This should be the case if these anomalies were real resonances. It is interesting to note that the two resonances at 13.12 and 13.43 MeV found in the present work have not been observed in other investigations which use less stringent resonance criteria.

The fact that most resonances reported in the literature have been observed in only one particular reaction channel and that their existence is based on structures in differential cross sections casts doubt on whether all anomalies are indeed due to resonances of the quasimolecular type. In fact, it is very likely that some of the structures observed are statistical fluctuations, interference patterns produced by direct and compound nuclear contributions or yrast effects. Yrast effects are important for the proton and for the deuteron exit channels. In both cases only some few high spin states in the vicinity of the yrast line of the residual nuclei ^{23}Na and ^{22}Na are able to carry away the high angular momenta of the entrance channel. Competition between different reaction channels in addition with penetrability effects can result in a resonancelike population of the high spin states mentioned above. Large direct contributions are very likely in case of the ^{8}Be exit channel (α-particle transfer).

The α-particle exit channel is not affected by these shortcomings: (i) There are many states in ^{20}Ne which are able to carry away flux from the entrance channel even at high incident energies; and (ii) direct contributions are rather small. Therefore, the α-particle exit channel is very much suited for resonance analyses provided that strongly populated states in the residual nucleus ^{20}Ne are included and provided that statistical effects can be eliminated. This has been taken care of in the present investigation: (i) We have analyzed 23 states in ^{20}Ne involving the most predominantly populated states; and (ii) we have measured angle integrated excitation functions which means that statistical fluctuations are strongly damped. Thus we can be quite sure that the resonances observed in this work are real resonances.

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