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^{12}C-^{12}C resonances studied through γ decay

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Resonances in the ^{12}C-^{12}C system and in the energy range $E_{\text{c.m.}} = 7\text{–}10$ MeV were studied through γ decay. Excitation functions of the γ decay of the first excited states of ^{20}Ne, ^{23}Na, and ^{23}Mg seen through the ^{12}C(^{12}C,α)^{20}Ne, ^{12}C(^{12}C,p)^{23}Na, and ^{12}C(^{12}C,n)^{23}Mg reactions corroborated the existence of resonances observed through various particle reactions. With the help of angular distributions from the ^{12}C(^{12}C,α)^{20}Ne$_{\text{g.s.}}$ reaction, one other resonance was established at $E_{\text{c.m.}} = 9.65$ MeV with $J^{\pi} = 8^{+}$.

[NUCLEAR REACTIONS ^{12}C(^{12}C,α)^{20}Ne, ^{12}C(^{12}C,p)^{23}Na, ^{12}C(^{12}C,n)^{23}Mg; E(^{12}C) = 14–20 MeV; measured $\sigma_{\gamma}(E)$, $\sigma_{\alpha}(E,\vartheta)$, deduced ^{24}Mg resonances; natural target.]

Since the early discovery[1] of three resonances in the ^{12}C-^{12}C system near and below the Coulomb barrier ($E_{\text{c.m.}} = 5\text{–}7$ MeV), the resonant behavior of this system and other similar ones has been the subject of extended experimental and theoretical investigation (see Refs. 2–5 and references therein).

The early experimental work in the ^{12}C-^{12}C system below the Coulomb barrier has been extended in recent years to energies near, and well above, the Coulomb barrier. The data revealed that the resonances ranging in spin from 0^{+} to 14^{+} follow a $J(J+1)$ rule indicating the presence of a rotational-like band in ^{24}Mg at excitation energies between 18 and 40 MeV. Another striking feature of those resonances is their fragmentation, the existence, i.e., of a number of resonances having the same spin and parity.

Most of the resonances have been revealed by observing the decay of the ^{12}C-^{12}C system through a particular channel, primarily the α or the ^{8}Be channel. This is due to the fact that the zero values of the entrance and exit channel spins allow a unique determination of the J^{π} of the resonance. It is not unusual, however, for a resonance not to exhibit appreciable strength in a particular channel. It is therefore necessary to observe the decay of the ^{12}C-^{12}C system through all possible channels and deduce from the correlated excitation function whether an anomaly seeing in the excitation function is a statistical fluctuation or a resonance.

A simultaneous observation of nearly all decay channels is afforded if one observes the γ rays emanating from the decay of the system. Such work has already been reported in the energy ranges 5.8 MeV$<E_{\text{c.m.}}<$8 MeV,[6,7] and 15 MeV$<E_{\text{c.m.}}$ $<$35 MeV.[8-10]

In this paper we report the results of our investigation in the $7<E_{\text{c.m.}}<10$ MeV range. The γ-ray excitation function was followed by alpha particle angular distribution measurements. We were thus able to observe all resonances previously reported as seen through a particular channel, plus another thus far unidentified resonance.

A 10 μg/cm^{2} ^{12}C target on a Ta backing was bombarded with ^{12}C ions from the "Demokritos" T11/25 Van de Graaff accelerator. The energy loss of the beam through the target was 40 keV for a 16 MeV ^{12}C projectile. A 45 cm^{3} Ge(Li) detector (8.5% efficiency) was used for the detection of gamma rays. Carbon buildup on the target was monitored and was found to be insufficient to alter the qualitative results of the data. The γ rays from the Coulomb excitation of the Ta backing were used for the normalization of the excitation function. The detector was placed at a distance of 10 cm from the target at an angle of 90° with respect to the beam. The excitation function was taken in steps of $\Delta E_{\text{c.m.}} = 50$ keV and from $E_{\text{c.m.}} = 7\text{–}10$ MeV. For the α particles resulting from the reaction ^{12}C(^{12}C, α)^{20}Ne, surface barrier detectors were used. To avoid pile up problems due to the ^{12}C elastic scattering, Al foils ranging in thickness from 10 μm to 50 μm were placed in front of the detectors. Angular distributions were taken with a set of four detectors and at twelve angles between 8° and 90° (c.m.).

Figure 1 shows a γ-ray spectrum taken at $E_{\text{c.m.}} = 10$ MeV. The identified lines of 1.634, 0.450, and 0.439 MeV correspond to the decay of the first excited state of the residual nuclei ^{20}Ne, ^{23}Mg,

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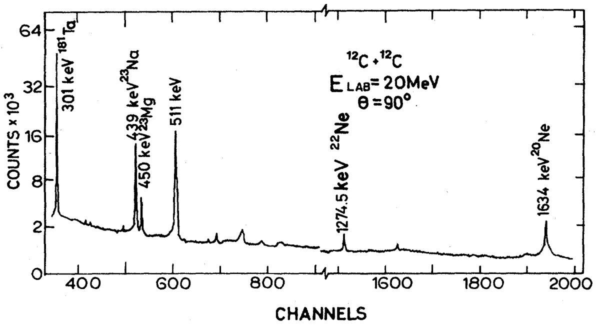

FIG. 1. Gamma ray spectrum from the bombardment of a ^{12}C target with a 20 MeV ^{12}C beam.

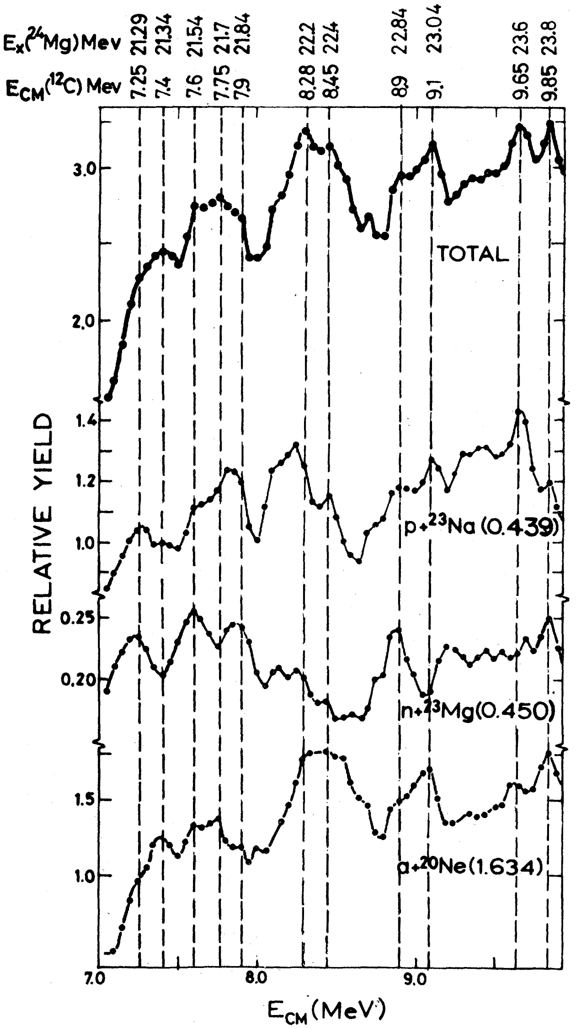

FIG. 2. Excitation function for the p, n, and α channels. Vertical dashed lines and corresponding numbers at the top of the figure identify the thus far known resonances in the ^{12}C-^{12}C system, in the indicated energy range.

and ^{23}Na, respectively. These nuclei are formed from the reactions ^{12}C(^{12}C, α)^{20}Ne, ^{12}C(^{12}C, p)^{23}Na, and ^{12}C(^{12}C, n)^{23}Mg. By observing the decay of the first excited state one can simultaneously observe the cumulative effect on the excitation function of many excited levels since a large percentage of those finally decay to it.[11] A further reasonable assumption is that any alignment of the magnetic substates of the first excited state will remain fairly constant over the energy range covered in this experiment. Owing to the high excitation of the compound nucleus formed, it is expected that the pattern of its decay to the low lying states will be insensitive to a change of a few MeV in the incident energy. This has been observed experimentally in a number of heavy ion experiments.[12]

Excitation functions for the p, n, and α channels are displayed in Fig. 2. They have been corrected for the relative efficiency of the Ge(Li) detector. Although ^{23}Mg is unstable and β decays to ^{23}Na, only 9% of the ^{23}Mg g.s. decays to the 0.440 MeV state in ^{23}Na. Therefore, the p channel has only a small contribution from the n channel. The top curve in Fig. 2 labeled "total" is obtained by summing the γ yields of the three measured exit channels.

The observed correlated structures having an experimental width between 100 and 300 keV agree with the resonances that have already been found through various reactions. Table I shows the present results together with other experimental results. As can be seen, the γ-ray measurements were able to reproduce all the resonances that have been observed thus far through several particle experiments. Furthermore, the resonances seen in the present experiment agree within 50 keV with those observed in other experiments.

The γ-ray data indicate the existence of one correlated anomaly at $E_{\text{c.m.}} = 9.65$ MeV that has been previously observed (see, for example, Ref. 3) but has not been analyzed. In order to find out whether it is a resonance with a certain spin and parity, the α particles coming from the reaction ^{12}C(^{12}C, α)^{20}Ne$_{\text{g.s.}}$ were studied. It should be pointed out that the excitation function of the 1.634 MeV γ ray of ^{20}Ne as seen in Fig. 2 corresponds to a summation over many alpha channels $\sum_i \alpha_i$, excluding α_0. It is therefore similar to the summation over many individual alpha channels observed through the (^{12}C, α) reaction.

Figure 3 shows the excitation function in the vicinity of $E_{\text{c.m.}} = 9.65$ MeV, summed over three angles, for alpha groups leading to the ground state of ^{20}Ne. These data together with the excitation function summed over many channels (Fig. 2) establish the existence of a correlated anomaly at 9.65 MeV. This peak has previously been ob-

TABLE I. Resonances observed in this work and other particle experiments for ^{12}C-^{12}C system.

Resonances from this work $E_{\mathrm{c.m.}}$ (E_x in Mg)	References of other particle experiments that have found resonances at energies around those observed in this work	Reference key	Reaction
7.25(21.2)	1	1. Ref. 15	Prediction
7.40(21.3)	2,3,4	2. Refs. 6,7,16	^{12}C(^{12}C,α)^{20}Ne also ^{12}C(^{12}C,$\alpha n p$,γ)
7.60(21.5)	3,5	3. Ref. 17	^{12}C(^{12}C,α)^{20}Ne also ^{12}C(^{12}C,p)^{23}Na
7.75(21.7)	2,3	4. Ref. 18	^{20}Ne(α,^{12}C)^{12}C
7.90(21.8)	6,7	5. Ref. 13	^{12}C(^{12}C,p)^{23}Na
8.27(22.2)	2,5,6	6. Ref. 19	^{12}C(^{12},α)^{20}Ne
8.45(22.4)	2,3,6,7	7. Ref. 20	^{12}C(^{12}C,^{16}O)^{8}Be
8.90(22.8)	3,5,6,8	8. Ref. 4	^{12}C(^{12}C,α)^{20}Ne
9.10(23.0)	2,5,6,9	9. Ref. 14	^{12}C(^{12}C,^{8}Be)^{16}O
9.65(23.6)	5,9		
9.85(23.8)	2,9		

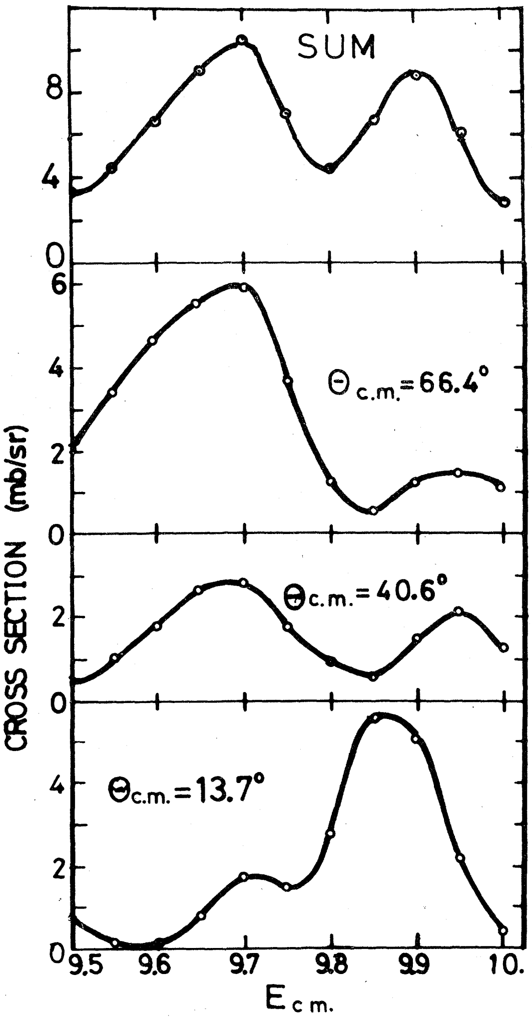

FIG. 3. Excitation function of the α particles from the reaction ^{12}C(^{12}C,α_0)^{20}Ne in the vicinity of $E_{\mathrm{c.m.}}$ = 9.65 MeV.

served through the ^{12}C(^{12}C, α)^{20}Ne (Ref. 3), ^{12}C(^{12}C,p)^{23}Na (Ref. 13), and ^{12}C(^{12}C, ^{8}Be)^{16}O (Ref. 14) reactions.

Figure 4 is the angular distribution of the α particles from the reaction ^{12}C(^{12}C, α_0)^{20}Ne at $E_{\mathrm{c.m.}}$ = 9.65 MeV. To establish the spin of the resonance, two methods of fitting the experimental angular distribution were employed. In the first method a fitting was attempted with a squared Legendre polynomial. The number of minima

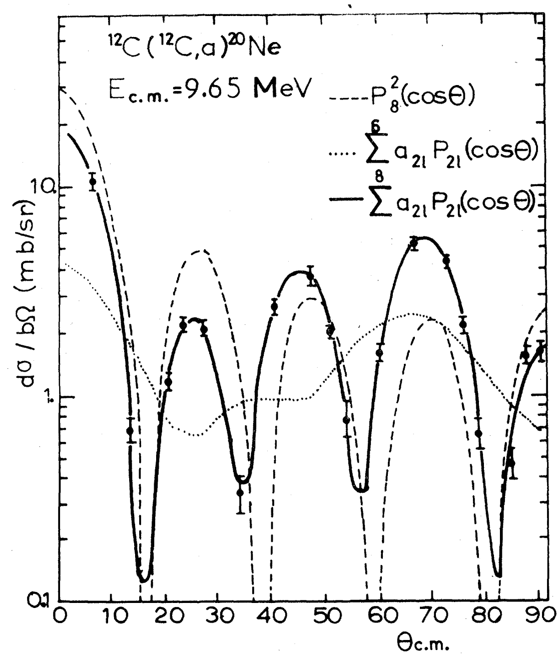

FIG. 4. Angular distribution of the α particles from the reaction ^{12}C(^{12}C, α_0)^{20}Ne at $E_{\mathrm{c.m.}}$ = 9.65 MeV. The lines have been obtained through x^2 fitting of the data points with the three Legendre polynomial functions indicated on the figure.

and maxima for a $P_8{}^2(\cos\Theta)$ function agreed well with the experimental distribution. In the second method, a least square fitting procedure was used where the data points were fitted with a $\sum_{l=1}^{n} \alpha_{2l} P_{2l}(\cos\Theta)$ function. The value of n was varied in order to establish the best x^2. A drastic change of x^2 (from 133 to 0.9) was observed as n was changed from 6 to 8, establishing unequivocally the spin of the 9.65 MeV resonance as $J^\pi = 8^+$.

In conclusion, the results of this work indicate that the γ-ray technique, where it is applicable (no side feeding of the observed decaying states due to neighboring unstable nuclei), is a reliable technique for detecting resonances in heavy ion reactions. Combined with outgoing α-particle angular distributions it can establish spins and parities of the resonances without making any assumptions that the direct reaction component is small, an assumption one has to make when studying reactions such as $^{12}C(^{12}C, \alpha)^{20}Ne$ at forward angles.

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