The $^{12}$C($^{8}$Be + $^{12}$C(0$^+_2$))$^6$He reaction has been studied with beam energies of 82–120 MeV to search for excited states in $^{20}$Ne that decay into $^{8}$Be + $^{12}$C(0$^+_2$). The detection of five of the six final-state $\alpha$ particles in an array of eight, sixteen-element, strip detectors permitted the full reconstruction of the reaction kinematics. Two $^{20}$Ne resonances at 35.2 and 36.5 MeV are observed, particularly at beam energies less than 93 MeV. An analysis of the angular correlations associated with the observed resonances indicates that an angular momentum of $10\hbar$ is important in this region, and thus it is possible that at least one of the resonances possesses $J^\pi = 10^+$. 

DOI: 10.1103/PhysRevC.71.047305

PACS number(s): 25.70.Ef, 25.70.Mn, 27.20.+n
a width, dominated by the experimental resolution, of 110 keV.

The events falling within these peaks were selected for further analysis if the following three conditions were satisfied: (1) three of the five $\alpha$ particles arose from the decay of the $^{12}$C($0^+_1$) state, (2) two of the three $\alpha$ particles selected in (1) arose from the decay of $^8$Be$_{gs}$, and (3) the remaining two particles from (1) arose from the decay of $^8$Be$_{gs}$.

In principle, this approach leads to the identification of the decay of $^{20}$Ne to $^8$Be $+ ^{12}$C($0^+_1$). However, it is possible that the events thus selected correspond to inelastic scattering reactions in which the two $^{12}$C nuclei are excited above their $\alpha$-decay thresholds, as measured in [11]. The reconstructed $^{12}$C excitation energy spectrum for the unobserved $\alpha$ particle and $^8$Be nucleus not associated with the $^{12}$C($0^+_1$) decay spanned a very broad excitation energy range (up to 50 MeV) and was found not to be dominated by $^{12}$C decays. This is mainly due to the kinematics that were experimentally selected, in which the detection of five high-energy $\alpha$ particles close to the beam direction resulted then in the sixth being a low-energy recoiling. Correspondingly, the relative velocity (and thus the reconstructed $^{12}$C excitation energy) is large. We return to this point later (see Fig. 3 and the associated discussion).

Having selected events with the above characteristics, we calculated the reaction $Q$ value, $Q = \sum_{i=1}^{5} E_{\alpha i} - E_{\text{beam}}$. The result is shown in Fig. 2(a) for the summed data taken at beam energies of 82, 84, 86, 88, and 90 MeV. A peak is observed at $Q = -13.0$ MeV (full width at half maximum = 2 MeV), whereas in theory it should lie at $-14.5$ MeV. The difference in energy is related to the calibration procedure, which was performed with $^{12}$C nuclei with a beam energy (35 MeV) above the range of the measured $\alpha$ particles rather than high-energy $\alpha$ particles. $^{12}$C nuclei possess differing energy loss characteristics than $\alpha$ particles of the same energy; for example, 35 MeV $^{12}$C nuclei lose 320 keV in 1 $\mu$m of silicon whereas the energy loss is a factor of 10 less for $\alpha$ particles of the same energy. Thus, dead layers on the front of the detectors of a few microns have a marked impact on the calibrations. This discrepancy in the energies is less important in the calculation of excitation energies from relative energies, as evidenced by the accuracy with which the excitation energies of the 2- and 3-$\alpha$ systems are reconstructed (Fig. 1).

Having selected events with the above characteristics, we calculated the reaction $Q$ value, $Q = \sum_{i=1}^{5} E_{\alpha i} - E_{\text{beam}}$. The result is shown in Fig. 2(a) for the summed data taken at beam energies of 82, 84, 86, 88, and 90 MeV. A peak is observed at $Q = -13.0$ MeV (full width at half maximum = 2 MeV), whereas in theory it should lie at $-14.5$ MeV. The difference in energy is related to the calibration procedure, which was performed with $^{12}$C nuclei with a beam energy (35 MeV) above the range of the measured $\alpha$ particles rather than high-energy $\alpha$ particles. $^{12}$C nuclei possess differing energy loss characteristics than $\alpha$ particles of the same energy; for example, 35 MeV $^{12}$C nuclei lose 320 keV in 1 $\mu$m of silicon whereas the energy loss is a factor of 10 less for $\alpha$ particles of the same energy. Thus, dead layers on the front of the detectors of a few microns have a marked impact on the calibrations. This discrepancy in the energies is less important in the calculation of excitation energies from relative energies, as evidenced by the accuracy with which the excitation energies of the 2- and 3-$\alpha$ systems are reconstructed (Fig. 1).

The presence of the peak confirms the assumption of the 6-$\alpha$ final state and events falling within the peak were selected in the reconstruction of the $^{20}$Ne excitation energy spectrum, Fig. 2(b).

The excitation energy spectra for the beam energies 82–120 MeV were analyzed individually. The lower beam energy spectra ($E_{\text{beam}} < 93$ MeV) showed evidence for a structure close to an excitation energy of 35–36 MeV, whose width and centroid remained independent of beam energy. At higher energies ($E_{\text{beam}} > 93$ MeV), there was little evidence for such a feature. To enhance the statistics, the excitation energy spectra from the beam energies 82–90 MeV are shown summed in Fig. 2(b). Given an expected excitation energy resolution of $\sim 1.2$ MeV, the spectrum shows perhaps two peaks at excitation energies of 35.2 and 36.5 MeV (with individual widths of 1.3 MeV) on a broad background. These would correspond to $^{20}$Ne excited states decaying into $^8$Be $\alpha$ $^{12}$C($0^+_1$). It is possible to estimate the excitation energy resolution from the measurements of the $^{12}$C($^{16}$O $\rightarrow 4\alpha$) described in [5], which indicated a resolution of 1.2 MeV. The suggested peak width in the present measurements of 1.3 MeV would thus be in agreement. The dominant contribution to the resolution is the precision with which the angle of emission of the detected particles is determined, i.e., the position resolution of the detectors (which is estimated to be 0.5 to 1 mm).

An examination of the excitation energy spectra at each beam energy provides no strong evidence for any further $^{20}$Ne excited states decaying to the present final state. Although, this could be attributed to a high density of similarly populated resonant states coupled with the finite experimental energy resolution. Moreover, the peak strength does not fluctuate strongly from one beam energy to the next.

It is possible for the $^8$Be $+ ^{12}$C($0^+_1$) $\rightarrow 4\alpha$ final state to be reached via a number of intermediate processes, thus providing an additional explanation for the background in the $^{20}$Ne excitation energy spectrum. For example, in addition to the
decay of $^{20}$Ne, the decay of $^{12}$C to $\alpha + ^{8}$Be$_{\psi}$, or $^{16}$O to $^{12}$C($0^+_2$) + $\alpha$ might be occurring.

Figures 3(a) and 3(b) show the reconstructed $^8$Be + $^{12}$C($0^+_2$) relative energy plotted versus that of the $^8$Be and $^{12}$C($0^+_2$) nuclei and the unobserved $\alpha$ particle. The reconstructed relative energy spectra for these decays are shown in Figs. 3(c) and 3(d). This analysis would reveal the contributions from decays of states in $^{12}$C and $^{16}$O, respectively. In both Figs. 3(a) and 3(b), the vertical locus corresponding to the states in $^{20}$Ne is observed. In (a) there appears to be no strong horizontal loci, although there may be contributions from a number of unresolved $^{12}$C states. In the case of the $^{12}$C($0^+_2$) + $\alpha$ final state, there appear to be horizontal loci at low relative energies in (b) which would correspond to excitations of $^{16}$O of $\sim$15–18 MeV. A measurement [4] of the $^{12}$C($0^+_2$) + $\alpha$ decay of $^{16}$O observed resonant decays in this region of excitation energy, which may correspond to the present observation. This contribution to the $^{20}$Ne excitation energy spectrum has been removed in Fig. 3(e) and the two peaks observed previously remain. It is clear from both of the bidimensional spectra that the presence of the peak in Fig. 2(b) may be attributed to resonant states in $^{20}$Ne.

The one benefit of averaging these data over a number of beam energies is that it leagens the effect of spurious peaks caused by, for example, oscillatory behavior in the angular distributions in other contaminating reaction channels such as those observed to arise from the decay of $^{16}$O in Fig. 3. Oscillatory angular distributions (whose periodicity would be expected to change with energy) in contaminant channels in principle can lead to yields localized in the $^{20}$Ne excitation energy phase space. This is not the case in the present data as evidenced by the vertical loci already noted in Fig. 3.

Finally, given that the decay of $^{20}$Ne proceeds via a final state in which there are two spin-zero particles, (moreover, all particles in the initial and final states are spin zero), then it is potentially possible to extract the spin of the resonance from the angular correlations of the decay products. The full details of the techniques involved in such an analysis are given in [12] and an example of their application to multi-$\alpha$-particle final states in [5]. In brief, the pattern of decay measured with respect to the c.m. emission angle of the $^8$Be nucleus ($\psi$, relative to the beam axis) and the c.m. emission angle of the excited $^{20}$Ne nucleus ($\theta^*$), reveals information regarding both the spin $J$ of the resonance and the orbital angular momenta of the reaction products, notably $l_i$ the entrance channel orbital angular momentum. A two-dimensional plot of the $\theta^*$-$\psi$ data produces, for such systems, a series of ridges whose periodicity
The grey shaded histogram corresponds to the same analysis of the ridge pattern appearing in the $^{12}\text{C}(^{12}\text{C},^{16}\text{O})$ reaction (19–21 ) [5]. It is clear from the quality of the data that there are other contributions to the data; indeed, the present correlations may be the result of the interference of two states with differing spins. Thus, this analysis is only suggestive of a spin and parity of $10^+$. 

The present data have no counterparts in tabulations for $^{20}\text{Ne}$ [13]. The present peaks would, however, lie along the extrapolated systematics of the resonances populated via the $^{16}\text{O} + \alpha$ entrance channel, which might indicate a link also with a $^{16}\text{O} + \alpha$ cluster structure. This is consistent with a reported measurement of the $^{16}\text{O}(\alpha, ^8\text{Be})^{12}\text{C}_{gs}$ reaction, which indicated the presence of a resonance close to $E_\gamma = 33$ MeV, with a possible spin of 11$^+$ [14], which again lies close to the extrapolated $^{16}\text{O} + \alpha$ systematics. It is interesting that the present measurement appears to select preferentially only two states. As noted above, other more weakly populated resonances potentially form a continuum in the excitation energy spectrum, but we observe that a significant fraction of the background data corresponds to unconnected reactions (as indicated by the unstructured background correlations). The observation of one or two strongly populated states may be taken as an indication of a strong structural link with the decay channel. Indeed, a calculation of the density of states based on the back-shifted Fermi gas model [15] suggests the density of 10$^+$ states close to 35 MeV is in excess of 10 MeV$^{-1}$.

To summarize, possibly two $^{20}\text{Ne}$ resonances at excitation energies of 35.2 and 36.5 MeV are observed in the $^{12}\text{C}(^{12}\text{C},^{20}\text{Ne})\alpha$ reaction and decay to the $^{8}\text{Be} + ^{12}\text{C}(0^+_2)$ final state. Angular distribution measurements provide tentative evidence that at least one of the resonances has spin and parity 10$^+$. 