I. INTRODUCTION

The structure of light nuclei is known to be associated with strong alpha-particle clustering. This is quite apparent in alpha-particle nuclei like $^8$Be and $^{14}$C which can be decomposed into multi-alpha particles. Clustering is also important in light non-alpha-particle nuclei. For example, the structure of $^9$Be ground and low-lying excited states has been described as two alpha-particle cores exchanging a neutron. Such states can be considered analogies to molecular structures, with the neutron occupying the "valence" neutrons are also predicted for $^{10}$Be [1]. Two rotational bands, based on the ground state and an excited 0+ state, have been observed. The 4+ members of both bands particle-decay to the $^6$He exit channel.

Molecular structures states have also been predicted for $^{12}$Be [1, 3, 4]. In experiments where $^{12}$Be beams were excited via inelastic scattering, evidence have been found for molecular states. Korsheninnikov et al. [5] detected recoil protons following $^{12}$Be+p scattering and identified $^{12}$Be states at 8.6, 10, and ~14 MeV. Freer et al. [6, 7] have found evidence for $^{12}$Be levels which decay through the $^6$He-$^8$He and alpha-$^8$He exit channels after scattering off carbon and (CH$_2$)$_n$ targets. The $^6$He-$^8$He breakup states were tentatively assigned spins of 4, 6, and 8 suggesting these are part of a rotational band. Saito et al. [8] present evidence for $^6$He-$^8$He breakup states following inelastic scattering from $^4$He. The states at 10.9 and 11.3 were assigned spins of 0 and 2, respectively. Combined with results of Freer et al., a rotational band with states of spin from 0 to 8 can be inferred with a large moment of inertia consistent with two touching $^6$He nuclei in a molecular configuration.

A $^6$He-$^8$He breakup states were also reported following $^{12}$C($^{14}$Be,$^{12}$Be) two-neutron removal reaction [9]. A state at 11.8 MeV level was tentatively assigned spin 0. In the three-neutron transfer reaction $^9$Be($^{15}$N,$^{12}$N)$^{12}$Be, Bohlen et al. report peaks at 10.7, 14.6, 19.2, and 21.7 MeV which they speculate are part of a molecular band [10]. In this study the decay of the excited $^{12}$Be fragments was not investigated. A more recent search with the $^{10}$Be($^{14}$C,$^{12}$Be) two-neutron transfer reaction failed to see any evidence for $^6$He-$^8$He or alpha-$^8$He breakup states [11].

All these previous studies suffer from limited statistics. It is thus important to try and confirm the existence of these levels and their spins assignments to make a solid understanding.
case for molecular structure in $^{12}$Be. In this work we confront these results with new experimental data using $^{12}$Be inelastic scattering. This work is similar to the study of Freer et al. in that both targets of polyethylene (CH$_2$)$_n$ and carbon were employed and $^{12}$Be breakup states are identified from correlations between the decay products. However, it differs in having a higher beam energy of $E/A$=50 MeV compared to 31 MeV for the latter study. In addition to the $\alpha$-$^{9}$He and $^{6}$He-$^{9}$He exit channels, other breakup modes, $t+^{7}$Li and $p+^{11}$Li will be examined. The $Q$-values for all possible binary-breakup channels are listed in Table I.

II. EXPERIMENTAL METHOD

A primary beam of $E/A$=120 MeV $^{18}$O was extracted from the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University. This beam bombarded a $^{9}$Be target and $^{12}$Be projectile-fragmentation products were separated by the A1900 separator. The secondary $^{12}$Be beam, with intensity of $1\times10^6$ s$^{-1}$, purity of 87%, and momentum acceptance of $\pm0.5\%$, impinged on targets of polyethylene and $^{12}$C with thicknesses of 1.0 mm and 0.4 mm, respectively. The beam spot on these targets was approximately 1 cm$\times$2 cm in area. Event-by-event time of flight was used to reject the beam contaminants.

Charged particles produced in the particle decay of excited $^{12}$Be fragments were detected in the HiRA array [12] consisting of 16 $E$-$\Delta E$ telescopes located 60 cm downstream of the target. The angular regions subtended by this array are shown in Fig. 1 covering an zenith-angle range of $2.7^\circ < \theta < 24.8^\circ$. Each telescope consisted of a 1.5 mm thick, double-sided Si strip $\Delta E$ detector followed by a 4 cm thick, CsI(Tl) $E$ detector. The $\Delta E$ detectors are 6.4 cm$\times$6.4 cm in area with the position-sensitive faces divided into 32 strips and the $E$ detectors are each subdivided into 4 subdetectors. Signals produced in the telescopes were read out with the HINP16C chip-readout electronics [13].

Recoil protons produced from inelastic scattering interactions of the $^{12}$Be projectile on the hydrogen component of the polyethylene target were detected is 4 Lassa detectors [14], each consisting of a 0.5 mm thick, double-sided Si strip $\Delta E$ detector followed by a 6 cm thick CsI(Tl) $E$ detector. The $\Delta E$ detectors are 5 cm$\times$5 cm in area with the position-sensitive faces divided into 16 strips.

Figure 1 also indicates the angular coverage of these detectors with zenith angles ranging from $29.4^\circ < \theta < 61.5^\circ$.

Energy calibrations of all Si detectors were obtained from a $^{228}$Th $\alpha$-particle source. The particle-dependent energy calibrations of the CsI(Tl) $E$ detectors were determined using $p$, $d$, $t$, $3,4,6,8$He and $6,7,8,9$Li beams and separated by the A1900 separator. Beam were extracted for typically 2 to 6 energies for each beam species. These were scattered off Au, C, and polyethylene targets into the HiRA and Lassa detectors and calibrations points were fit to linear or 2nd-order polynomial expressions for the energy region of interest. The calibrations for the Li isotopes were found independent of mass number and thus these calibrations were also used for $^{11}$Li fragments.

III. MONTE CARLO SIMULATIONS

Monte Carlo simulations were performed to establish the resolution of the reconstructed excitation energy in the experiment. In these simulations, the interaction depth in the target was chosen randomly and the effects of energy loss [15] and small-angle scattering [16] on the particles as they leave the target were included. The lateral location of the interaction on the target was chosen based on the measured beam-spot shape. The simulated events were passed through a detector filter and the energy and position resolutions of the detectors were added. Subsequently, the events were analyzed in the same manner as the experimental events. The energy and angular distributions of the reconstructed par-

TABLE I: Breakup $Q$-values for the different breakup channels observed in this work.

<table>
<thead>
<tr>
<th>channel</th>
<th>$Q$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$-$^{9}$He</td>
<td>8.95</td>
</tr>
<tr>
<td>$^{6}$He-$^{9}$He</td>
<td>10.11</td>
</tr>
<tr>
<td>$t+^{7}$Li</td>
<td>14.82</td>
</tr>
<tr>
<td>$p+^{11}$Li</td>
<td>23.00</td>
</tr>
</tbody>
</table>

FIG. 1: (Color online) Angular coverage of the detector in the experiments. The HiRA was used to detected breakup products of the excited $^{12}$Be fragments. Recoil-proton detectors used to detector recoil-protons following interactions on the hydrogen component of the polyethylene target are indicated. The cross indicates the beam axis.
ent fragments were chosen such that the reconstructed distributions of the “detected” events matched the experimental distribution. To evaluate the accuracy of these simulations, they were compared to experimental distribution for prominent narrow levels observed in the experiment. The histogram in Fig. 2a shows the experimental $^6$Li excitation-energy distribution determined from $d$-$\alpha$ pairs. The prominent peak is associated with the first excited state of $^6$Li ($E_x=2.186$ MeV, $\Gamma=24$ keV, $J^P=3^+$). Similarly in Fig. 2b, a prominent peak associated with $\alpha$-$^8$Li decay of the isobaric analog state in $^{12}$B ($E_x=12.75$ MeV, $\Gamma=85$ keV, $J^P=0^+$) is observed. The latter state was produced in the $^{12}$Be$(p,n)^{12}$B reaction, while the $^6$Li state is associated with more complicated interactions with both the hydrogen and carbon components of the polyethylene target. The experimental widths for both peaks are significantly larger than their intrinsic values, highlighting the importance of the experimental resolution for these chosen examples. The smooth lines in Fig. 2 indicate the predictions of the Monte Carlo simulations. The dashed curves show background contributions which were added to aid in the comparison with data. The simulated results reproduce the experimental distributions quite well, over estimating the widths slightly. Thus this comparison gives us confidence in the predictions of the simulations.

The large beam-spot size on the target has little effect on the reconstructed excitation energy as the measured relative-angle of the decay products is, to first order, independent of the lateral location on the target. However, the beam-spot size reduced the resolution in reconstructing the parent $^{12}$Be fragments velocity and scattering angle. The beam-spot size is a larger problem for the recoil proton detector which is significantly closer to the target.

IV. RESULTS

A. $\alpha$+$^8$He Decay

Each each detected $\alpha$-$^8$He pair, a reconstructed velocity of the parent excited $^{12}$Be fragment was determined as their center-of-mass velocity. Joint distributions of the parallel $V_\parallel$ and perpendicular $V_\perp$ components of this velocity are displayed in Figs. 3a and 3b for the polyethylene and carbon targets, respectively. The dashed curves in both figures indicate the kinematic solutions expected for inelastic scattering on a $^{12}$C target nucleus with a $Q$-value of -13 MeV. The solid curve in Fig. 3 gives the equivalent results after interacting with a hydrogen nucleus. The experimental results obtained with the carbon target follow the dashed curve confirming the presence of inelastic scattering on $^{12}$C. This component is also present in the polyethylene results, but its relative contribution is significantly reduced. The dominant component obtained with the polyethylene target is consistent with the solid curve (scattering off hydrogen), but only the kinematic solutions with the largest parallel velocities are populated. Both the hydrogen and carbon kinematic solutions overlap near $\theta=0^\circ$ and thus it is not possible to completely separate the two polyethylene components from kinematics.

The presence of inelastic scattering from hydrogen can be confirmed by observing the recoil target protons. Figure 4a shows the distribution of $\Delta\phi$, the difference in azimuthal angles between the reconstructed parent $^{12}$Be fragment and a proton detected in the recoil-proton detectors. The observed yield obtained with the polyethylene target (histograms) is peaked at $\Delta\phi=180^\circ$ as expected for a recoil proton. The contribution from the carbon component of the target was determined with the carbon target and scaled to account for the relative carbon content and beam currents used with the two targets. This contribution is displayed as the connected lines and is essentially insignificant for all $\Delta\phi$ values. The resolution associated with $\Delta\phi$ is governed mostly by the size of the beam spot.

From the relative energies of the $\alpha$-$^8$He pair and the breakup $Q$-value, a reconstructed excitation energy $E_x$ of the parent $^{12}$Be fragment is determined. In addition from the reconstructed parent velocity, a $Q$-value associ-
FIG. 3: (Color online) Joint distributions of parallel and perpendicular velocity for $^{12}$Be fragments reconstructed from $\alpha$-8He pairs with the a) polyethylene and b) carbon targets.

FIG. 4: (Color online) Distributions of relative azimuthal angle between protons detected in the recoil-proton detector and reconstructed $^{12}$Be fragments determined from a) $\alpha$-8He, b) 6He+6He, c) t+8Li, and d) p+11Li pairs. The histograms and connected lines were obtained with the polyethylene and carbon targets, respectively.

FIG. 5: (Color online) a) Distributions of the sum of the $Q$-value determined assuming an interaction with hydrogen target nucleus and the $^{12}$Be excitation energy reconstructed for $\alpha$-8He pairs. Results are shown for a the polyethylene (poly) target. The distribution obtained with the carbon ($^{12}$C) target indicates the background expected from the carbon contribution of the polyethylene target. b) Distribution of the sum of the $Q$-value determined assuming an interaction with a carbon target nucleus and the reconstructed excitation energy scaled by 1.4. The latter factor accounts approximately for the excitation energy of the $^{12}$C fragments.

FIG. 6: (Color online) a) Distributions of the sum of the $Q$-value determined assuming an interaction with hydrogen target nucleus and the $^{12}$Be excitation energy reconstructed for $\alpha$-8He pairs. Results are shown for a the polyethylene (poly) target. The distribution obtained with the carbon ($^{12}$C) target indicates the background expected from the carbon contribution of the polyethylene target. b) Distribution of the sum of the $Q$-value determined assuming an interaction with a carbon target nucleus and the reconstructed excitation energy scaled by 1.4. The latter factor accounts approximately for the excitation energy of the $^{12}$C fragments.

The vertical dashed lines in Figs. 5a and 5b, indicates gates $G_H$ and $G_C$ used to select events. The gate $G_H$
indicates the event is consistent with hydrogen scattering while $G_C$ is consistent with carbon scattering. Figure 6a shows the reconstructed excitation-energy distribution obtained from both targets. It includes events in the $G_H$ and $G_C$ gates for the polyethylene target and in the $G_C$ gate for the carbon target. Two broad square-sharpened peaks at $E_x=12.8$ and 15.5 MeV (indicated by the arrows) are visible. The widths of these structures $\sim$1.5 MeV are significantly larger than the experimental resolutions of $FWHM=0.5$ and 0.6 MeV at these two energies. The square shapes of these two structures indicate they cannot be associated with a single state (with a Lorentzian shape), but that they are multiplets, probably doublets. In addition to the broad structures, a wide, low-energy shoulder at $\sim$10.2 MeV is evident.

To investigate the target-nucleus dependence of these structures, the events were subdivided. The cleanest sample on events associated with hydrogen scattering was obtained a $G_H\&G_C$ gate on the polyethylene events. The $E_x$ distribution associated with these events is shown in Fig. 7a. This distribution is similar to the original distribution, except the doublet at $E_x=15.5$ MeV is not evident. However, the $G_H\&G_C$ gate removes the most forward-angle events so it is possible that this doublet is still excited by hydrogen scattering.

A clean sample of carbon scattering events is obtained from the $G_C$-gated carbon target events plus the $G_C\&G_H$-gated polyethylene events and the $E_x$ distribution is displayed in Fig. 8a. Both doublets are present, but the statistical significance of the higher-energy one is diminished. The relative yield in the low-energy shoulder ($\sim$10.2 MeV) has been significantly enhanced. From Figs. 7a and 8a, we conclude that the 10.2 MeV low-energy shoulder and the 12.8 MeV doublet are excited from both hydrogen and carbon scattering. The origin of the higher-energy doublet is less clear.

The work of Freer et al. [6] identified a number of peaks in equivalent distributions gated on hydrogen and carbon scattering. The locations of the peaks tabulated by Freer et al. are indicated by the diamonds in Figs. 7a and 8a. However, neither of these spectra are very similar to those of this work. The broad doublets were not observed, though some of the listed peaks energies could be consistent with being one member of the doublet states.

B. $^6$He+$^6$He Decay

The velocity distributions for $^{12}$Be fragments reconstructed from $^6$He-$^8$He pairs is quite similar to the $\alpha$-$^8$He results and will not be shown. The $\Delta\phi$ distribution in Fig. 4b confirms the presence of recoil protons from the polyethylene target. Excitation-energy spectra for all events and those associated with hydrogen and carbon scattering are displayed in Figs. 6b, 7b, and 8b, respectively. Statistical fluctuations are too large in the latter two spectra to make any peak assignments. In the $E_x$ spectra for all events, we have indicated peaks at 13.5 and $\sim$14.5 MeV.

Freer et al. identified a number of peaks in their combined $^{12}$C and $(CH_2)_2$ data. Again the location of these peaks are indicated in the figures by the diamonds. The lowest-energy peak at 13.2 MeV identified by Freer et al. is consistent with our 13.5 MeV peak. Freer et al. associated this peak with spin 4, based on angular correlations of the $^6$He fragments [7]. Due to the low signal-to-background ratio in the present work, we could not confirm this assignment. The second listed peak of Freer et al. at 14.9 MeV may also be consistent with our $\sim$14.5 MeV peak, though this peak was not well developed in the spectra of Freer et al..

C. $t+^9$Li Decay

Significant yield was also observed for $t+^9$Li coincidences. The join velocity distributions in Fig. 9a indicates that the majority of these events have the kinematics associated with hydrogen scattering. Compared to the $^6$He-$^8$He and $\alpha$-$^8$He results, the angular distribu-
FIG. 7: (Color online) Distributions of excitation energy reconstructed from a) $\alpha^+{^4}\text{He}$ and b) $^6\text{He}^+{^6}\text{He}$ pairs for interactions on the hydrogen component of the polyethylene target. The arrows indicate the location of the structures discussed in the text. The diamonds indicate the location of peaks identified in Ref. [6]. Examples of the predicted experimental response are indicated by the curves along the Ex axis.

FIG. 8: (Color online) As for Fig. 7, but now the events are associated with scattering from the $^{12}\text{C}$ target nuclei.

D. $p+{^{11}}\text{Li}$ Decay

A small number of $p+{^{11}}\text{Li}$ pairs were detected. The joint velocity distributions in Fig. 10a again indicate that the parent fragments were excited by interactions with hydrogen target nuclei. The detection efficiency for small $V_\perp$ is suppressed due to the angular acceptance of the heavy $^{11}\text{Li}$ fragment, which essentially defined the center of mass. Otherwise, the reconstructed parents uniformly occupy the full range of center-of-mass angles. As for the other channels, the $\Delta\phi$ distribution of Fig. 4d confirms the presence of recoil protons. For this decay channel, the reconstructed excitation-energy distribution with $G_H$ gate in Fig. 10b has some prominent and significant features. Most notable is a wide peak at $Ex=28$ MeV of width $2.7$ MeV. This is significantly larger than the experimental resolution of $FWHM=400$ keV. From the statistical fluctuations, it is difficult to say whether this structure is a single peak or a multiplet. There is also strong indications of a narrower peak at $Ex=25$ MeV.

V. DISCUSSION AND CONCLUSIONS

Apart from $p+{^{11}}\text{Li}$ results, the peaks that have been identified are not prominent and sit on large backgrounds. These background events have consistent kinematics and reconstructed excitation energies and thus correspond to real projectile-breakup events. The presence of a background of real events is not surprising at high excitation energies were the density of states and their typical widths are large. The background is therefore associated with the summation of unresolved states. The very prominent peaks observed for the $p+{^{11}}\text{Li}$ channel at $Ex=25$-$30$ MeV are therefore quite interesting and probably indicates that the associated states have strong $p+{^{11}}\text{Li}$ structure.

How do we reconcile this work to that of Freer et al.? We have only confirmed the two lowest-energy peaks associated with $^6\text{He}^+{^6}\text{He}$ breakup. Yet, the number of detected $^6\text{He}^+{^6}\text{He}$ and $\alpha^+{^8}\text{He}$ pairs in the present work...
FIG. 9: (Color online) Results obtained from $^{12}\text{Be}$ fragments reconstructed from $t$-$^9\text{Li}$ pairs. a) The join distribution of parallel and perpendicular velocities. The circular curve indicated the kinematic solution expected for inelastic scattering from a hydrogen target nucleus exciting the $^{12}\text{Be}$ to 28 MeV of excitation energy. b) The reconstructed excitation energy distribution of the $^{12}\text{Be}$ fragments. Examples of the predicted experimental response are indicated by the curves along the $E_x$ axis.

is significantly larger. The resolution of the present work is comparable to Freer et al. They quote an excitation-energy resolution of $FWHM = 800\text{ keV}$ for $10 < E_x < 25\text{ MeV}$ [7] compared to 300-800 keV in this work. Due to the limited statistic it is possible that some of the levels identified by Freer et al. are statistical flukes. It also may be possible that relative excitation of these peaks is strongly diminished at higher bombarding energies of this work making these states more difficult to isolate from the background.

This work has some consistency with the other previous studies. For instance, our $\sim 10.2\text{ MeV}$ state maybe related to the 10 MeV state of Korsheninnikov et al. [5] and/or the 10.7 MeV state of Bohlen et al. [10]. Similar our $\sim 14.5\text{ MeV}$ state maybe related to the $\sim 14\text{ MeV}$ state of Korsheninnikov et al. and the 14.6 MeV state of Bohlen et al.

In comparing the structure observed in the two helium decay channels, it is important to realize that the $\alpha$-$^8\text{He}$ decay channel can be accessed by states of both parities, while only positive parity states can decay by $^6\text{He}$-$^6\text{He}$ breakup. The 13.5 MeV peak in the $^6\text{He}$-$^6\text{He}$ distribution may be the upper member of the 12.8 MeV doublet observed for $\alpha$-$^8\text{He}$ events. The absence of the lower member of this doublet in the $^6\text{He}$-$^6\text{He}$ channel, suggests that lower state has negative parity. The doublet would then have negative and positive parity states. In the work of Freer et al., the upper state was assigned a spin of $4^+$ [7]. Using the Generator Coordinate Method for just the $\alpha$-$^8\text{He}$ molecular configurations,Descouvemont and Baye predict doublets each containing a member of a positive and a negative parity molecular band [4]. They even predict a ($5^-, 4^+$) doublet very close to our observed 12.8 MeV doublet. However when they allow mixing with $^6\text{He}$-$^6\text{He}$ molecular configurations, the
ordering of the doublet is reversed. The 12.8 MeV shoulder structure in the $^\alpha$-He spectra could be the lower ($3^-, 2^+$) members of these molecular bands. However, the upper 15.5 MeV doublet is too low in energy to be the ($7^-, 6^+$) members. Therefore, the exact nature of all the observed states is not clear.

In conclusion, $^\alpha$-He, $^6$He+$^6$He, $t$+$^9$Li, and $p$+$^11$Li decays of $^{12}$Be fragments excited via inelastic scattering with hydrogen and carbon target nuclei have been observed. Events where the $Q$-value associate with the initial primary inelastic scattering interactions and the excitation energy determined from the relative energy of the secondary decay fragments were isolated. The $^\alpha$-He and $^6$He+$^6$He decays have significant contributions from both $^{12}$C and $^p$ scattering, while the $t$+$^9$Li and $p$+$^11$Li channels were produced predominantly through $p$ scattering. The excitation-energy distributions determined for all breakup channels have large backgrounds from unresolved states. For $^\alpha$-He decay, two doublets were observed at 12.2 and 15.5 MeV of excitation energy and the presence of additional state(s) is indicated by a shoulder in the spectra at 10.2 MeV. Two peaks were observed for $^6$He+$^6$He decay at 13.5 and 14.5 MeV. The overall agreement with the work of Freer et al. which reported evidence for molecular structures is not large. Of the many levels reported in that work, only the two lower two $^6$He+$^6$He peaks were confirmed. The $p$+$^11$Li channel was found to display quite prominent structure in the excitation-energy spectra at $Ex$=25-30 MeV.

Acknowledgments

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