Invariant-mass spectroscopy of $^{18}$Ne, $^{16}$O, and $^{10}$C excited states formed in neutron transfer reactions.

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Neutron transfer reactions with fast secondary beams of $^{17}$Ne, $^{15}$O, and $^9$C have been studied with the HiRA and CAESAR arrays. Excited states of $^{18}$Ne, $^{16}$O, and $^{10}$C in the continuum have been identified using invariant-mass spectroscopy. The best experimental resolution of these states is achieved by selecting events where the decay fragments are emitted transverse to the beam direction. We have confirmed a number of spin assignments made in previous works for the negative-parity states of $^{18}$Ne. In addition we have found new higher-lying excited states in $^{16}$O and $^{18}$Ne, some of which fission into two ground-state $^9$Be fragments. Finally for $^{16}$O, a new excited state was observed. These transfer reactions were found to leave the remnant of the $^9$Be target nuclei at very high excitation energies and maybe associated with the pickup of a deeply-bound $^9$Be neutron.

I. INTRODUCTION

Invariant-mass spectroscopy with fast radioactive beams has proven a valuable tool for studying the structure of light exotic isotopes near the drip lines. With the High Resolution Array (HiRA) [1], we have focused our studies on states produced in nucleon knockout reactions for isotopes near and beyond the proton drip line [2–6]. However in the same experiments, we also obtained data for a number of other reactions types [3, 7]. In this work we will report on levels obtained from neutron-transfer reactions with fast $^{17}$Ne, $^{15}$O, and $^9$C secondary beams using experimental data sets for which knockout results have already published. One advantage of the invariant-mass technique is its selectivity to the decay channel. This allows one to isolate small cross sections associated with exotic exit channels and determine branching ratios in decays.

The experimental technique will be validated by studying the well-known spectroscopy of $^{16}$O states which can be produced with the $^{15}$O beam. In particular we will look at the $\alpha$-particle branching ratio for the $J^\pi=2^+$ level which is important to determine its isospin mixing with the neighboring $J^\pi=2^-$ level [8]. With the $^{17}$Ne beam, we will look at the low-lying levels of $^{18}$Ne. The structure of $^{18}$Ne has attracted considerable interest due to its importance for the resonant component of the $^{14}$O($\alpha,p$)$^{17}$F and $^{17}$F($p,\gamma$)$^{18}$Ne reactions in astrophysics [9–11]. In the course of such studies, Hahn et al. [9] produced an evaluated level scheme for this isotope and made spin assignments based on the level widths, cross sections and angular distributions in various reactions, and Thomas-Ehrman shifts relative to the mirror $^{18}$O system. Due to the selectivity of transfer reactions, only levels of certain spins and parity will be strongly populated with a $^{17}$Ne beam and this can be used to check the spin assignments of Hahn et al. In addition for all three projectiles, we will look for previously unobserved higher-lying excited states. Here the power of the invariant-mass technique will allow us to observe highly-fragmented decay channels with interesting decay modes.

Our main interest is the low-lying particle-unstable states formed by neutron capture to the $p$ and $sd$ shells. However from semi-classical models of this process [12], transfer of a nucleon to such orbitals with fast beams ($E/A$=60-70 MeV) is poorly matched in terms of linear and angular-momentum transfer leading to small cross sections. Moreover, transfer reactions also have selectivity to structures with single-particle-like configurations and can be used to probe such structures and constrain models. Indeed at lower energies where linear and angular momentum are better matched, transfer reactions such as $(d,p)$ have contributed significantly
to this area using the missing-mass technique. Indeed, such cases are amenable to simple reaction theory (Distorted Wave Born Approximation for instance) and spectroscopic strengths and spin assignments can be inferred from the detected cross sections and angular distributions. However with fast secondary beams, the missing-mass technique requires thinner targets than those typically used with the invariant-mass technique. In addition, because of the large phase space of these secondary beams, beam tracking is required for the determination of absolute angles, whereas relative angles are only important in the invariant-mass technique, which in HiRA, are almost insensitive to the size of this phase space. In this work we will explore the role that the invariant-mass technique can play in these transfer reactions and present its advantages and disadvantages. Finally this work is complementary to recent studies using γ-ray spectroscopy following transfer reactions with fast secondary beams where the final projectile-like fragment is detected in a spectrometer [13–15].

II. EXPERIMENTAL METHOD

The data presented in this work was obtained from experiments performed at the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University. Details of these experiments have been described in Refs. [4–6] and only a brief description will be given here. A secondary beam of intensity 948.1 MeV, respectively. In a separate experiment, a secondary beam of intensity 1.5 × 10^14 pps was obtained from the fragmentation of an E/A=170-MeV 20Ne primary beam (80 pA). This beam contained 17Ne (11%) and 16O (80%) with energies in the center of a 1-mm-thick Be target of E/A =58.2 and 48.1 MeV, respectively. In a separate experiment, a secondary beam of intensity 9 × 10^4 pps was obtained from an E/A = 150-MeV 16O primary beam (175 pA). This beam contained 9C at the 52% level with an energy in the center of the same target of E/A=64.6 MeV. The other main component of this beam was 6Li.

Charged particles produced from reactions with the target were detected in the High Resolution Array (HiRA) [1] consisting of 14 ∆E − E telescopes arranged around the beam to cover zenith angles from 2° to 13.9°. The double-sided Si strip ∆E detectors permitted accurate determination of the scattering angles of the detected fragments. The heavier fragments (A >10) were only identified in the central two telescopes where the ∆E strips were set up with dual gains. Energy calibrations of the CsI(Tl) E detectors were achieved using a series of cocktail beams including E/A=55 and 75 MeV protons and N=Z fragments, and E/A=73.4 and 95.2 MeV 7Be fragments. Other fragments such as 15N and 17F have only a single calibration point each at E/A=40.1 and 51.3 MeV, respectively. In these cases, we use the calibration point to define effective thicknesses of the Si ∆E detectors and then use energy-loss tables [16] to determine E from the ∆E measurement. The relative locations of each HiRA telescope and the target were determined very accurately using a Coordinate Measurement Machine arm.

The CAESAR (CAESium iodide ARray) detector [17] was positioned to surround the target in order to detect γ rays emitted in coincidence with charged particles. For this experiment, the array consisted of 158 CsI(Na) crystals covering polar angles between 57.5° and 122.4° in the laboratory frame with complete azimuthal coverage. The first and last rings of the full CAESAR array were removed due to space constraints.

For the normalization of cross sections, the number of beam particles was determined by counting using a thin plastic-scintillator foil placed in the focal point of the A1900 fragment separator. For the 17Ne-18O beam, the loss in the beam flux due to its transport to the target and the relative contribution from each beam species was determined by temporarily placing a CsI(Tl) detector just after the target position. These fluxes were also corrected for the detector dead time measured with a random pulse generator. No similar calibrations was performed for the 5C beam. Here we rely on a previous experiment with the same beam energy, target, and detector setup where a similar calibration was performed [3]. Normalization of cross sections in the present case was determined by reproducing the value for 8C g.s. from the previous experiment. The uncertainties quoted for the cross sections in remainder of this work are statistical only. In addition to these, there is also a systematic uncertainty of ±15% for the 18Ne and 16O states and ±20% for the 10C states.

III. INVARIANT-MASS METHOD

For a group of detected fragments believed to be the decay products of a nuclear level, we can calculate its excitation energy as

\[ E_{n}\gamma = E_{\text{inv}} - E_{g.s} \]  \hspace{1cm} (1)

where \( E_{\text{inv}} \) is the invariant mass of the fragments and \( E_{g.s.} \) is the ground-state mass of the decaying nucleus. However, the quantity \( E_{n}\gamma \) is only the true excitation energy if no γ-rays were emitted in the decay. For example, the particle decay of a state may leave one or both of the decay fragments in particle-bound excited states which subsequently γ decay. In such cases, the true excitation energy is obtained by adding the γ-ray energies, i.e.,

\[ E^* = E_{n}\gamma + \sum_i E_i^\gamma. \]  \hspace{1cm} (2)

The use of the CAESAR γ-ray array allows us to identify such cases and apply this correction.

The experimental apparatus is only sensitive to particle decays of projectile-like states which are produced at laboratories angles close to the beam axis (\( \theta_{lab} < 10^\circ \)). For two-body decays where the invariant mass
can be determined solely from the relative velocity between the two fragments, the experimental resolution depends very strongly on the decay direction. For example, Fig. 1 shows the simulated resolution (App. A) expressed as a FWHM of the invariant-mass peak for a level with zero intrinsic width and $E^* = 5.135$ MeV. Results are shown as a function of the $\theta$, the emission angle of the proton in the $^{18}\text{Ne}^*$ frame where $\theta = 0^\circ$ corresponds to emission along the beam axis.

For transverse decays ($\cos \theta \sim 0$), uncertainties in the energies of the detected fragments act perpendicular to the decay axis and thus only contribute to the invariant-mass uncertainty in second order. In this case, the experimental resolution is dominated by the angular resolution. On the other hand for longitudinal decays ($|\cos \theta| \sim 1$), the angular uncertainty contributes in second order and the experimental resolution is now dominated by the contribution from the energy. If there are enough statistics, it is clearly advantageous to restrict the analysis to events which decay transversely. For example, Fig. 1 shows the simulated resolution (App. A) expressed as a FWHM of the invariant-mass peak for a level with zero intrinsic width and $E^* = 5.135$ MeV and zero intrinsic width. The angle $\theta$ is the emission angle of the proton in the $^{18}\text{Ne}^*$ center-of-mass frame with $\theta = 0^\circ$ corresponding to emission along the beam axis. This strong angular dependence reflects the fact that we have excellent relative-angle resolution, but poorer energy resolution, and the relative contribution of these to the total resolution is strongly $\theta$-dependent. In both cases, these resolutions are dominated by the effect of the thick target. For the relative-angular resolution, it is the small-angle scattering of the decay products in the target material which is important, while for the energy resolution, the uncertainty in the interaction depth in the target leads to an uncertainty in the energy loss of the decay fragments as they leave the target.

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For similar reasons, the transverse-gated spectra also have reduced sensitivity to errors in the CsI(Tl) energy calibrations, thus reducing the systematic uncertainty in the fitted peak energies. To estimate the magnitude of this uncertainty we have fitted nine invariant-mass peaks associated with proton decay of $^{12,13,14,15}\text{O}$ and $^{14,15}\text{O}$ levels which have small intrinsic widths and their decay energies are well known. The weighted mean deviation from the ENSDF [18] decay energies is $-1.5(33)$ keV. Thus we chosen a $2\sigma$ deviation of 6.6 keV as a reasonable choice for this systematic uncertainty.

**IV. $^{16}\text{O}$ EXCITED STATES**

Neutron pickup by the $^{15}\text{O}$ beam provides an excellent test of our understanding of transfer reactions at these higher energies as the $^{16}\text{O}$ states of interest are well characterized and one can compared to lower-energy data from the mirror reaction, proton transfer to $^{15}\text{N}$ [19, 20]. The ground-state configuration of $^{15}\text{O}$ consists predominantly of a neutron hole in the $p$ shell. In neutron-transfer reactions, the lower-energy states are produced
by either filling this hole and making a $J^\pi=0^+$ state, or, by capturing the neutron into the sd shell. Of these possibilities, neutron capture to either the $d_{5/2}$ or $d_{3/2}$ level forming $J=1^-$, $2^-$, or $3^-$ states will have the smaller momentum mismatch and thus are expected to produce the largest cross sections at these energies. Capture to the $pf$ shell will generally produce states of larger excitation energy where the level density increases and our experimental resolution is poorer making it generally more difficult to isolate and identify them.

Invariant-mass spectra for the $p+^{15}N$ and $\alpha+^{12}C$ transverse decay channels of $^{16}O$ formed with the $^{15}O$ beam are plotted in Figs. 3(a) and 3(b). The observed peaks for $p+^{15}N$ are all associated with decay to the ground-state of $^{15}N$ apart from the highest-energy one ($E_\gamma^*=\sim13.7\ MeV$) which will be discussed later (Sec. IV B). The $\gamma$-ray spectrum in coincidence with the detected $\alpha+^{12}C$ pairs is shown in the inset in Fig. 3(c) where a peak associated with the $E_\gamma=4.438\text{-MeV} \ \gamma$-ray from the decay of the first-excited state of $^{12}C$ is visible. Below this, the first escape peak is also clearly evident. Using the $\gamma$-ray gate indicated in the inset of Fig. 3(c) which encompasses both peaks, the resulting $^{16}O$ excitation-energy spectrum is shown Fig. 3(c). Comparing this $\gamma$-gated and the inclusive spectra of Fig. 3(b), one finds both are almost identical in shape below $E^*=10\ MeV$ but not above and thus the lower-energy peak structures must be associated with decays to the first excited state of $^{12}C$, while the higher-energy structures observed in Fig. 3(b) are associated with decays to the ground state.

Both the $p+^{15}N$ and $\alpha+^{12}C$ invariant-mass spectra have been fitted with peaks from the $^{16}O$ levels that were observed in the lower-energy proton-transfer experiments with $^{15}N$ targets [19, 20]. The peak energies and intrinsic widths were fixed to their values in [18], while their intensities and a smooth background are varied to reproduce the data. Detector resolution is included via the Monte Carlo simulations (App. A). The results are shown by the solid curves (red) with individual components indicated by the solid (green) curves for decay to the ground state or dashed (magenta) curves for decay to the excited state. Note that for the $\alpha+^{12}C_g.s.$ decay channel, no $J^\pi=0^-$, $2^-$ levels are considered as such decays would violate parity conservation. These fits show that both spectra are dominated by the decay of two $T=1$ states: the $J^\pi=3_3^+$ state at $E^*=13.259\ MeV$ observed in the $p+^{15}N$, $\alpha+^{12}C_g.s.$, and $\alpha+^{12}C4.438\text{-MeV}$ exit channels and a $J^\pi=2_2^-$ state ($E^*=12.969\text{MeV}$) observed in the $p+^{15}N$ and $\alpha+^{12}C4.438\text{-MeV}$ channels. In addition the $T=0$, $J^\pi=2_2^-$ state at $E^*=12.530\ MeV$ is observed at lower intensity in the $p+^{15}N$ and $\alpha+^{12}C4.438\text{-MeV}$ channels. Finally there is evidence for a peak at $E^*=11.096\ MeV$ in the $\alpha+^{12}C_g.s.$ channel at low yield which corresponds to a $J^\pi=3^+$ state, involving the capture of a $f$-shell neutron. The fits confirm our expectation that states formed by neutron capture to the $d$-orbital will dominate. Also, the experimental spectra were fit without any significant contribution from the $E^*=10.957$ and $12.796\ MeV J^\pi=0^-$ states and the $E^*=12.440$ and $13.090\ MeV, J^\pi=1^-$ states which all involve capture to the second $s_{1/2}$ level even though their spectroscopic factors are significant [20]. This suppression of $s_{1/2}$ capture is consistent with a larger momentum mismatch at these higher bombarding energies.

### A. Branching Ratio of $J^\pi=2_3^-$ Level

The $J^\pi=2^-$ states at $E^*=12.530\ MeV$ ($T=0$) and $12.969\ MeV$ ($T=1$) are close enough in energy that there is some isospin mixing. The magnitude of this mixing can be determined from their $\alpha$-particle reduced widths [8]. However there is a disagreement in the value of the $\alpha$ partial width or branching ratio for the ($T=1$) $12.969\ MeV$ state. Historically, the first information on this branching ratio is from the compilation of Ajzenberg-Selove [21] giving $\Gamma_{\alpha}/\Gamma=0.36(5)$. This value was referenced to a paper of Rolf and Rodney [22] where the branching ratio is not given or discussed, so details of the derivation of this value are unknown. Later Leavitt et al. measured a similar value of 0.37(6) from which they extracted a mixing parameter and the charge-dependent matrix element [8]. Subsequently Zijderhand and Van der Leun [23] measured a smaller value of 0.22(4) which is in disagreement with the two previous measurements. It is this final value that is listed in the current ENSDF evaluation [18].

We have extracted the relative strength of the proton and alpha branches for transverse decay only. For longitudinal decay, the experimental resolution is much poorer making it very difficult to separate the $12.969$ and $13.259\ MeV$ states in both exit channels. If we assume the decay angular distributions are isotropic, then $\Gamma_{\alpha}/\Gamma=0.49$ which is larger than all of the other measurements.

However to the extent that these transfer reactions are peripheral, then the orbit of the neutron before transfer in the target and after transfer in the projectile should lie predominantly in the reactions plane. As such the spin vector of the $^{16}O$ excited states may show an overall alignment perpendicular to the beam axis. A minimum value of the branching ratio can be obtained using angular distributions calculated assuming the $J^\pi=2^-$ state has maximal alignment, i.e. $M=0$ with the beam axis as the quantization axis. Taking the proton decay as a $d_{3/2}$ emission [20], we obtain $\Gamma_{\alpha}/\Gamma>0.32$ which is inconsistent with Zijderhand and Van der Leun, but consistent with the other measurements.

### B. $p+^{15}N + \gamma$ Exit Channels

The $\gamma$-ray spectrum measured in coincidence with the detected $p+^{15}N$ pairs is displayed in the inset in Fig. 4(b). A peak at $E_\gamma \sim 5.28\ MeV$ and its first escape shoulder are observed. These events can be associated with
either the first ($E^* = 5.270\text{ MeV}, J^\pi = 5/2^+$) or second ($E^* = 5.298\text{ MeV}, J^\pi = 1/2^+$) excited state of $^{15}\text{N}$. In addition we see peaks at $1.885\text{ MeV}$ and $2.297\text{ MeV}$ that are produced in the decay of the $E^* = 7.155\text{MeV}, J^\pi = 5/2^+_2$ and $E^* = 7.567\text{MeV}, J^\pi = 7/2^+_1$ excited states, respectively. For reference, a partial level scheme of $^{15}\text{N}$ is shown in Fig. 5.

The excitation-energy spectrum for coincidences with either the $5.270$ or $5.298\text{MeV} \gamma$ ray (gate $G_2$ in Fig. 4) is plotted in Fig. 4(a). Three clear peak structures are observed and the solid curve shows the results of a fit. The lower-energy peak has been fitted as a doublet where the energy and width of the lower-energy member are constrained with a second $\gamma$ peak. This second gate ($G_1$) is around the $2.297\text{MeV} \gamma$ ray [gate $G_1$ in Fig. 4(b)] and we used the adjacent higher-energy $\gamma$ rays [gate $G_b$ in Fig. 4(b)] to estimate the background under this peak. The background-subtracted spectrum is displayed in Fig. 4(b) and only the lower-energy member of the doublet is now present as demonstrated in our fit (curve). Clearly this lower-energy member of the doublet is associated with the $7.567\text{MeV}, J^\pi = 7/2^+_1$ excited state of $^{15}\text{N}$ which decays by emitting both a $2.297\text{MeV}$ and a $5.270\text{MeV} \gamma$ ray. The deduced total excitation energies, including the $\gamma$-ray contributions are listed in Table I and the decays are illustrated in Fig. 5.

### C. Four-$\alpha$ Exit Channels

A large number of $4\alpha$ events were detected with the $^{15}\text{O}$ beam, but the invariant-mass spectrum for all events did not show any significant peak structures. However, such events can be obtained from a number of different decay scenarios, but one interesting possibility is the fission of $^{16}\text{O}$ into two ground-state $^8\text{Be}$ fragments. Such events are easy to separate by looking at the momentum correlations between the $\alpha$ particles. We have selected events where the relative energy between one pair of $\alpha$ particles is consistent with $^8\text{Be}$ decay and similarly for the remaining pair. The relative energy distribution is very sharply peaked for $\alpha$ pairs from the decay of $^8\text{Be}$ and we find there is almost no background under it. Therefore $^8\text{Be}_{g.s.} + ^4\text{He}$ decay can be isolated relatively cleanly. The excitation-energy spectrum for such events is displayed in Fig. 6 and shows a large peak at $19.26\text{ MeV}$ plus a broader structure at $\sim 21\text{ MeV}$. The latter was fit as a doublet in Fig. 6 where the widths of the two members were taken as equal. Fitted decay widths and cross sections are listed in Table II and the decay scheme is also illustrated in Fig. 4. As the decay channel consists of two identical $J = 0$ Bosons, then these states must have positive parity and even values of $J$. Therefore they are not produced by the capture of a $d$-wave neutron, but presumably result from capture to the $f^4_7/2$ or $f^4_5/2$ levels which would not be unreasonable at these higher excitation energies. As such, these peaks must be either $J^\pi = 2^+$

### Table I. Parameters for the levels in $^{16}\text{O}$ obtained from the fitting the $\gamma$-gated $p + ^{15}\text{N}$ excitation-energy distributions in Fig. 4. These include the fitted centroid of each peak $E_{\gamma}$ and its excitation energy $E^*$ when the $\gamma$-rays energies are included, and finally the fitted intrinsic width $\Gamma$.

| $E_{\gamma}^*$ [MeV] | $E^*$ [MeV] | $\Gamma$ [keV] |
|----------------------|--------------|----------------|
| 12.863(14)           | 20.430(14)   | 77(38)         |
| 12.993(11)           | 18.269(11)   | <30*           |
| 13.373(12)           | 18.643(12)   | <60*           |
| 13.729(12)           | 18.999(12)   | <40*           |

* $1\sigma$ limit

### Figure 3.

Distribution of $^{16}\text{O}$ excitation energy reduced by the total energies of emitted $\gamma$ rays for events detected with the $^{15}\text{O}$ beam. (a)+(b) Data points show the experimental distribution for all detected $p + ^{15}\text{N}$ and $\alpha + ^{12}\text{C}$ pairs, respectively. The solid-red curves show fits to these distributions using known $^{16}\text{O}$ levels. The individual contributions from these levels are shown as the solid curves for decays to the respective ground states. In (b), decays to the first excited state of $^{12}\text{C}$ are indicated by the dotted curves. Background contributions (dash-blue curve) was also included in the fit. (c) Excitation-energy spectrum gated on $\gamma$-rays from the decay of the first excited state of $^{12}\text{C}$. The inset shows the Doppler-corrected $\gamma$ spectrum measured in coincidence with $\alpha + ^{12}\text{C}$ pairs and the gate used to select $\gamma$-rays from the decay of this excited state.
measured the 12 MeV peak originally identified by Chevallier et al. A significant number of levels have been found. Our investigation in a number of other studies [24–30] and signed a spin of $J^*$. However we have low sensitivity to detecting such a proton branch as it will have low efficiency and poor experimental resolution.

The $^8$Be$_{g.s.}$+$^8$Be$_{g.s.}$ exit channel of $^{16}$O has been investigated in a number of other studies [24–30] and a significant number of levels have been found. Our 19.26(4)-MeV peak may be associated with the 19.35-MeV peak originally identified by Chevallier et al. [24] in the $^{12}$C($^4$He,$^8$Be)$^{16}$Be reaction, however, they assigned a spin of $J^*=6^+$ from the measured angular distributions. Subsequently, Freer et al. identified a peak in the $^{12}$C($^{16}$O,$^8$Be+$^8$Be)$^{12}$C reaction at 19.3 MeV and assigned a spin of $J^*=4^+$ [28]. Later Curtis et al. re-measured the $^{12}$C($^4$He,$^8$Be)$^{16}$Be reaction with better resolution and the 19.3-MeV peak was found to be a doublet (19.29 and 19.36 MeV) [30]. They argued that this doublet is actually an interference effect and corresponds to a narrow resonance with either $J^*=2^+$ or $4^+$. The fitted intrinsic width of our peak is $\Gamma=435(15)$; 2.9 $\sigma$ away from zero so it is probably not narrow. In addition according to Freer et al., the 19.3-MeV states decays more strongly to the $\alpha+^{12}$C$(0^+_2)$ channel with $\Gamma_{\alpha}\mathrm{Be}/\Gamma_{^{12}\mathrm{C}(0^+_2)}=0.47(15)$.

We can also relatively cleanly gate on such decays from our detected 4α events by selecting out those where three of the four $\alpha$ particles has an invariant mass associated with the Hoyle state ($^{12}$C$(0^+_2)$) state. The excitation-energy spectra is displayed as the data points in Fig. 7. For comparison, the two curves separated by the hatched region are simulated results using our best-fit intrinsic width for the 19.262-MeV state and incorporating the experimental resolution. The magnitudes of the two curves are chosen to give the experimental outer limits of the branching ratio given by Freer et al. Clearly the experimental spectrum does not show such a peak and the branching strength to this channel must be at least a factor of 4 smaller than that given by Freer et al. Probably our peak is associated with a different $^{16}$O excited state, one that does not process pure cluster configurations but contains some neutron single-particle strength permitting its formation in neutron transfer reactions. In the work of Curtis et al. [30], a 21.10-MeV level was observed and assigned $J^*=4^+$ or $6^+$ and this is consistent with our 20.987(6)-MeV peak.

For the most significant peak at 19.262 MeV in Fig. 6, the angular distribution of the $^8$Be+$^8$Be axis relative to the beam direction is displayed in Fig. 8. It has been corrected for the angle-dependent efficiency as determined in our Monte Carlo simulations (App. A). It is possible that there is some small alignment of the $^{16}$O$^*$ parent spin perpendicular to the reaction plane, but with the large error bars, the experimental distribution is also consistent.

![FIG. 4. Distribution of $^{16}$O excitation energy reduced by the total energies of $^{15}$N $\gamma$ rays for $\alpha$+$^{15}$N pairs detected with the $^{16}$O beam. Data points show the experimental distributions, while solid-red curves show fits to these data. The dash-blue curves indicate the fitted background. The inset shows the Doppler-corrected $\gamma$-ray spectrum for all detected $\alpha$+$^{15}$N pairs with the energies of known $\gamma$ rays indicated with the arrows. (a) Distribution gated on the $G_2$ gate shown in the inset. (b) Background-subtracted distribution gated on the $G_1$ gate in the inset. As the 2.297-MeV $\gamma$-ray sits on a significant background, the events in the $G_0$ gate, suitably scaled in magnitude, were used to remove this background.](image1)

![FIG. 5. Decay scheme of the newly-found high-lying states in $^{16}$O obtained from fits to the $\alpha$+$^{15}$N$+\gamma$ and $^8$Be$_{g.s.}$+$^8$Be$_{g.s.}$ exit channels of $^{16}$O.](image2)
V. 18Ne Excited States

The 18Ne level scheme evaluated by Hahn et al. [9] is shown in Fig. 9 and compared to that for the 18O mirror. Some of these states can be produced by neutron capture to the 17Ne beam. The 17Ne ground-state wavefunction \( J^\pi = 1^- \) consists predominantly of two protons in the sd shell, coupled to zero spin, and a single neutron hole in the p shell [31]. If the captured neutron with isotropic decay. The yields quoted in Table II and subsequent tables assumed isotropic decay in extrapolating from the transverse gate. They should only be used as a rough gauge of the cross sections unless the angular distributions are measured.

### Table II. Fitted mean excitation energies \( E^* \), intrinsic widths \( \Gamma \), and peak cross sections obtained for the 16O levels decaying to the \(^8\)Be\(_{g.s.}\) + \(^8\)Be\(_{g.s.}\) channel observed in Fig. 6.

| \( E^* \) [MeV] | \( \Gamma \) [keV] | \( \sigma_{\text{peak}} \) [\( \mu \)b] |
|-----------------|-----------------|------------------|
| 19.262(38)      | 435(151)        | 29(18)           |
| 20.987(52)      |                 |                  |
| 21.922(87) \(^a\) | 57(256)        | 14(6)            |

\(^a\) doublet

fills this hole, then a \( J^\pi = 0^+ \) state in 18Ne is formed. Otherwise neutron capture to the sd shell will produce negative-parity states. Given that the momentum mismatch will favor capture to the \( d_{3/2} \) and \( d_{5/2} \) levels, this reaction should predominantly populate \( J^\pi = 1^-, 2^-, \) and \( 3^- \) states. Other positive-parity states can be populated by capture to the pf shell, but these will have larger excitation energies, where the level density is greater, making separation of the individual levels more difficult.

The \( E^*_n\gamma \) distribution for transverse proton decay of 18Ne is shown in Fig. 10. The residual 17F nucleus has one particle-bound excited state at 495 keV so attention must be given to the possibility of decay through this state. The Doppler-corrected \( \gamma \)-ray spectrum in coincidence with the \( p^{+15}\)O decay channel associated with the second excited state of 17Ne [7]. This 17Ne state does not produce \( \gamma \) rays so only a background contribution is present. This background spectrum was normalized to give the same yield for \( E_\gamma > 0.8 \) MeV as that for the detected \( p^{+17}\)F pairs. It is clear that, relative to this background, the \( p^{+17}\)F...
The excitation-energy spectrum, shown as the data points in Fig. 11(b), is gated on the 495-keV \( \gamma \) ray using the \( E_{\gamma} \) limits indicated by the dashed-vertical lines in Fig. 11(a). It should be compared to the inclusive spectra (blue histogram) which is normalized to the same maximum value and both were obtained requiring \(|\cos \theta| < 0.7\) to increase statistics. Given that there is background under the 495-keV peak, then the gated spectrum will still contain decays to the ground state of the \( ^{17}\text{F} \), but the decays to the excited state will be strongly enhanced. The largest relative enhancements are found for the small \( E^* \sim 4.1 \) MeV peak, just above the \( p^{+\text{17F}} \) threshold of 3.923 MeV, and for the background either side of the wide \( E^* \sim 6.3 \) MeV peak, with the enhancement of the high-energy side being largest. Therefore, these regions appear to be dominated by decay to the first excited state. The origin of the background around the 6.3 MeV peak is not clear, we do not expect very wide excited states in this region and so it must be produced from some other background process.

As the ground and first excited states of \( ^{17}\text{F} \) are expected to have little neutron strength in the \( sd \) shell, then the spectroscopic factor for the proton decay of the \( ^{18}\text{Ne} \) states formed by neutron capture to this shell will be very small and hence lead to narrow intrinsic widths. The only exception would be for \( J^\pi=0^+ \) states formed by filling the neutron hole in \( ^{17}\text{Ne} \) where larger \( p^{+\text{17F}} \) spectroscopic factors are possible. However the only observed \( J^\pi=0^+ \) state was close to the \( p^{+\text{17F}} \) threshold and the barrier penetration factor should also give this state a narrow width as well. Shell-model calculations suggest the widths should be at most a few keV. In comparison our simulated dispersion associated with the experimental resolution has a FWHM of \( \sim 200 \) keV. Thus in fitting the measured excitation-energy spectrum, we can ignore the contribution from the intrinsic widths and use these simulations to give the experimental line shapes.

The fit to the excitation-energy spectrum displayed in Fig. 10 was made using these line shapes and including two peaks for each level, one for decay to the ground state (solid lines) and a second peak, located 495 keV lower in mean energy, for a decay branch to the first excited state (dashed curves). Peaks for these latter decays are not resolved in most cases, but we can extract maximum yields for these decays consistent with data. The results we obtain are probably an overestimation of these excited-state branches as other sources of background are


A. 4.099-MeV Peak

The lowest-energy peak observed in Fig. 10 is about 200 keV above the 3.923-MeV threshold for the \( p^{+19}\text{F} \) decay channel. From Fig. 11, we argued that this peak is associated with decay to the first excited state of \( ^{17}\text{F} \) rather than the ground state like the other observed peaks. Given that the decay energy to the ground state is much larger (\( \sim 700 \) keV above threshold) one might expect its smaller barrier penetration factor would kill any significant decay branch to the excited state unless this state had some special structure.

Including the \( \gamma \)-ray energy (495 keV), our peak corresponds to a level at \( E^\ast=4.594(12) \) MeV which is consistent with the energy of the \( J^\pi=0^+_2 \) level measured by Nero et al. (see Sec. V B). The structure of the lowest three \( 0^+ \) states in \( ^{16}\text{Ne} \) can be gauged from studies of their analogs in \( ^{18}\text{O} \). Fortune and Hadley argue that these states have proton \( (1s_{1/2})^2 \) and \( (0d_{5/2})^2 \) components as well as a collective \( 4p-2h \) contribution [35]. They also indicate that the wavefunction for the third of these states is dominated by the \( (1s_{1/2})^2 \) contribution which will give a large spectroscopic factor for the \( p^{+17}\text{F}^+_J=1/2^+ \) decay channel. Of course the \( (0d_{5/2})^2 \) component will be associated with decay to the \( J^\pi=5/2^+ \) ground state of \( ^{17}\text{F} \). In addition to the larger spectroscopic factor for decay to the excited state, this mode will be further enhanced by a smaller centrifugal barrier; \( \ell=0 \) compared to \( \ell=2 \) for ground-state decay. Both of these two properties conspire to counter the effect of the small decay energy and give a significant branch to the excited state. However we expect that decay to the ground state is also significant. Yield from such a branch would produce an enhancement to the high-energy tail of the 4.514-MeV peak (Sec. V B). With the maximum amount of this contribution allowed in our fit, we conclude that the minimum branching ratio to the first excited state is 16% at the \( 2\sigma \) level.

Our shell-model predictions give a value of 3.6% for this branching ratio using the level energy 4.950(8) MeV listed in [18]. The calculated branching ratio is quite sensitive to this energy, with its value increasing to 7.6% if the energy is increased by twice its statistical uncertainty. However it is still smaller than the experimental lower limit of 16% suggesting that the relative contribution of \( (1s_{1/2})^2 \) to \( (0d_{5/2})^2 \) of 5.5 is underestimated in these shell-model calculations. In the work of Fortune and Hadley, the strengths of the different configurations in the \( 0^+ \) wavefunctions were constrained using experimental data giving a \( (1s_{1/2})^2 \) to \( (0d_{5/2})^2 \) ratio of 14.4 for this state. This is a factor of 2.6 larger than our shell-model calculations and allows for consistency with our experimental limit.

The shell model predicts a large spectroscopic factor of \( C^2 S(p_{1/2})=0.66 \) for neutron capture to the \( p_{1/2} \) level. However the larger momentum mismatch for \( p \)-wave capture should suppress the yield of this case relative to those for \( d \)-wave capture. We measured a cross section of

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**FIG. 11.** (a) Spectrum of Doppler-corrected \( \gamma \) rays measured with CAESAR (with add-back contributions from neighboring detectors) in coincidence with the detected \( p^{+17}\text{F} \) pairs showing the peak at 495 keV associated with the decay of the first excited state of \( ^{17}\text{F} \). The lower histogram shows an estimate of the background contribution, while the dashed lines indicates the outer limits of our \( \gamma \)-ray gate around the 495 keV peak. (b) The data points show the \( \gamma \)-ray-gated spectrum of \( E_{n\gamma} \) for detected \( p^{+17}\text{F} + \gamma \) events which is compared to the histogram for all detected \( p^{+17}\text{F} \) pairs. Both spectra were obtained with \( |\cos(\theta)| < 0.7 \).
TABLE III. Parameters obtained from the fit to the excitation-energy spectrum of $^{18}\text{Ne}$ in Fig. 10. The quantity $E^*_{\gamma}$ is the centroid of the peak in the spectrum while $E_{level}$ is the energy of the decaying level. These energies are different when the decay is to the first excited state of $^{17}\text{F}$. The assigned spin-parity of the level is given by $J^\pi$, while $\sigma_{peak}$ is the cross section of the peak in the fit. Experimental and theoretical branching ratios for the decay to the first excited state of $^{17}\text{F}$ are also listed.

| $E^*_{\gamma}$ [MeV] | $E_{level}$ [MeV] | $J^\pi$ | $\sigma_{peak}$ [µb] | $\Gamma_{J^\pi=1/2^+}/\Gamma_{tot}$ | $\Gamma_{J^\pi=3/2^+}/\Gamma_{tot}$ |
|----------------------|-------------------|--------|----------------------|---------------------------------|---------------------------------|
| 4.099(12)            | 4.594(12)         | $0^+_3$ | 11(3)                | $<0.16^c$                       | 0.036                           |
| 4.514(4)             | 4.514(4)          | $1^+_1$ | 133(8)               | $<0.125^b$                      | $1.32 \times 10^{-6}$           |
| 5.135(2)             | 5.135(1)          | $3^+_1$ | 1206(20)             | $<0.009^b$                      | $3.6 \times 10^{-4}$            |
| 5.457(8)             | 5.457(8)          | $2^+_1$ | 186(13)              | $<0.19^b$                       | 0.0022                          |
| 6.150$^c$            | 6.150$^c$         | $1^+_2$ | $<5^b$                | 0.65$^{cc}$                     | $<0.12^b$                       |
| $\sim$6.3            | $\sim$6.3         | (2$^-_3$, 3$^-_2$) | 354(17)              |                                 |                                 |

$^a$ Fixed to value from [18]
$^b$ 2σ limit
$^c$ Fixed to value from [34]

13(3) µb for the proton decay branch to the first excited state of $^{17}\text{F}$. However, based on the minimum limit for this branching ratio in Table III, the total cross section for this state must be less than 81µb. This is more than a factor of 15 smaller than the yield for the 5.135-MeV, $J^\pi=3^-_1$ state (Sec. V C) which has a predicted spectroscopic factor of similar magnitude, but is associated with d-wave capture. This result is thus consistent with a large suppression due to the momentum mismatch.

B. 4.514-MeV Peak

Nero et al. [36] reported a doublet at $E^* \sim 4.5$ MeV. In the $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$ reaction the level energies were determined as 4.513(13) and 4.587(13) MeV while in the $^{20}\text{Ne}(p,t)^{18}\text{Ne}$ reaction they are 4.522(10) and 4.592(10) MeV, respectively. Nero et al. concluded that the lower-energy member is $J^\pi=1^-_1$ while the higher-energy member is $J^\pi=0^+_3$. Our peak at $E^*=4.514(4)$ MeV is thus consistent with the $J^\pi=1^-_1$ level.

Although we list a limit of 12.5% for the excited-state branching ratio, the actual value is expected to be extremely small as decay to the excited state is only 97 keV above threshold compared to 592 keV for ground-state decay. The shell-model estimate is $\sim 10^{-6}$.

The $n+^{17}\text{Ne}$ spectroscopic factor predicted for this state is large, however the shell-model calculations suggested it should be largely due to s-wave capture [$C^2S(d_{3/2})=0.015$, $C^2S(s_{1/2})=0.365$] and thus should be suppressed due to the larger momentum mismatch. Either the effect of the momentum mismatch is not as large as we expect or these shell-model predictions are in error.

C. 5.135-MeV Peak

The dominant peak in the excitation-energy spectrum of Fig. 10 occurs at 5.135(2) MeV. Nero et al. [36] reported on a doublet at $E^* \sim 5.1$ MeV using data from two reactions. In the $^{16}\text{O}(^3\text{He},n)^{18}\text{Ne}$ reaction, the level energies were determined as 5.075(13) and 5.135(25) MeV, while in the $^{20}\text{Ne}(p,t)^{18}\text{Ne}$ reaction they are 5.099(10) and 5.151(10) MeV. From angular distributions measured in that work and also by Falk et al. [37], one of these states was determined to be a $J^\pi=2^+_1$ and the other a $J^\pi=3^-_1$, but which one is the $2^+_1$, and conversely, which one is the $3^-_1$ was unknown.

In order to reproduce the measured intrinsic widths of these states, Hahn et al. [9] subsequently argued that the higher-energy state is $J^\pi=3^-_1$, while the lower-energy state is $J^\pi=2^+_1$. This is in contrast to Wiescher et al. [38] and Funck et al. [39, 40] who put these states in reverse order in their $^{14}\text{O}(\alpha,p)^{17}\text{F}$ rate calculations for astrophysics.

If these two peaks were both present in our data, our energy resolution would not be sufficient to separate the two, however given by Hahn et al. [36] and thus with the spin order given by Hahn et al. In the shell-model calculations, this state has the largest spectroscopic factor for neutron capture to a $d$ level [$C^2S=0.65 (d_{3/2})$] and therefore it is not surprising that it is the strongest state populated in this reaction.

Almaraz-Calderon et al. observed a peak at a similar energy ($E^*=5.10(10)$ MeV) in the $^{16}\text{O}(^3\text{He},n)$ reaction but did not have enough resolution to separate the two members of the doublet if they both were present. They measured a branching ratio to the first excited state of $^{17}\text{F}$ of 0.110 which is large compared to our upper limit of 0.009. The $J^\pi=2^+_1$ member would have to have a large branching ratio and contributed significantly to their observed peak to be consistent with our results. However, our shell-model calculations suggest that this $2^+_1$ state
has a very small branching ratio of 0.002.

D. 5.457-MeV peak

A state is resolved on the higher-energy side of the dominant 5.135-MeV peak in Fig. 10 at 5.457(8) MeV. This energy is consistent with a level at 5.453(10) MeV measured by Nero et al., in the \(^{20}\text{Ne}(p,\alpha)\) reaction [36]. However, no other information on this level was determined due to its low population in that work. Hahn et al. list a level at 5.454 MeV as \(J^\pi=2^-\) based on Coulomb-energy shifts and angular distributions in two transfer reactions, but mostly the fact that the analogs of all other \(^{18}\text{O}\) excited states in this energy region have all been identified except for this \(J^\pi=2^-\) state. The observation of a 5.457(8)-MeV state in this work confirms this assignment. The shell-model calculations also suggest that this state has a strong \(n+^{17}\text{O}\) spectroscopic factor with \(C^2S(d_{5/2})=0.23\) and \(C^2S(d_{3/2})=0.12\).

E. 6.3-MeV Peak

The second-most intense peak seen in Fig. 10 occurs at approximately 6.3 MeV with a width that is larger than the predicted experimental resolution for this energy. Assuming that the intrinsic widths of all states in this region as very small, then this peak must be a multiplet. Hahn et al. list three negative-parity levels in this energy region that could be excited in our reaction [9]: a \(J^\pi=3^-\), \(2^-\) doublet at \(E^*=6.286\) and 6.345 MeV and in addition the \(J^\pi=1^-\) level at \(E^*=6.15\) MeV that can contribute to the low-energy tail. For this latter state, He et al. determine that the excited-state and ground-state decay branches are approximately equal [41], while Blackmon et al. measured \(\Gamma_{J=1/2^+}/\Gamma_{tot} = 0.73\) [34]. In addition our shell-model calculations also give a large branching ratio, \(\Gamma_{J=1/2^+}/\Gamma_{tot} = 0.65\). With such values, any ground-state-decay yield that makes a significant contribution to the low-energy side of the 6.3-MeV peak will produce too much yield in the \(E^*\) region associated with excited-state decay. Thus we conclude that this level does not contribute significantly to the observed peak.

The fit shown in Fig. 10 was obtained as the sum of two peaks of similar intensities with energies of 6.279(36) and 6.369(36) MeV which are consistent with the energies of the aforementioned doublet listed by Hahn et al. The spin order of this doublet is not well determined, but the preference of Hahn et al. is the opposite order to that for the analog states in \(^{18}\text{O}\) (see Fig. 9). In Table III we list only the total cross section and the average branching ratio for these two states.

F. Decay Angular Distributions

In our Monte Carlo simulations (App. A) used in the fitting of the excitation spectrum for \(|\cos \theta|<0.2\), we have assumed that the decay of the \(^{18}\text{Ne}\) fragments is isotropic in space. However for these transfer reactions one should consider the possibility that the spin vectors of the \(^{18}\text{Ne}\) states have a strong alignment perpendicular to the reaction plane leading to deviations from isotropic emission. As such, the extrapolation from \(|\cos \theta|<0.2\) region will be incorrect leading to errors in the extracted cross sections and branching ratios presented in Table III.

The best state to look for such an effect is the dominant 5.135-MeV state where the statistics are large and the background is small apart from a \(\sim 10\%\) contribution from the neighboring 5.457-MeV state which cannot be separated from the dominant peak at larger \(|\cos \theta|\) values due to the degraded resolution. The efficiency-corrected \(\cos \theta\) distribution is plotted as the data points in Fig. 12. This distribution is largely isotropic apart from an enhancement at \(\cos \theta\sim 1\). As the distribution should be symmetric about \(\cos \theta=0\), this enhancement cannot be real and may be associated with the background.

While a similar analysis is not possible for the other states due to statistical and background issues, we find that simulations of \(p_{3/2}\) decay of aligned \((M=0\) projection on beam axis\) \(^{18}\text{Ne}\) fragments to \(^{17}\text{F}\) \(_{g.s.}\) can only lead to, at most, a reduction of 30\% in yield due to the extrapolation to larger \(|\cos \theta|\) values. On the other hand in the decay to the excited state of \(^{17}\text{F}\), we find instead enhancements in the yield due to this extrapolation of up to a factor of 2 for \(p_{3/2}\) and \(f_{7/2}\) decays. If there is significant alignment, then our limits to the branching ratios in Table III obtained from the isotropic simulations will be too small for \(J \neq 0\). However based in result in Fig. 12, we do not expect this to be significant.
TABLE IV. Fitted mean excitation energies $E^*$, intrinsic widths $\Gamma$, and cross sections of states obtained from fitting the $^{18}$Ne$\to\alpha+^{11}$O decay spectrum in Fig. 14 and the $^{18}$Ne$\to 2p + \alpha + ^{12}$C decay spectrum in Fig. 15(a).

| $E^*$ [MeV] | channel | $\Gamma$ [keV] | $\sigma_{\text{peak}}$ [$\mu$b] |
|------------|---------|---------------|-----------------|
| 9.111 (25) | $\alpha + ^{14}$O | $< 60^a$ | 52(5) |
| 11.584 (64) | $\alpha + ^{14}$O | $< 650^a$ | $\sim 18$ |
| 16.794(29) | 2$p + \alpha + ^{12}$C | 328(68) | 182(11) |

$^a$ 1$\sigma$ limit

G. Branching ratios

The extracted limits to the branching ratios to the first excited state of $^{17}$F are listed in Table III and compared to values from our shell-model calculations. Some of these cases have already been discussed in the previous sections. Apart from the 4.594-MeV $J^z=0^+_3$ state, our maximum limits are all much larger than, and thus consistent with, the theoretical values. The only other negative-parity state which is expected to have a significant branching ratio, the 6.150 MeV $J^z=1^+_2$ level [34, 41], was not resolved in this work but may contributed to the enhanced yield of the $\gamma$-ray gated yield in Fig. 11(b) between the 5.349 and 6.3-MeV peaks.

H. Other exit channels

Apart from the $p + ^{17}$F exit channel, we have also observed three peaks in the $\alpha + ^{14}$O and 2$p + \alpha + ^{12}$C invariant-mass distributions which correspond to higher-lying excited states. The extracted level information is listed in Table IV and the decay of the states are illustrated in the level diagram in Fig. 13. No evidence of these levels has been observed in other decay channels, though the $p + ^{17}$F decay channel in particular will have low efficiency and poor resolution so our sensitivity is significantly reduced.

The excitation-energy distribution from the $\alpha + ^{14}$O channel is shown in Fig. 14. A rather narrow level ($\Gamma < 60$ keV) is observed at 9.111(25) MeV and a higher-energy peak is also present at 11.58(64) MeV. The lower-energy peak was not observed in an $\alpha + ^{14}$O elastic scattering experiment, where a $E^*$=9.2 MeV level was found, but its width is much larger ($\Gamma$=300 keV) [42]. The presence of the wider peak at almost the same energy may have reduced their sensitivity to the level we observed, but on the other hand with its small decay width, it may not have a strong $\alpha$-cluster structure and thus was not strongly excited in the $\alpha$-scattering experiment.

For highly-fragmented decay channels, it can be difficult to determine the decay path as there are many possible intermediate states and it become especially difficult if there are multiple decay paths as is the case for the peak in 2$p + \alpha + ^{12}$C channel. The invariant-mass spectrum for this channel, shown as the black circular data points in Fig. 15(a), contains a peak at 16.794(20) MeV. Due to the low statistics, no transverse gate has been applied for this channel. After selecting events in this peak [gate G18 in Fig. 15(a)], the excitation-energy spectra of the various possible intermediate states are plotted in Figs. 15(b) to 15(e) as the magenta triangular data points. As there are two possible protons to construct the potential $^{17}$F$\to p + \alpha + ^{12}$C and $^{13}$N$\to p + ^{12}$C intermediate states, we have determined the excitation energy using each of these protons in turn, i.e., these spectra were incremented twice for each event. For comparison, the arrows show the locations of the energy levels listed in the ENSDF data base [18]. Of the possible intermediate states, one stands out very clearly, the $1/2^+_1$, first excited state of $^{13}$N at $E^*$=2.365 in Fig. 15(e). To confirm this state is associated with the peak and not the
spectrum is about half of the ungated version if smooth in Fig. 15(a). The fitted yield in this new gated $^{18}\text{Ne}$ spectrum is about half of the ungated version if smooth in Fig. 15(a). The fitted yield in this new gated $^{18}\text{Ne}$ spectrum is about half of the ungated version if smooth in Fig. 15(a).

Let us concentrate of the decay pathway though the $J^\pi=1/2^+_1$, $^{13}\text{N}$ state first. If the $^{18}\text{Ne}$ state decays via a series of sequential decay steps, then in order to pass through the $^{13}\text{N}$ intermediate state, it must first decay to a $^{17}\text{F}$ or $^{14}\text{O}$ intermediate state. See the level schemes of these and other nuclei of interest in Fig. 13. To search for such states, we have further applied the G13 gate on the $^{17}\text{F}$ and $^{14}\text{O}$ excitation-energy spectra in Figs. 15(b) and 15(d) (red square data points). For the $^{17}\text{F}$ case, this gated yield is peaked around the energy of the known isobaric analog state (IAS) ($T=3/2$, $J^\pi=1/2^-$, $\Gamma=0.18$ keV) at $E^*=11.192$ MeV. The solid curve through these data points is a simulation of the detector response of this narrow state which reproduces its shape very well. Thus we conclude that this decay pathway is described by an initial proton decay to the $^{17}\text{F}_{\text{IAS}}$ which subsequently $\alpha$ decays to the $^{13}\text{N}$ state, which then proton decays to the ground state of $^{12}\text{C}$.

Given that this new $^{18}\text{Ne}$ state has a strong proton-decay branch to a high-$T$ state in $^{17}\text{F}$, it is quite probable that this new $^{18}\text{Ne}$ state is itself high $T$, i.e. $T=2$ in this case. Its excitation energy is appropriate for it to be an analog of a low-lying state in $^{18}\text{Na}$ (see later). Now if the second decay pathways involves a second decay branch of $^{18}\text{Ne}$, then to conserve isospin and energy, it should be a proton decay to the next analog state in $^{17}\text{F}$ at $E^*=12.550$ MeV. However, the latter decay is only $\sim$300 keV above threshold and will be suppressed by the small Coulomb penetration factor. In addition we do not see any indication of significant yield for this intermediate state in Fig. 15(b). Thus it is more likely that the second decay pathway involves a second decay branch of $^{17}\text{F}_{\text{IAS}}$. Note that $^{17}\text{F}_{\text{IAS}}$ itself, has no isospin-allowed particle decay modes which are above threshold, so we expect all of its decay branches to violate isospin symmetry.

We have dismissed the possibility that this second decay branch of $^{17}\text{F}_{\text{IAS}}$ is an $\alpha$-decay to higher-lying states of $^{13}\text{N}$ as there is no indication of any significant yield for such states in Fig. 15(c). Thus we restrict ourselves to a proton decay branch to either the $1^+_2$, $2^+_2$, or $4^+_2$ excited state in $^{16}\text{O}$. As such, we have simulated the decay of the $^{18}\text{Ne}$ state as an initial proton decay to $^{17}\text{F}_{\text{IAS}}$, followed by either another proton decay to one of these three $^{16}\text{O}$ intermediate states or alternatively an $\alpha$ decay to the $J^\pi=1/2^+_1$, $^{13}\text{N}$ intermediate state, with these latter intermediate states subsequently decaying to give us the $2p+\alpha+^{12}\text{C}$ exit channel. For each possible $^{16}\text{O}$ intermediate, the $p/\alpha$ branching ratio of $^{17}\text{F}_{\text{IAS}}$ was adjusted to best fit both the gated and ungated $^{18}\text{Ne}$ excitation-energy spectra in Fig. 15(a).

Note that $^{18}\text{Ne}$ has a strong proton-decay branch to the $1^+_2$ $^{16}\text{O}$ state, which then proton decays to the ground state of $^{14}\text{O}$. Indeed the fitted intrinsic width of $^{14}\text{O}$ is roughly a 30% background under the ungated $^{18}\text{Ne}$ peak in Fig. 15(a), the predicted distributions should not account for the total experimental yield in these panels. Thus consistency with the experiment data occurs if these simulated distributions do not pass above the data points. In this regard, the simulation for the $4^+_2$ $^{16}\text{O}$ intermediate state (green dashed curves) must be clearly be discarded. The simulation for the $2^+_2$ state (solid blue curves) is consistent with all distributions, while for the $2^+_2$ state (magenta dotted curve), the curve in Fig. 15(c) overshoots the experiments distribution by roughly 30-50% at its peak. Thus the second decay branch of $^{17}\text{F}_{\text{IAS}}$ involves proton decay to the $1^+_2$ $^{16}\text{O}$ state, but we cannot rule out in addition some smaller branch to the $2^+_2$ state and smaller yields for other decay paths. The fitted branching ratio of $^{17}\text{F}_{\text{IAS}}$ is $\Gamma_\alpha/\Gamma_p=0.65(9)$.

For an isospin multiplet, the mass excesses are expected to be well described by the isospin multiplet mass equation (IMME) [43]

$$M(T, T_Z) = a + bT_Z + cT_Z^2,$$

where $a$, $b$, and $c$ are constants. Except for a few cases, deviations from the quadratic $T_Z$ dependence are quite small. For the $A=18$, $T=2$ multiplets, only a few cases have at least three members known to constrain the three constants. In Fig. 16 we show quadratic IMME fits to the $J^\pi=2^+_1$ and $3^+_1$ members using mass excesses determined for $^{18}\text{Na}$ from [44]. For the $^{18}\text{O}$, and $^{16}\text{O}$ cases, we have used ground-state masses from the AME2016 tabulation [45] and excitation energies from [18, 46]. For comparison, the location of the new $^{18}\text{Ne}$ peak is shown as the blue square data point. It is closer to the fitted curve for $J^\pi=3^+_1$ levels, but 140(34) keV below. Generally we expect deviation from the IMME to be much smaller than this, so probably the observed peak in not purely from this level in $^{18}\text{Ne}$. Indeed the fitted intrinsic width of this state is relatively large, $\Gamma=328(68)$ keV, significantly larger than that of the $3^-$ state in $^{18}\text{Na}$ ($\Gamma=42(10)$ keV [44]). In $^{18}\text{Na}$, a very wide $\Gamma=900(100)$ keV was observed $\sim$50 keV below this $3^-$ state while a very narrow state ($\Gamma<1$ keV) was observed $\sim$100 keV below. It is possible that the observed peak is a multiplet with contributions from a number of $^{18}\text{Ne}$ levels in this energy region.

VI. $^{10}\text{C}$ Excited States

The ground state of $^9\text{C}$ is $J^\pi=3/2^-$. This is mostly a $p$-shell nucleus and the transfer of another neutron into the $p$-shell will populate $J^\pi=0^+, 1^+, 2^+, 3^+$ states in $^{10}\text{C}$. At higher excitation energies, negative-parity levels can be populated by adding the extra neutron to the $sd$ shell.
The ground and first excited states of $^{10}$C are particle bound and at $E^*=3.73$ MeV, the $2p+2\alpha$ decay channel opens up. This is the only available final exit channel for particle decay until $E^*=15.0$ MeV when the $^3$He$+^7$Be channel is available. A number of invariant-mass studies have investigated $2p+2\alpha$ exit channels produced in the inelastic excitation of the $^{10}$C beam [47–50]. Numerous states were observed whose decay are initiated by either by $p$, $\alpha$, or direct two-proton emission. In all the cases, the remnant nucleus undergoes further particle emission producing the observed exit channel. Many of the states are expected to have large $\alpha$-particle cluster structure like that of the ground-state configuration.

The $2p+2\alpha$ and $^3$He$+^7$Be excitation-energy spectra obtained in the neutron pick reactions of this work are displayed in the Fig. 17. The results for the $2p+2\alpha$ channel in Fig. 17(a) are consistent with that obtained at the same bombarding energy and target in Ref. [3] and is dominated by a state at $E^*=9.69$ MeV. This previous work also identified smaller peaks at $E^*=10.48(20)$ and $11.44(20)$ MeV as indicated by the arrows in Fig. 17(a). These secondary peaks are not so obvious in the present data, but our statistics are lower making them more difficult to discern if present. In addition the location of the $2p+2\alpha$ peaks observed in the $^{10}$C inelastic excitation studies are also indicated by the arrows in Fig. 17(a); a doublet at $E^*=5.25$ MeV, a triplet $E^*\sim6.56$ MeV, and a broader peak at $E^*=8.4(1)$ MeV. Such peaks are either significantly suppressed or not observed in this work, consistent with their presumed strong cluster structure. The stronger yield of the 9.69-MeV state indicates it has a more shell-model-like structure.

In Ref. [3], the 9.69-MeV state was shown to have $\alpha+^6$Be$_{g.s.}$ and $p+^{3}$B$_{2.34MeV}$ decay branches in addition.
to a more unusual branch where the $\alpha$-\alpha relative energy is consistent with the $J^\pi=2^+$ $^8$Be resonance, all the $p$-$\alpha$ relative energies are consistent with $^5$Li$_{g.s.}$ resonances, and the $p$-$p$ relative energy is small reminiscent of a di-proton final-state interaction. We presume this state is produced from neutron transfer to the $p$-shell and is thus either $J=0^+$, $1^+$, $2^+$, or $3^+$. Indeed the emission of a $p$-shell proton should leave the system in a negative-parity state consistent with the significant proton decay branch (17%) to the $J^\pi=5/2^-$, $E^\pi=2.34$ MeV state of $^9$B [3].

Based on the known levels in the mirror nucleus $^{10}$Be, the most likely analog is the 9.64-MeV, $J^\pi=2^+$ state. Note that we are using the excitation energy from Refs. [50–52] rather than the compiled value of $E^*=9.560$ MeV [18]. The width of our $^{10}$C peak ($\Gamma = 490$ keV [3]) is of similar magnitude but larger than the value of $\Gamma = 141$ keV [18] for the $J=2^+$ level in the mirror system which is not unreasonable as the proton-rich member of a mirror pair of levels in the continuum generally has a larger width.

The $^3$He$^+7$Be excitation-energy-energy spectrum for transverse decay, shown in Fig. 17(b), is dominated by a single peak at $E^* \sim 17$ MeV. This peak is associated with decay to the ground state of $^7$Be as no enhancement of the 429-keV $\gamma$ rays associated with the first excited state of $^7$Be was observed in CAESAR. The solid red curve shows a fit to the experimental data with a Beit-Wigner-shaped peak (modified by the detector resolution) and the blue dashed curve is the fitted background contribution. Fitted parameters are listed in Table V. The fitted peak energy is $E^*=17.17(4)$ MeV with an intrinsic width consistent with zero [$\Gamma = 57(256)$ keV]. There are no known states in the mirror system $^{16}$Be close to this energy so no assignment to analog states can be made at present.

In Fig. 17(a) there is no indication of any decay branch of this state to the $2p+2\alpha$ channel (see dotted line for the

FIG. 16. Known mass excesses of the $J^\pi=2^-$ and $3^+$, $A=8$, $T=2$ multiplets are plotted as the circular data points. The curves are fits with the IMME [Eq. (3)]. The location of the $^{18}$Ne→$2p+\alpha+^{12}$C state is shown by the blue square.

Table V. Fitted mean excitation energies $E^*$, intrinsic widths $\Gamma$, and cross sections obtained for the $^{10}$C levels observed in Fig. 17.

| $E^*$ (MeV) | Channel | $\Gamma$ (keV) | $\sigma_{\text{peak}}$ (µb) |
|------------|---------|---------------|-----------------|
| 9.69$^a$   | $2p+2\alpha$ | 490$^a$ | 369(73) |
| 17.17(4)   | $^3$He$^+7$Be | 221(117) | 6.9(13) |

$^a$ from Ref. [3]

 energies of the fitted level). However at such large decay energies, the detection efficiency of the $2p+2\alpha$ channel is very small as many of the decay fragments are emitted outside the angular acceptance of the HiRA. The simulated efficiency of detecting all four particles is a factor of 6 smaller than the $^3$He$^+7$Be result with the transverse decay cut ($|\cos \theta| < 0.2$). Combined with a larger simulated experimental resolution (FWHM 700 keV), it is possible that this peak contributes to the observed mostly-flat background at large energies in Fig. 17(a) and thus we cannot rule out that this state also has a non-negligible branching ratios to the $2p+2\alpha$ channel.

VII. REACTION MECHANISM

One might imagine that these transfer reactions are very peripheral and the loosely-bound valence neutron in the $^9$Be target nucleus (separation energy of 1.66 MeV) is transferred to the projectile leaving a remnant $^8$Be nucleus is its ground or a low-lying excited state. However, the reactions are more complex than that. Information of the remnant target system can be gleaned from reconstructing its excitation energy using energy and momentum conservation from the initial beam momentum and final momenta of the projectile fragments measured in the experiment. By using the term “excitation energy” we do not wish to imply that the 8 remnant target nucleons are necessarily left in an excited state of $^8$Be. Rather this term is used to just give the energy of these nucleons in their center-of-mass frame above the $^8$Be ground-state energy.

The distribution of this energy is plotted in Fig. 18(a), as the data points, for the 9.69-MeV state of $^9$C [Fig. 17(a)]. For comparison, the solid curve shows the simulated result (App. A) for a single value of the target excitation energy ($E^*_{\text{target}}$=33 MeV). The large simulated width is predominantly a result of the uncertainty in the magnitude of the energy loss of the decay fragments in the target material. We have chosen the $2p+2\alpha$ exit channel for this demonstration, as the energy calibrations of the CsI(Tl) light output are well constrained for these particles and their energy loss in the target is relatively small. Although the simulations explain a significant fraction of the experimental width, the most striking feature is that there is no peak near zero excitation energy and the average is around 40 MeV. This
FIG. 17. Excitation-energy spectra obtained for (a) the $2p+2\alpha$ and (b) the $^3\text{He}+^7\text{Be}$ exit channels of $^{10}\text{C}$. For the four-body exit channel in (a), all detected $2p+2\alpha$ events are included, while in (b), only the transverse decays ($|\cos \theta| < 0.2$) are used in constructing the spectrum. A fit to the $^3\text{He}+^7\text{Be}$ data is shown as the solid red line in (b), where the individual Breit-Wigner peaks (modified by the detector resolution) are indicated by the dotted green curve. The dashed blue curve is an estimate of the background. The arrows in (a) show the location of peaks identified in Refs. [3, 50].

castes doubt on the presumption of the peripheral nature of these collisions.

For comparison in Fig. 18(b), we show the distribution of $^{9}\text{Be}$ target excitation energy associated with inelastic scattering of the $^{9}\text{C}$ projectile to its first excited state. The invariant-mass spectrum obtained from the decay of this state to the $p+^{9}\text{B}$ channel was presented in [7]. In this case there is a strong peak at $E_{\text{target}}^{*} \sim 0$ MeV and so the inelastic-excitation process has a strong peripheral component that appears to be lacking for the transfer reaction. We find similar results for the other states formed in the transfer reactions in this work. For example in Fig. 18(c), the excitation-energy distribution for the $^8\text{Be}$ remnant associated with the 19.262-MeV $^8\text{Be}_{g.s.}+^8\text{Be}_{g.s.}$ states (Fig. 6) is shown as the black circular data points. This peak sits on a significant background and we have used the adjacent low-excitation-energy region to estimated this contribution. The blue-square data points show this contribution after normalizing its magnitude to be consistent with background decomposition in Fig. 6. This background accounts for most of the yield at negative values of $E_{\text{target}}^{*}$. However at positive excitation energies, the distribution above the background is very broad extending up to $\sim 200$ MeV. This is much broader than the experimental resolution which is indicated by the solid curve which was generated from our simulations with $E_{\text{target}}^{*} = 100$ MeV.

The larger values of $E_{\text{target}}^{*}$ may be a consequence of the large momentum mismatch at the high bombarding energies of this work. For instance this mismatch will be reduced for less peripheral collisions where the transferred neutron can be placed more in the interior of the projectile. Of course such collisions may also lead to knockout of the projectile’s nucleons and other dissipative processes and the events we observed represent a balance between the likelihood of these processes and the difficulty of momentum matching in peripheral collisions.

In the study of neutron transfer reactions with a $^{22}\text{Mg}$
The knockout cross sections to the ground and first
suggested neutron knockout \cite{4, 6} and inelastic excitation
have studied. For our
the measured cross sections.
Born-approximation calculation was able to reproduce
result. Here the yields were found to be consistent with
$^{12}$ et al.
the reactions with the
well-defined excited states. In addition they inferred that
the target after the transfer were not both left in
reactions were not two-body in nature, i.e., the projec-
tile fragments, they also concluded that these transfer
longitudinal momentum distribution of the final projec-
tile and target after the transfer were not both left in
bound
$^{9}$Be target were too large to be explained by the pickup of the weakly-
bound $^{9}$Be valance neutron \cite{14}. From the measured
longitudinal momentum distribution of the final projec-
tile fragments, they also concluded that these transfer
reactions were not two body is nature, i.e., the projectile
and target after the transfer were not both left in
well-defined excited states. In addition they inferred that the reactions with the $^{9}$Be target were dominated by the pickup of one of the deeply-bound neutrons which would lead to $E^*_{\text{target}} > 20$ MeV. This is qualitatively consistent with our observations. Gade et al. also studied transfer reaction with a $^{12}$C target and found a very different result. Here the yields were found to be consistent with a two-body reaction mechanism and a coupled-channel-Born-approximation calculation was able to reproduce the measured cross sections.

Finally is it interesting to compare the yields for these transfer reaction to those for other types of reactions we have studied. For our $^{17}$Ne beam, we have also measured neutron knockout \cite{4, 6} and inelastic excitation \cite{7}. The knockout cross sections to the ground and first
excited states of $^{16}$Ne are 2.91(9) and 0.92(5) mb, re-
spectively, both greater than the largest transfer yield of
$0.813(18)$ mb for the 5.135-MeV state of $^{18}$Ne. The yield
for the inelastic excitation of the projectile to its second
excited state ($E^*=1.76$ MeV, $J^\pi=5/2^-$) is even larger at
8.8(2) mb.

For the $^{9}$C beam, the largest transfer cross section of
$369(73)$ µb is for the 9.69-MeV state in $^{10}$C. In com-
parison, the cross sections for other simple processes we
studied are much larger. The neutron knockout cross
section to the ground state of $^{8}$C \cite{3} is 3.8(3) mb, while
the proton knockout cross sections to the first, second, and
isobaric analog states of $^{8}$B \cite{5} are 12.0(20), 42.0(40),
and 1.2(1) mb, respectively. Finally the inelastic scat-
erring cross sections to first, second, and forth excited
states of $^{9}$C \cite{7} are 3.74(20), 5.91(40), and 4.12(40) mb,
respectively.

The cross sections for these neutron transfer reactions
are smaller than other reaction types, even smaller than those for neutron knockout reactions, which for such proton-rich beams are known to be suppressed relative to Eikonal-model predictions \cite{53}. However even in the present studies which were optimized for producing two-
proton emitters via such knockout reactions, the detected transfer yields were adequate to identify a number of
states. Partly this results from the fact that most of these states undergo two-body decay and thus have higher de-
tector efficiencies than the three-body and high-order de-
cays associated with the two-proton emitters.

FIG. 18. Spectra of the reconstructed excitation-energy of
the target nucleus after a transfer or inelastic-scattering re-
action. The experimental results are indicated by the data
points. The solid-red curves shows the results from the Monte
Carlo simulations with an single value of $E^*_{\text{target}}$ to indicate
the experimental resolution. In (c), the blue-squares show an estimate of the background contribution.

VIII. CONCLUSION

We have used invariant-mass spectroscopy with the
HiRA and CAESAR arrays to study excited states in the
continuum produced in neutron transfer reactions to fast
secondary beams of $^{9}$C, $^{15}$O, and $^{17}$Ne. With the thick
$^{9}$Be target, which was selected to produced adequate yields with the low beam rates, the experimental reso-
lution was found to be very sensitive to the orientation
of the decay axis of these states. For two-body decays in
particular, the best resolution was found for events
where the decay axis is perpendicular to the beam direc-
tion. Here the uncertainty associated with energy-losses
of the decay products in leaving the target material are
minimized. These transfer reactions were found to leave
the remnant target nucleons with large excitation ener-
gies. Futher studies are needed to understand this, but
at present this excludes the extraction of spectroscopic factors from comparisons with DWBA calculations.

With the $^{17}$Ne beam, we have confirmed the spin as-
signments made by Hahn et al. \cite{9} for a number of $^{18}$Ne
excited states. In addition we have found new excited states in $^{16}$O and $^{18}$Ne at high excitation energies. Some
of these decays are highly fragmented with up to four
particles in the continuum. This includes an exotic fis-
sion mechanism for $^{16}$O states resulting in two $^{8}$Be$_{g.s.}$
fragments. A newly-found high-$T$ state in $^{18}$Ne was ob-
served to decay to the isobaric analog state in $^{17}$F. The latter was also found to have isospin non-conserving $\alpha$ and proton decay branches. Finally a new excited state in the $^{10}$C was also found.

This work demonstrates the usefulness of invariant-mass spectroscopy in transfer reaction with fast fragmentation beams. Unfortunately, cross sections are typically much smaller than other simple reaction mechanisms such as knockout or inelastic excitation. However, as in the present work, transfer data can be obtained in concert with data from other reactions.

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Appendix A: Monte Carlo Simulations

The experimental resolution and detection efficiency were determined from Monte Carlo simulations of the reactions which incorporated the following effects.

1. The energy loss of the beam particle and decay fragments in the target material were taken from Ref. [16]. The reaction is assumed to occur randomly in depth within the limits of the physical target.

2. Small-angle scattering of the beam particle and decay fragments in the target material following Ref. [54].

3. The effect of a realistic beam spot size ($\sim 1$ cm diameter) and the known momentum acceptance of the secondary beam are included.

4. The angle resolution associated with the pixel-size of the Si strip $\Delta E$ detectors are included.

5. The energy resolution of the CsI(Tl) detectors are estimated based on our calibration beams.

6. The detection efficiency includes the loss due to nuclear reactions of the incident particles with the Cs and I nuclei in the $E$ detector [55, 56].

7. The intrinsic line shapes of resonances were taken to have a Breit-Wigner form with the centroid and width adjusted in the fits unless otherwise specified.

The Monte Carlo events produced by the simulation are analyzed in the same manner as the experimental data. The ingredients in the simulations were fine tuned by fitting known narrow resonances. For example, the $p+^{17}$F resolution was fine tuned by fitting the $2p+^{15}$O resonance peak associated with the decay of the second excited state of $^{17}$Ne as discussed in the [4, 6]. Both transverse and longitudinal decays are considered as these have sensitivities to different ingredients. For the fission of $^{16}$O states into two $^8$Be$_{g.s.}$ fragments producing a final exit channel of four $\alpha$ particles, three resonances were used for fine tuning. These are the $^8$Be$_{g.s.} \rightarrow 2\alpha$ resonance plus the $3\alpha$ resonances associated with the $^{12}$C second (Hoyle state) and third ($J^p=3^-$) excited states.

Input primary angular and velocity distributions of the parent fragments formed in the transfer reactions were adjusted so that reconstructed secondary distributions (obtained from the decay fragments after the effects of the detector acceptance and resolution are incorporated) match their experimental counterparts. For asymmetric exit channels like $p+^{17}$F, these is an uncertainty in extrapolating to zero degree as the detection efficiency vanishes here and this adds uncertainty to our final cross sections. However, as the $d\sigma/d\theta$ must vanish as one approaches zero degrees, this uncertainty is not large. We estimate this uncertainty is less than 15%. For the $^{16}$O fission channels, this zero degree region is sampled by the experimental events so a similar problem does not exist.

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