Inverse-kinematics one-neutron pickup with fast rare-isotope beams

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New measurements and reaction model calculations are reported for single neutron pickup reactions onto a fast 22Mg secondary beam at 84 MeV per nucleon. Measurements were made on both carbon and beryllium targets, having very different structures, allowing a first investigation of the likely nature of the pickup reaction mechanism. The measurements involve thick reaction targets and γ-ray spectroscopy of the projectile-like reaction residue for final-state resolution, that permit experiments with low incident beam rates compared to traditional low-energy transfer reactions. From measured longitudinal momentum distributions we show that the 12C(22Mg, 23Mg + γ)X reaction largely proceeds as a direct two-body reaction, the neutron transfer producing bound 11C target residues. The corresponding reaction on the 9Be target seems to largely leave the 9Be residual nucleus unbound at excitation energies high in the continuum. We discuss the possible use of such fast-beam one-neutron pickup reactions to track single-particle strength in exotic nuclei, and also their expected sensitivity to neutron high-ℓ (intruder) states which are often direct indicators of shell evolution and the disappearance of magic numbers in the exotic regime.

I. INTRODUCTION

The spectroscopy and ordering of nucleon single-particle levels along extended isotopic chains is of importance for understanding emerging and dissolving shell structures. One- and two-nucleon removal reactions from fast rare-isotope beams are making a significant contribution to such studies in some of the rarest isotopes. This information, in turn, allows an assessment of shell model effective interactions and of their predictions near both the weakly- and strongly-bound Fermi-surfaces in highly neutron-proton asymmetric nuclei. By their nature these nucleon removal reactions preferentially populate states in the heavy residual nuclei with a strong hole-like parentage upon the projectile ground state. For the spectroscopy of particle-like states, light-ion single-nucleon transfer reactions, such as the (d, p) reaction, are very often the reaction of choice. These reactions are best and most often carried out at relatively low incident energies such that linear and angular momentum matching and hence the reaction yields are optimal. The beam intensity, (thin) target, and detection system demands for such measurements, of final-state-resolved transfer cross section angular distributions in inverse kinematics, are however high and such studies remain impractical, currently, for many of the most exotic nuclei.

In this paper we consider test case measurements and associated direct reaction model calculations for reaction events in which a single neutron is picked up by a fast secondary beam of mass A. The measurements employ thick targets and γ-ray spectroscopy and thus take full advantage of fast beams produced by fragmentation; the resulting high luminosity allows for experiments with low incident beam rates. Related previous studies considered reactions involving the pickup of a strongly bound proton from a 9Be target. Here we discuss first measurements for a 22Mg beam of about 84 MeV per nucleon incident energy. An important aspect of the present analysis is that measurements are made using both carbon and beryllium reaction targets, with very different neutron structures. Two of our primary aims here are to investigate (a) the nature of the fast pickup reaction mechanism, and (b) the magnitudes of the measured and calculated pickup reaction yields. In doing so we hope to gain a first insight into the potential to use such reactions, in combination with γ-ray spectroscopy of the populated mass A+1 final states, to determine quantitative particle state spectroscopy information on exotic nuclei produced at energies of order 100 MeV per nucleon. Specifically, we aim to clarify if the reaction proceeds predominantly by a direct single-particle pickup mechanism and, if this is the case, to quantify the measured and calculated cross sections for transfers involving different orbital angular momenta ℓ. Such information will illustrate, for instance, the capability for future measure-
ments to identify high-ℓ neutron intruder components in the low energy spectra of the pickup residues. Since such high-ℓ intruder configurations are typically angular momentum mismatched, they are more weakly coupled and populated in lower energy (d, p) transfer reactions.

We make clear in advance that the fast nucleon pickup events considered here are not well-matched in either transferred linear or angular momentum, in the sense used in semi-classical model discussions of transfer reactions between heavy ions [7, 8]. We also make clear that the 23Mg residues in the present analysis, having a high first nucleon threshold, do not permit a detailed or quantitative spectroscopy in this case. Our aims here are more modest and were stated above. In addition, to help direct future experiments, we assess the effectiveness of our two light target choices: (a) 12C, that makes available four well-bound p3/2 neutrons with a ground-state separation energy of $S_n = 18.72$ MeV, and (b) 9Be, that offers one weakly-bound valence neutron of $S_n = 1.665$ MeV, while $S_{2n} > 20$ MeV, in providing a source of neutrons with sufficiently high momentum components to contribute strength to the pickup reaction yields. We will show that the measured and calculated pickup reaction yields and the 23Mg residue momentum distributions measured on the two targets help to provide such a clarification and guide to future studies.

II. EXPERIMENTAL DETAILS

The projectile beam of 22Mg was obtained by fragmentation of a 170-MeV per nucleon 24Mg primary beam provided by the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory (NSCL) on the campus of Michigan State University. The 9Be fragmentation target of 1904 mg/cm2 thickness was located at the midacceptance target position of the A1900 fragment separator [9]. An achronomic aluminum wedge degrader of 600-mg/cm2 thickness and slit systems were used to purify the beam. The momentum acceptance of the separator was restricted to $\Delta p/p = 0.14\%$. The resulting cocktail beam of $N = 10$ isotones contained 22Mg (74%), 21Na (24.5%) and 20Ne (1.5%).

Targets of 188-mg/cm2 thick 9Be and 149.4-mg/cm2 thick natC (vitreous Carbon with a density of $\rho = 1.54$ g/cm3, 98.9% enriched in 12C) were placed at the reaction target position of the S800 spectrograph [10] to induce the one-neutron pickup onto the 22Mg projectiles. The target position was surrounded by the high-resolution γ-ray detection system SeGA, an array of 32-fold segmented high-purity germanium detectors [11].

The high degree of segmentation allows for event-by-event Doppler reconstruction of the γ rays emitted by the projectile-like reaction residues in flight. The angle of the γ-ray emission entering the Doppler reconstruction is determined from the location of the segment that registered the largest energy deposition. The photopeak efficiency of the detector array was calibrated with standard sources and corrected in-beam for the Lorentz boost of the γ-ray distribution emitted by nuclei moving at $v/c > 0.35$.

Event-by-event particle identification was performed with the focal-plane detection system [12] of the large acceptance S800 spectrograph. The energy loss measured with the S800 ionization chamber and time-of-flight information taken between plastic scintillators, corrected for the angle and momentum of each ion, were used to unambiguously identify the projectile-like reaction residues exiting the target. The incoming projectiles were identified from their flight-time difference measured with plastic timing detectors. The particle-identification spectrum for 23Mg produced in 22Mg + 12C is shown in Fig. [1].

For each target, the inclusive cross section for the one-neutron pickup to all bound final states of 23Mg was determined from the yield of detected pickup residues divided by the number of incoming projectiles relative to the number density of the 9Be and 12C reaction targets, respectively. The γ-ray spectra observed in coincidence with 23Mg, event-by-event Doppler reconstructed, are displayed in Fig. [2]. Partial cross sections to individual final states were obtained from the efficiency-corrected full-energy peak areas relative to the number of pickup products and corrected for feeding. Unfortunately, the statistics were not sufficient to tag the final state of the 11C target nuclei in the laboratory-frame γ-ray spectra ($v/c \approx 0$).

Position information from the two cathode readout drift chambers (CRDCs) of the S800 focal-plane detection system together with trajectory reconstruction employing the optics code COSY [13] were used to reconstruct the longitudinal momentum distributions of the pickup residues on an event-by-event basis. Fig. shows for both the Be and the C targets the momentum dis-
distributions of the pickup product $^{23}$Mg together with the momentum profile of the $^{22}$Mg beam passing through the target essentially un-reacted. The width of the $^{22}$Mg momentum profile as measured in the spectrograph’s focal plane is dominated by the energy (momentum) straggling of the projectiles in the respective reaction target. The curves through the data points are to guide the eye and have been used in the case of the $^{23}$Mg distributions to determine acceptance corrections on the low-momentum side caused by a beam blocker in the S800 focal plane that was necessary to prevent the direct beam from entering the detection system.

If the neutron pickup reaction is strictly two-body, i.e., it involves only transfers between bound states of the target and the projectile and also leaves a bound target-like residue, then the intrinsic, reaction-mechanism-induced parallel momentum distribution of the heavy projectile-like residues, $d\sigma/dp_\parallel$, will be very narrow. The necessary formula is given by Eq. (1) of Ref. [2]. So, unlike knockout reaction measurements, the residue momentum distribution does not provide spectroscopic (orbital angular momentum) information, however, it carries a reaction mechanism diagnostic, as follows.

Following strict two-body transfers, the intrinsic $d\sigma/dp_\parallel$ momentum distribution is essentially $\delta$-function like in comparison to the incident beam momentum resolution $\Delta p/p \approx 0.14\%$ and the energy broadening due to passage through the target. Thus, the extent to which the measured $^{23}$Mg residue momentum distribution differs from that of the un-reacted $^{22}$Mg beam provides direct evidence for events that go beyond a two-body reaction model description. We note that this direct comparison of the measured $^{23}$Mg distributions from the carbon and beryllium targets with that of the un-reacted $^{22}$Mg, induced by both targets. The spectra demonstrate that essentially the entire final state distributions and yield are within the spectrograph’s angular acceptance.
III. REACTION MODEL CALCULATIONS

We consider the neutron-pickup reactions to be described by a post form, fully-finite-range, coupled channels Born approximation (CCBA) reaction analysis. The neutron pickup from the light target(s) is assumed to take place in a single step and we include transfers to $^{22}$Mg in its ground and first excited $2^+$ state. We carry out these CCBA calculations using the flexible direct reactions code FRESCO [15].

The (all-order) inelastically coupled $0^+$ and $2^+$ $^{22}$Mg core states and the single-step transfer channel paths included in our calculations are shown in Fig. 5. The $^{23}$Mg bound states populated by neutron capture onto the $^{22}$Mg($2^+$) core, which all involve a 1$d_{5/2}$ orbital, are represented by dashed lines. We note that the proton threshold in $^{23}$Mg is at $S_p = 7.58$ MeV, and thus only the strongest low-lying shell model states have been included in Fig. 5. The shell model also predicts fragmented sd-shell strength to states up to the proton threshold that will be quantified, approximately, later. The entrance and exit channel distorting optical model interactions used and our treatment of the $^{22}$Mg projectile excitation are also discussed later.

We first consider the possible implications of the light target nucleus structures on our reaction treatment. We note that our two-body CCBA reaction methodology assumes kinematics and dynamics in which the projectile and target in the initial and final states separate as two bound systems. The neutron is assumed transferred from bound states in the target to bound states in the projectile residue, the target residue remaining bound. For the carbon target case our expectation is that this two-body picture will be an excellent approximation (for either neutron or proton pickup). Here we make use of the $^{12}$C ($= ^{11}$C+n) structure information as was deduced for the corresponding neutron knockout reactions from $^{12}$C, as discussed in Ref. 10. The ground-state neutron separation energy is $S_n = 18.72$ MeV and neutron pickup will leave the $^{11}$C residue predominantly in its ground state (3/2$^-$) or the excited states at 2.000 (1/2$^-$) and 4.804 MeV (3/2$^-$). These three states lie well below the first $^{11}$C threshold of 8.69 MeV. Theoretically the shell-model spectroscopic factors to these three states, calculated with the Warburton and Brown p-shell (WBP) interaction [17], are $C^2S = 3.16$, 0.58, and 0.19 and are seen to essentially exhaust the four units of single particle strength expected. The very small remainder, of 0.07, is fragmented over numerous $^{11}$C states above 10 MeV in

![FIG. 4: Laboratory frame scattering-angle distribution, $d\sigma/d\theta_L$, of the heavy residues measured in the experiment for the carbon (upper panel) and the beryllium (lower panel) targets. For the carbon target a calculated laboratory frame angular distribution is also shown (dashed curve) for pickup to a single final state, the 0.451 MeV, 5/2$^+$ state (with $^{11}$C left in its 3/2$^-$ ground state). The latter curve has been scaled to the measurements to aid comparison of the shapes but does not take into account small folding effects due to the finite emittance of the incident beam and from angular straggling in the target. The spectra show that the distributions fit well into the elliptical angular acceptance of the S800 spectrograph ($\pm 5^\circ \times \pm 3.5^\circ$) in agreement with the calculations.](image)

![FIG. 5: (Color online) Schematic of the CCBA channel-coupling scheme used for the $^{22}$Mg($^{12}$C,$^{11}$C)$^{23}$Mg($J^+$) and $^{22}$Mg($^{9}$Be,$^{8}$Be$^*$)$^{23}$Mg($J^+$) neutron pickup reactions. The solid lines (from $^{22}$Mg to $^{23}$Mg) represent one-step single particle transfers to the final states indicated. The dashed lines show two-step pathways to $^{23}$Mg states, by neutron capture onto the $^{22}$Mg($2^+$) core. All of these involve a 1$d_{5/2}$ neutron orbital.](image)
excitation. These WBP interaction spectroscopic factors agree well with other p-shell shell model calculations and thus this description of the $^{12}$C target is robust.

We also take from Ref. [16] the $^{11}$C+n Woods-Saxon binding potential geometry used to calculate these p-shell neutron overlaps. These have radius and diffuseness parameters of 1.310 fm and 0.55 fm, respectively. A $^{11}$C ($^{12}$C) root mean squared (rms) matter radius of 2.12 (2.32) fm was assumed for the calculation of the $^{11}$C+$^{23}$Mg ($^{12}$C+$^{23}$Mg) distorting potentials, as described below.

For the $^{9}$Be target the situation is significantly more complex. The configurations of the single weakly-bound valence neutron, with $S_n=1.665$ MeV, relative to the unbound (but near the two-α particle threshold) $^{8}$Be 0$^+$ and 2$^+$ states have been studied in some detail. The associated neutron overlaps and their spectroscopic factors from the variational Monte Carlo (VMC) wave functions of Wiringa et al. [18,19] and from extended microscopic cluster model wave functions, e.g. Arai et al. [20], are in rather close agreement. In both cases the [0$^+_1 \otimes p_{3/2}/3/2$] and [2$^+_1 \otimes p_{3/2}/3/2$] configurations are completely dominant. The cluster model (VMC) spectroscopic factors for these two configurations are 0.553 (0.591) and 0.514 (0.583), respectively. In the following we use the numerical $^{8}$Be 0$^+$ and 2$^+$ core state overlaps from Arai et al. [21] (as shown in Fig. 4(a) of Ref. [20]).

For convenience, these overlaps were fitted to single-particle wave functions calculated in Woods-Saxon potential wells, with separation energies of 1.665 and 4.695 MeV. The fitted (reduced radius, diffuseness) spin-orbit strength parameters were (1.09 fm, 0.59 fm) 6.0 MeV and (1.09 fm, 0.75 fm) 6.0 MeV. As will be discussed further, the amplitudes for valence neutron pickup will leave the target-like residues unbound/resonant (though only very weakly so). However, if the reaction proceeds by the pickup of a more strongly bound neutron (from the $^{8}$Be core) the resulting target residues will be left at high excitation in the continuum: this core state single-particle strength being in the vicinity of 15 MeV of excitation in $^{8}$Be$^+$. We noted already the qualitative difference between the measured momentum distributions of the $^{23}$Mg residues from reactions on the beryllium and carbon targets. These, and the cross sections presented below indicate that such core neutron pickup events are dominant in the case of the $^{9}$Be target and hence that our two-body dynamical model is not appropriate for a quantitative discussion of fast pickup reaction yields in this case.

Concentrating first on the $^{12}$C case, the pickup reaction is computed as $^{22}$Mg($^{12}$C,$^{11}$C($I^\pi$)$^{23}$Mg($J^\pi$) leading to the $I^\pi = 3/2^-$, 1/2$^-$ and 3/2$^+$ states of $^{11}$C at 84 MeV per nucleon incident energy. The (absorptive) nuclear optical interactions were calculated, as is done in the fast nucleon knockout reaction studies, by double folding the neutron and proton densities of $^{22}$Mg ($^{23}$Mg), obtained from spherical Skyrme (SkX interaction) Hartree-Fock (HF) calculations [22], and of $^{12}$C ($^{11}$C), assumed a Gaussian with rms radius given earlier, with an effective nucleon-nucleon (NN) interaction [23]. The $^{22}$Mg was allowed to inelastically excite, Fig. 5, enabled by deforming the entrance channel nuclear distorting potential with a deformation length of $\delta_2 = 1.95$ fm. This corresponds to an assumed mass $\beta_2$ value of 0.58, consistent with the charge $\beta_2$ of 0.58(11) from Ref. [24]. The binding geometry and spectroscopic factors of the $^{11}$C+n overlaps were already detailed above.

The required neutron-projectile bound states/overlaps $^{22}$Mg($0^+, 2^+ \otimes n_f/j_f$) and their spectroscopic amplitudes were taken from full sd-shell-model calculations that use the recently re-derived USBd, Universal sd-shell Hamiltonian of Brown and Richter [23]. As is indicated in Fig. 5 there are interfering paths for population of the $^{23}$Mg(3/2$^+$) ground state, via the [0$^+ \otimes 1d_{3/2}$] and [2$^+ \otimes 1d_{5/2}$] transfers. Both of these paths are weak in the present case resulting in a small predicted $^{23}$Mg ground state cross section. The first excited 5/2$^+$, 451 keV state is also shown to proceed by both direct and indirect, 2$^+$ state, paths. However, this calculated [2$^+ \otimes 1d_{3/2}$] USBd spectroscopic factor is 0.005, so this (negligible) two-step path is not considered further. The state at 2.715 MeV, shown in the literature as 9/2$^+$, (5/2$^+$), is assumed in our calculations to be a 9/2$^+$ state, and can be associated with a large amplitude [2$^+ \otimes 1d_{5/2}$]9/2 core-coupled shell model state at 2.762 MeV. There is no shell model candidate for a 5/2$^+$ state near this energy.

The USBd shell model spectroscopic factors $C_2S$ are collected in Tables I and II. The associated single-particle states were calculated in real Woods-Saxon potential wells, all with diffuseness parameter $a_0 = 0.7$ fm and a spin-orbit interaction of strength 6 MeV. The reduced radius parameters $r_0$ of these potentials were adjusted to reproduce the rms radius of each single-particle orbital, as given by the same Hartree Fock calculations as used to calculate the projectile densities, as has been discussed in detail elsewhere [26]. These $r_0$ were 1.284, 1.315 and 1.134 fm for the $1d_{3/2}$, $1d_{5/2}$ and $2s_{1/2}$ orbitals, respectively. These overlap functions were calculated using their physical separation energies, computed from the ground state separation energy, $S_n = 13.15$ MeV and the excitation energies. The theoretical reaction yields for the carbon target are collected in Table I. These are shown summed with respect to the three $^{11}$C final states and which are dominated, because of the large spectroscopic factor, by the ground state contribution. The cross sections are computed by integrating the calculated center-of-mass frame differential cross sections for angles $\theta_{cm} < 40$ degrees. At this upper angle limit the cross sections have fallen to $10^{-9}$ of their values at forward angles.

Calculations in the $^{9}$Be target case were identical as far as the projectile-like system is concerned. Regarding the target, the neutron pickup was computed as due only to the weakly bound valence neutron, i.e. $^{22}$Mg($^{9}$Be,$^{9}$Be($0^+, 2^+ \otimes ^{23}$Mg($J^\pi$)). The summed spectroscopic strength to these two $^{9}$Be final states is of order
unity. The nuclear distorting interactions were calculated assuming Gaussian $^9$Be and $^8$Be matter densities both with rms radius of 2.36 fm. The $^{22}$Mg deformation was treated as for the carbon target case. The binding geometry and spectroscopic factors of the $^8$Be+n overlaps were detailed above, taken from the model of Arai et al. [20]. The theoretical reaction yields are collected in Table I where they are summed with respect to the two $^8$Be final states.

**IV. RESULTS AND DISCUSSION**

The $^{12}$C($^{22}$Mg, $^{23}$Mg + $\gamma$)X one-neutron pickup reaction was performed at 84.7 MeV per nucleon mid-target energy. The longitudinal momentum distribution of the $^{23}$Mg residues, reconstructed in the focal plane of the S800 spectrograph [see Fig. 2 (top)], was cut by the spectrograph’s beam blocker; necessary to stop the direct $^{22}$Mg beam passing through the target. A 5% correction for the missing counts was applied to the cross section. The inclusive cross section, including the acceptance correction, amounts to $\sigma_{inc} = 2.40(19)$ mb. A 6% systematic uncertainty, attributed to fluctuations in the incoming beam composition, was added in quadrature to the statistical uncertainty. From the $\gamma$-ray spectra taken in coincidence with the $^{23}$Mg reaction products, the partial cross sections for the population of the $5/2^+$, $7/2^+$, $1/2^+$ and the proposed $9/2^+$, $5/2^+$ level at 451, 2052, 2359 and 2715 keV, respectively, were obtained from the intensity of the observed $\gamma$-ray transitions and the known feeding patterns. Known transitions that were not observed in the present experiment due to limited statistics or $\gamma$-ray detection efficiency, for example the 2359 keV ground-state transition of the first $1/2^+$ state, are included in our partial cross sections by using the reported branching ratios in the literature [14]. The partial cross section for the $3/2^+$ ground state was derived from the inclusive cross section by subtraction of all observed feeders. The possible population of the $(3/2, 5/2)^+$ state at 2.9 MeV is included in the uncertainty. We stress that, due to possible unobserved feeding by higher energy $\gamma$-ray transitions, the ground state cross section, in particular, should be considered an upper limit. The measured cross sections are summarized in Table II where they are compared to calculations.

The results for the calculation of the carbon-induced reaction are expected to be reliable, quantitatively. The momentum distribution comparison made in Fig. 3 provides first evidence that the reaction proceeds as a direct neutron transfer reaction producing bound $^{11}$C residues. The calculated cross sections track the values and trends of the measurements, reasonably accurately, the exception being the larger experimental yield recorded against the ground state transition (i.e. all reaction events without an identifiable $\gamma$ ray). As was stated earlier, the present $^{23}$Mg final state case is very challenging, with the proton decay threshold only at 7.58 MeV. As will be seen from Table II the USDB shell model calculation predicts a state with appreciable $[0^+ \otimes 1d_{5/2}]$ strength near a known $(5/2, 3/2)^+$ state at 2.908 MeV with a calculated cross section of 0.33 mb. This state was not clearly identified in the current experiment; however, assuming that the peak structure in the $\gamma$-ray spectra at 2900 keV is the ground-state transition of this state, the partial cross section for its population is estimated to be around 0.2 mb.

**TABLE I:** Experimental cross sections are compared to the CCBA reaction and shell-model calculations for the fast single-neutron pickup reactions $^{22}$Mg($^{12}$C, $^{11}$C($^n$))$^{23}$Mg($J^+$) at 84 MeV per nucleon. The theoretical cross section $\sigma^{th}$ is inclusive with respect to the population of the $I^+ = 3/2^−$, $1/2^−$ and $3/2^+$ states of the $^{11}$C target residue. The spectroscopic amplitudes of the interfering $[0^+ \otimes 1d_{3/2}]$ and $[2^+ \otimes 1d_{5/2}]$ ground state paths have the same sign.

| $J^+$ | $E$ (keV) | $\sigma_f$ (mb) | Configuration | $C^2S$ | $\sigma^{th}$ (mb) |
|------|---------|----------------|-------------|-------|------------------|
| $3/2^+$ | 0.0 | $\leq 0.77^{+0.09}_{-0.13}$ | $[0^+ \otimes 1d_{3/2}]$ | 0.054 | 0.083 |
| $5/2^+$ | 451 | $1.27(14)$ | $[0^+ \otimes 1d_{5/2}]$ | 0.410 | 1.448 |
| $7/2^+$ | 2051 | $0.18(5)$ | $[2^+ \otimes 1d_{5/2}]$ | 0.574 | 0.054 |
| $1/2^+$ | 2359 | $0.08(5)$ | $[0^+ \otimes 2s_{1/2}]$ | 0.242 | 0.010 |
| $9/2^+$ | 2715 | $0.10(5)$ | $[2^+ \otimes 1d_{5/2}]$ | 0.366 | 0.096 |
| $3/2^+$ | 2908 | — | $[0^+ \otimes 1d_{3/2}]$ | 0.238 | 0.326 |

inclusive cross section: 2.40(19) mb

**TABLE II:** Experimental cross sections are compared to the CCBA reaction and shell-model calculations for the fast single-neutron pickup reactions $^{22}$Mg($^8$Be,$^8$Be($^n$))$^{23}$Mg($J^+$) at 84 MeV per nucleon. The theoretical cross section $\sigma^{th}$ is inclusive with respect to the population of the $I^+ = 0^+$ and $2^+$ states of the $^8$Be target residue. The spectroscopic amplitudes of the interfering $[0^+ \otimes 1d_{3/2}]$ and $[2^+ \otimes 1d_{5/2}]$ ground state paths have the same sign.

| $J^+$ | $E$ (keV) | $\sigma_f$ (mb) | Configuration | $C^2S$ | $\sigma^{th}$ (mb) |
|------|---------|----------------|-------------|-------|------------------|
| $3/2^+$ | 0.0 | $\leq 0.86^{+0.08}_{-0.11}$ | $[0^+ \otimes 1d_{3/2}]$ | 0.054 | 0.010 |
| $5/2^+$ | 451 | $1.32(12)$ | $[0^+ \otimes 1d_{5/2}]$ | 0.410 | 0.206 |
| $7/2^+$ | 2051 | $0.15(4)$ | $[2^+ \otimes 1d_{5/2}]$ | 0.574 | 0.006 |
| $1/2^+$ | 2359 | $0.13(4)$ | $[0^+ \otimes 2s_{1/2}]$ | 0.242 | 0.003 |
| $9/2^+$ | 2715 | $0.13(4)$ | $[2^+ \otimes 1d_{5/2}]$ | 0.366 | 0.010 |
| $3/2^+$ | 2908 | — | $[0^+ \otimes 1d_{3/2}]$ | 0.238 | 0.037 |

inclusive cross section: 2.58(16) mb
Similarly, the shell model predicts a summed $[0^+ \otimes 1d_{5/2}]$ strength of 0.64 to final states up to 8 MeV in excitation in $^{23}\text{Mg}$. Only 0.41 of this strength has been accounted for in the 451 keV $5/2^+$ state, that is responsible for a calculated cross section of 1.45 mb. It is likely therefore that there is population of fragmented $d$-wave states with a summed direct reaction cross sections yield near to that recorded against the ground state, 0.77$^{+0.09}_{-0.13}$ mb. This value should thus be considered as an upper limit and an estimate of these direct populations of unobserved fragmented states and that decay by energetic $\gamma$ rays. In the present case, in addition to the $sd$-shell model states discussed, there may also be unobserved contributions from bound $f_{7/2}$ fragments at higher excitation energy. The present experiment and data set shows no evidence for and does not allow any meaningful discussion of such configurations.

The $^{9}\text{Be}(^{22}\text{Mg},^{23}\text{Mg} + \gamma)X$ one-neutron pickup reaction was performed at 84.2 MeV per nucleon mid-target energy. The inclusive cross section was measured for several data runs and found to be consistent within the statistical uncertainty. Since for this target the longitudinal momentum distribution of the $^{23}\text{Mg}$ residues is much wider than for the carbon target-induced reaction [see Fig. 3 (bottom)], the low-momentum tail of the distribution is cut more severely by the beam blocker. A 9.9% correction for the missing counts was applied to the cross section. The inclusive cross section, including the acceptance correction and with a 6% systematic uncertainty added, amounts to $\sigma_{\text{inc}} = 2.58(16)$ mb. The $\gamma$-ray spectra and population patterns for the carbon and beryllium-induced reactions are very similar. In fact, the partial cross sections are identical within uncertainties. Again, the partial cross section for the $3/2^+$ ground state was obtained from subtracting the populations from all observed feeders, with the possible population of the $(3/2, 5/2)^+$ state at 2.9 MeV included in the uncertainty. In addition, due to possible unobserved feeding by higher energy $\gamma$-ray transitions, the ground state cross section is expected to be an upper limit. The measured cross sections are summarized in Table I and discussed below.

The results for the $^{9}\text{Be}$ target allow us to draw some immediate conclusions. The cross sections in Table I calculated assuming pickup only of the valence neutron, are considerably smaller than those measured. This result, combined with the similarity of the measured values to those of the carbon target, and the (non-two-body) width of the measured $^{23}\text{Mg}$ momentum distribution for this target, see Fig. 3, all point to the dominance of reaction events involving the pickup of strongly-bound neutrons from $^{9}\text{Be}$. We conclude that the momentum composition of the wave function of the weakly-bound neutron does not match effectively to the needs of the fast pickup mechanism. As was discussed earlier, the strength associated with the core neutrons is located at $^{8}\text{Be}$ excitation energies high in the continuum, near to and in excess of 15 MeV, and so cannot be modelled quantitatively within the CCBA framework. It is interesting to observe that empirically these four neutrons in the (two $\alpha$-particle) $^{8}\text{Be}$ core contribute approximately the same cross sections, state-by-state, as for the carbon target (see Table I).

It can be deduced from Table I that the fast pickup reaction is also selective in populating the states with higher orbital angular momentum transfer. In the present experiment our ability to probe this aspect of the reaction is limited since only $s$- and $d$-wave neutron final states are resolved. The $[0^+ \otimes 1d]$ configurations are seen to dominate. However, we can begin to clarify this expected orbital angular momentum sensitivity using our theoretical CCBA calculations for the carbon target. To make transparent this $\ell$-sensitivity, without the need to remove spectroscopic factors and $Q$-value considerations, we calculated the pickup cross sections for assumed $2s_{1/2}$, $1p_{3/2}$, $1d_{5/2}$, and $1f_{7/2}$ transfers, all with unit spectroscopic factor and with all states located at the position of the physical 0.451 MeV state; and so with separation energy 12.70 MeV. The summed (over $^{12}\text{C}$ final states) single-particle cross sections obtained are $\sigma_{\text{sp}} = 0.04, 0.58, 3.51$, and $11.12$ mb, respectively. These values represent real enhancements with $\ell$, due to improved linear and angular momentum matching, above those due to the advantageous $2J + 1$ final states multiplicative factor. This is clear from the re-scaled values $\sigma_{\text{sp}}/(2J + 1) = 0.02, 0.116, 0.585$, and 1.39 mb, respectively. This suggests that there is the potential for this reaction mechanism to help locate emerging particle strength associated with high-$\ell$ intruder orbitals that enter the low-energy levels spectrum of rare nuclei.

V. CONCLUDING COMMENTS

In summary, new measurements and reaction model calculations are presented for the fast one-neutron pickup reactions $^{12}\text{C}(^{22}\text{Mg},^{23}\text{Mg} + \gamma)X$ and $^{9}\text{Be}(^{22}\text{Mg},^{23}\text{Mg} + \gamma)X$ at mid-target energies of about 84 MeV per nucleon. Measurements were made using both carbon and beryllium targets, having distinctly different nucleon single-particle configurations. Significant differences in the widths of the $^{23}\text{Mg}$ longitudinal momentum distributions for the two different targets were observed, pointing to the differences in the corresponding reaction mechanisms. These data thus provide evidence that the $^{12}\text{C}(^{22}\text{Mg},^{23}\text{Mg} + \gamma)X$ reactions proceed largely as a direct neutron transfer - producing $^{11}\text{C}$ target residues in bound states - while the corresponding pickup reactions induced by $^{9}\text{Be}$ appear to leave the $^{8}\text{Be}$ target-like residue highly excited and in the continuum.

Partial cross sections to $^{23}\text{Mg}$ final states are calculated (inclusive with respect to the target residue final states) based on the coupled channels Born approximation and assuming shell-model configurations for the $^{23}\text{Mg}$ final states. These cross sections are in reasonable quantitative agreement with the measured excited state partial cross section values. Clearly these pickup partial cross
sections in themselves provide insufficient information to
determine empirically both the dominant single-particle
transferred angular momentum and their spectroscopic
strengths - and must be used in conjunction with struc-
ture theory. Based on our observed (theoretical) sen-
titivity of the fast pickup reactions to high-momentum
components in the nuclear wave function and the ℓ of the
transferred nucleon, we propose their possible application
in helping to map the descent of high-ℓ neutron single-
particle (intruder) states in regions of shell evolution
where traditional neutron magic numbers break down.
Specifically, we envisage that the fast pickup mechanism
could be used, together with theoretical predictions of
level ordering and spectroscopic factors, to study the sys-
tematics of and test level migration predictions along iso-
topic chains - assessing shell-model and effective interac-
tion predictions. This could provide complementary in-
formation to transfer reaction studies, where these over-
lap, and with the prospect of extending measurements
into regions currently inaccessible (by virtue of beam in-
tensity) to transfer. Examples are the most neutron-rich
Ne, Na and Mg isotopes approaching $N = 20$ where the
neutron intruder $f_{7/2}$ orbital comes down in energy and
dominates ground-state and low-lying configurations in
the so-called “Island of Inversion” [27].

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