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# Probing elastic and inelastic breakup contributions to intermediate-energy two-proton removal reactions

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The two-proton removal reaction from  $^{28}\text{Mg}$  projectiles has been studied at 93 MeV/u at the NSCL. First coincidence measurements of the heavy  $^{26}\text{Ne}$  projectile residues, the removed protons and other light charged particles enabled the relative cross sections from each of the three possible elastic and inelastic proton removal mechanisms to be determined. These more final-state-exclusive measurements are key for further interrogation of these reaction mechanisms and use of the reaction channel for quantitative spectroscopy of very neutron-rich nuclei. The relative and absolute yields of the three contributing mechanisms are compared to reaction model expectations - based on the use of eikonal dynamics and *sd*-shell-model structure amplitudes.

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## I. INTRODUCTION

In fast surface-grazing collisions with a light target nucleus the removal of two protons (neutrons) from an intermediate-energy neutron-rich (deficient) projectile beam has been shown to proceed as a *direct* reaction [1–3]. Both the measured distributions of the reaction cross section among the available bound final states of the projectile-like residues [3, 4] and the associated residue momentum distributions [5, 6] are correctly predicted using an eikonal-model description of the reaction dynamics, that assumes sudden, single-step two-nucleon removal, plus shell-model two-nucleon structure information. The reaction mechanism, that in general populates several final states, thus gives access to spectroscopic information on states of some of the most neutron-rich (deficient) exotic species, e.g. [7–9]. The reaction also promises a rather unique and practical tool to probe the spatial correlations of the removed nucleons. It is these correlations that drive the sensitivity of the momentum distributions to the spins,  $J$ , of the final-states, allowing  $J$ -assignments of states of the projectile-like residues [5, 6, 10]. Two-nucleon removal reactions thus offer a complementary method to study the structure of exotic nuclei at fragmentation facilities. Compared to Coulomb excitation, they populate a more diverse set of final-state spins  $J^\pi$  [11].

In a one-nucleon knockout reaction the nucleon is re-

moved in a peripheral collision of the projectile with the target nucleus. Events can result from elastic (diffractive dissociation) or inelastic (stripping) collisions between the nucleon and the target, which must be summed. The first precise measurements to quantify the relative importance of these two reaction mechanisms used the one-proton removal reaction from the weakly-bound proton-rich nuclei  $^9\text{C}$  and  $^8\text{B}$  [12]. Both the measured cross sections and the relative contributions from the stripping and diffraction events were in good agreement with the reaction calculations with their sudden, eikonal dynamics description.

It follows, in one-step two-nucleon removal, that three reaction mechanisms may contribute to the cross section: (i) the inelastic removal of both nucleons (stripping), (ii) the elastic removal of one nucleon and the inelastic removal of the second (diffraction-stripping), and (iii) the elastic dissociation of both nucleons (diffraction). Both (i) and (ii) involve energy transfer to and excitation of the target nucleus. Calculations based on eikonal reaction dynamics and *sd*-shell-model structure input [2, 4] can provide quantitative estimates of the yields due to these different mechanisms. In particular, the diffraction mechanisms (ii) and (iii), where at least one of the nucleons is removed by elastic interactions with the target, are predicted to contribute about 40 % of the two-proton removal cross section, even for the case considered here which has well-bound protons with two-proton separation energy  $S_{2p} = 30.0$  MeV [13]. The reaction model, at present, makes predictions for the cross sections from these three mechanisms that (a) are exclusive with respect to the final states of the heavy projectile-like residues, as is essential for spectroscopy of these prod-

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ucts, but (b) are inclusive with respect to the (complete) set of final states of the target and of the removed protons.

A more quantitative confrontation of these reaction model predictions, through measurements of these three contributing reaction mechanisms, is of importance for the development of and confidence in the exploitation of these techniques. In this article we present the first such measurements to determine the relative importance of the three two-nucleon removal mechanisms defined above, now denoted str, diff-str and diff, via the measurement also of light, charged reaction fragments. The new measurements are also able to characterize aspects of the correlations of the detected protons in the final state, which will be discussed elsewhere [14].

The inclusive  ${}^9\text{Be}({}^{28}\text{Mg}, {}^{26}\text{Ne})\text{X}$  reaction is used at an intermediate energy of 93 MeV/u. The reaction calculations for this system, using the methods and inputs detailed in Ref. [4], predict that the two-proton removal cross sections due to mechanisms (i) and (ii) are  $\sigma_{\text{str}} = 1.70$  mb and  $\sigma_{\text{diff-str}} = 1.13$  mb, respectively. The cross section for process (iii), the elastic removal of both protons is small and was only estimated, based on the calculated probability for one of the nucleons to be diffracted, i.e.  $\sigma_{\text{diff}} = [\sigma_{\text{diff-str}}/(2 \cdot \sigma_{\text{str}})]^2 \times \sigma_{\text{str}}$ , giving 0.19 mb for the present case. Thus the measurement of this diffraction component (predicted to be only 6.3 % of the total yield) is a significant experimental challenge. The chosen reaction was studied previously in a  ${}^{26}\text{Ne}-\gamma$  coincidence measurement [1], and was used to study the relative populations of the four observed  ${}^{26}\text{Ne}$  bound final states. These relative populations were in excellent agreement with the direct two-proton removal mechanism predictions and the *sd*-shell-model spectroscopy, that is also used here [4]. Furthermore, these calculations predict that the fractional contributions of the three removal mechanisms to each of the  ${}^{26}\text{Ne}$  final states are essentially the same. Thus, since this previous experiment was not designed to detect light charged particles in the final-state, it could not differentiate the contributions from the individual reaction mechanisms, the subject of interest here.

## II. EXPERIMENT

The  ${}^9\text{Be}({}^{28}\text{Mg}, {}^{26}\text{Ne})$  reaction measurement was performed at the Coupled Cyclotron Facility at NSCL. The  ${}^{28}\text{Mg}$  secondary beam with an energy of 93 MeV/u was produced by projectile fragmentation of a 140 MeV/u  ${}^{40}\text{Ar}$  primary beam and selected using the A1900 fragment separator [15]. The  ${}^9\text{Be}$  reaction target with a thickness of 100 mg/cm<sup>2</sup> was placed at the target position of the high-resolution S800 magnetic spectrograph [16]. The incoming beam was identified event-by-event from the measurement of the time-of-flight difference between two plastic timing scintillators positioned before the target. The purity of  ${}^{28}\text{Mg}$  in the beam was 98.5 % with

a rate on target of typically  $5 \times 10^5$  particles/s. Two position sensitive PPACs allowed for the correction of the momentum dispersion in the incoming beam. The  ${}^{26}\text{Ne}$  reaction residues were identified event-by-event by measuring the energy loss in the ionization chamber in the S800 focal plane and the time of flight between scintillators before and after the target, corrected for the trajectory of the ion, as shown in Fig. 1. The  ${}^{26}\text{Ne}$  ener-

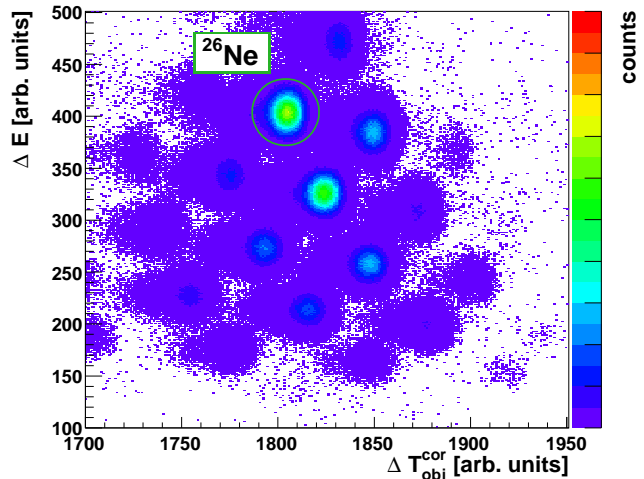


FIG. 1: (color online) Event-by-event particle identification spectrum of the reaction residues from the  ${}^{28}\text{Mg}$  secondary beam. Plotted is the energy loss versus the corrected time of flight measured between scintillators before and after the target. The circle indicates the  ${}^{26}\text{Ne}$  two-proton removal reaction residues of interest.

gies and momenta were reconstructed from the measured positions and angles in the S800 focal plane using the position-sensitive CRDCs and ray-tracing. Protons and other light charged particles were detected and identified in the High Resolution Array (HiRA) [17]. In the configuration used in the present study, this array consists of 17  $\Delta E-E$  telescopes made of 1.5 mm thick double-sided silicon strip detectors backed by 4 cm deep CsI crystals.

This allowed for the identification of protons with kinetic energies larger than 15 MeV and other light charged particles such as deuterons and tritons. The polar angle coverage was from  $9^\circ$  to  $56^\circ$  in the laboratory system. The solid angle covered by the HiRA array and the geometric efficiency for the configuration used in the present study are shown in Fig. 2 (a) and (b), respectively.

## III. RESULTS

The  ${}^9\text{Be}({}^{28}\text{Mg}, {}^{26}\text{Ne})\text{X}$  inclusive cross section was determined from the number of detected  ${}^{26}\text{Ne}$  residues relative to the number of incoming  ${}^{28}\text{Mg}$  and target nuclei. The result was  $\sigma^{\text{inc}} = 1.475(18)$  mb, in excellent agreement with the previous measurement of 1.50(10) mb [1]. Besides the statistical error, the quoted uncertainty includes contributions from the acceptance correction,

beam intensity, target thickness, particle identification and detection efficiency.

Triple coincidence events, comprising two charged particles in HiRA and  $^{26}\text{Ne}$  in the spectrograph, were corrected for the geometric efficiency of the HiRA array, i.e. for the azimuthal ( $\varphi$ ) angle coverage, shown in Fig. 2 (b). The resulting cross section for triple coincidences in the

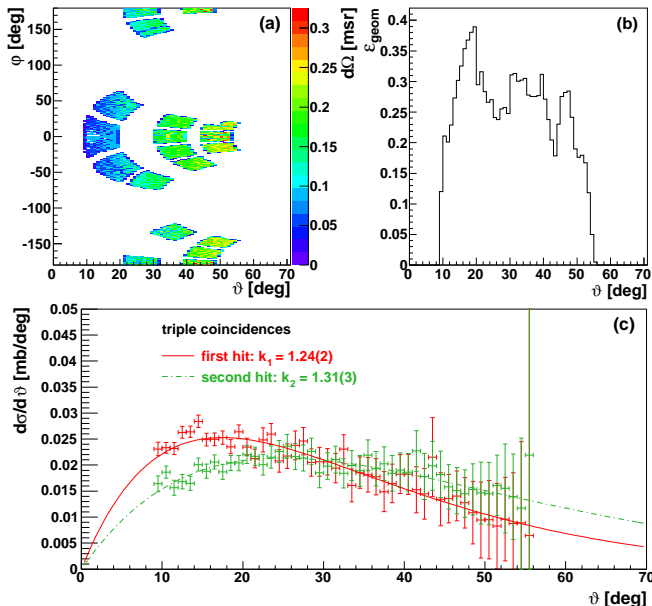


FIG. 2: (color online) Extrapolation of the measured cross section for the range of polar angles not covered by HiRA. (a) Solid angle covered by the HiRA array in the configuration used in the present study. (b) Geometric efficiency of the HiRA array. (c) measured cross section for triple coincidences as a function of  $\vartheta$ , where “first hit” denotes the detected particle with the lower mass, or the higher energy in case of identical particles (see text).

observed polar ( $\vartheta$ ) angular range is  $\sigma_{\text{obs}}^{\text{tot}} = 0.88(2)$  mb. Besides protons also other light charged particles have been detected. 28.4 %, 51.1 % and 20.5 % of the cross section is associated with triple coincidences with two, one and no detected protons in HiRA as shown in Table I. The observed deuteron, triton,  $^3\text{He}$  or  $\alpha$  particles

TABLE I: Triple coincidence cross sections in the polar angular range covered by the HiRA detectors. In addition to proton-proton coincidences (pp), also events where one (px) or both (other) of the detected particles is another light ion (deuteron, triton,  $^3\text{He}$  or  $\alpha$  particle) or an unidentified particle, with an energy below the identification threshold, have been observed.

	fraction [%]	$\sigma_{\text{obs}}$ [mb]	$\sigma_{\text{extr}}$ [mb]
tot		0.88(2)	1.43(5)
pp	28.4	0.25(2)	
px	51.1	0.45(4)	
other	20.5	0.18(2)	

are originating from inelastic (pickup) reactions of the removed protons with the target nucleons. Low energy fragments of the target itself have not been observed.

The triple coincidence cross section ( $\sigma_{\text{obs}}^{\text{tot}} = 0.88(2)$  mb) is then corrected for the range of polar ( $\vartheta < 9^\circ$  and  $> 56^\circ$ ) angles not covered by HiRA (see Fig. 2 (b)). The angular distribution  $d\sigma/d\vartheta$  of light particles for triple coincidences is shown in Fig. 2 (c). Here the first-hit distribution refers to the detected particle in HiRA with the smaller mass (i.e. the proton in case of proton-deuteron-residue coincidences), or, in the case of two identical light particles detected, to the particle with the higher energy. The second hit denotes the particle detected in HiRA with the larger mass, or lower energy. These angular distributions are then fitted with an exponential function combined with the solid angle factor  $2\pi \sin \vartheta$  to extract extrapolation parameters  $k_{1,2}$  to correct for the unobserved cross section. Extrapolated cross sections are then obtained by multiplying the cross section in the observed polar angular range with the extrapolation parameters, i.e.

$$\sigma_{\text{extr}} = k_1 \cdot k_2 \cdot \sigma_{\text{obs}}. \quad (1)$$

The extrapolated total cross section is  $\sigma_{\text{extr}}^{\text{tot}} = 1.43(5)$  mb, in excellent agreement with the inclusive cross section. This means that for essentially every knockout event one finds two light charged particles in the exit channel, originating either from the diffraction mechanism or from more complex (inelastic) reactions of the removed protons with the target nucleons. Similarly, the total cross section can also be extracted independently from events where only one light particle was detected in coincidence with the  $^{26}\text{Ne}$  residue. Here the number of counts had to be divided by two to correct for the fact that two particles were emitted ( $\sigma'_{\text{obs}} = 0.85(2)$  mb). Assuming that there is no angular correlation between the two light particles ( $k'_1 = k'_2 = 1.31(2)$ ), the total cross section extracted using this method amounts to  $\sigma'_{\text{extr}} = 1.46(4)$  mb in agreement with the inclusive and triple-coincidence-deduced values.

To determine the individual contributions from the three removal reaction mechanisms, the missing mass of each triple coincidence event was reconstructed from the observed energies and momenta of the three particles. Fig. 3 (a) shows the missing-mass spectrum for events where two protons were detected. With this data selection, all three reaction processes that remove two protons, i.e. stripping, diffraction-stripping, and diffraction, can contribute. The spectrum was fitted with two Gaussian functions leaving all six parameters free to vary. The lower peak, at  $M_{\text{miss}} = 8.399(3)$   $\text{GeV}/c^2$ , is at the mass of the target nucleus ( $M(^9\text{Be}) = 8.395$   $\text{GeV}/c^2$ ), and is thus attributed to the diffraction mechanism since no energy is transferred to the target in this elastic two-proton removal process. Its width ( $\sigma = 32.5(11)$   $\text{MeV}/c^2$ ) is in good agreement with the expected resolution from the energy spread of the incoming beam (25 MeV), the differential energy loss in the target (21 MeV), and the combined

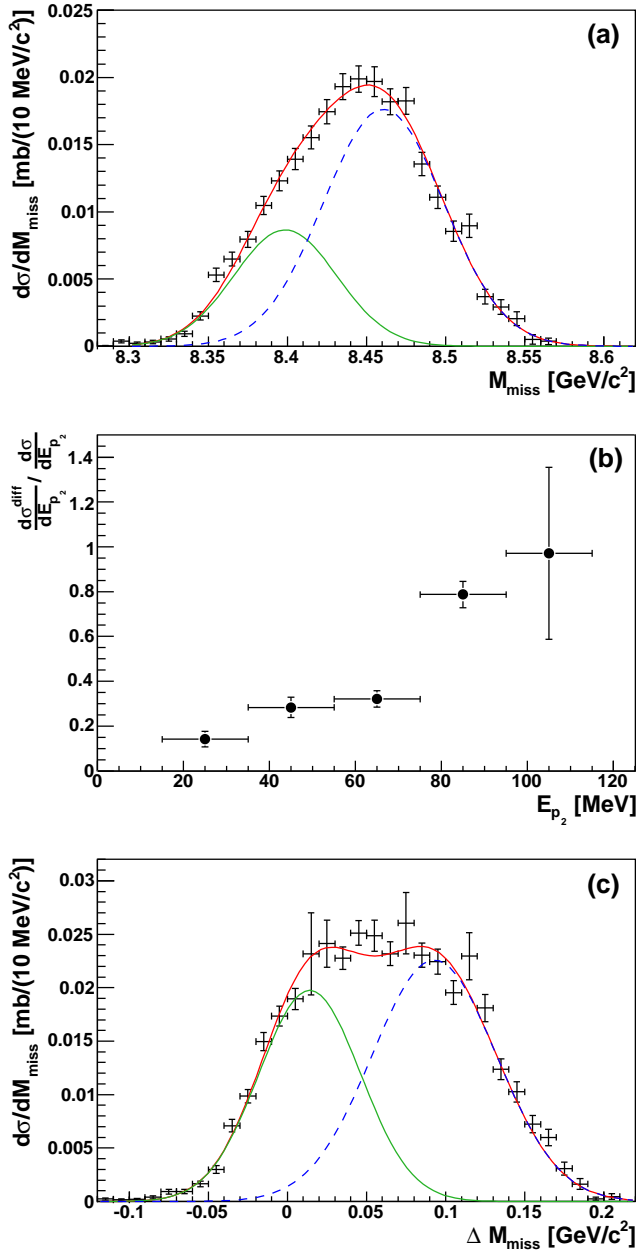


FIG. 3: (color online) (a) Missing-mass spectrum for events where two protons were detected. The cross section for observing two protons in coincidence with the  $^{26}\text{Ne}$  residue amounts to  $\sigma_{\text{obs}}^{\text{PP}} = 0.25(2)$  mb. The spectrum was fitted with two Gaussian peaks. The lower peak, at the target mass, is due to the diffraction mechanism (green, solid line), the larger peak is attributed to events where at least one proton was removed in an inelastic collision with the target. (b) Relative diffraction yield as a function of the smaller of the two proton energies,  $E_{p_2}$ . (c) Missing-mass difference spectrum for events where one of the detected particles is a proton, and the other is a light ion, e.g. a deuteron or triton. The individual spectra have been shifted ( $\Delta M_{\text{miss}} = M_{\text{miss}} - M(^{8}\text{Be}), M(^{7}\text{Be})$  etc. and then added. From the fit the ratio of diffraction-stripping to stripping events was extracted.

resolution for light particles detected in HiRA (5 MeV). The second, broader distribution originates from the inelastic stripping and diffraction-stripping mechanisms, which cannot be resolved in this spectrum. The extracted cross section for diffraction of both protons in the polar angular range covered by HiRA amounts to  $\sigma_{\text{obs}}^{\text{diff}} = 0.07(2)$  mb. As is expected for the diffraction mechanism, its cross section increases for large proton energies. This is shown in Fig. 3 (b) where the relative diffraction yield,  $(d\sigma^{\text{diff}}/dE_{p_2})/(d\sigma/dE_{p_2})$ , is plotted as a function of the smaller of the two proton energies  $E_{p_2}$ .

The ratio of diffraction-stripping to stripping events was extracted by fitting similar missing-mass spectra for events where one of the detected particles is a proton, and the other is a light ion, e.g. a deuteron or triton. Since the residue nucleus  $^{26}\text{Ne}$  is identified in the S800 spectrograph, the additional neutrons in the light particles can only originate from inelastic pickup reactions on the target. In a one-proton knockout reaction these pickup reactions lead to a sharp peak in the missing mass at  $M_{\text{miss}} = M(^{8}\text{Be}) = 7.456$  GeV/ $c^2$  in case of residue-deuteron coincidences and  $M_{\text{miss}} = M(^{7}\text{Be}) = 6.536$  GeV/ $c^2$  for events where tritons are detected [18]. In the two-proton knockout reaction the missing mass is thus expected to be  $M_{\text{miss}} = M(^{7,8}\text{Be})$  for events where the proton was removed in an elastic collision and larger values for  $M_{\text{miss}}$  for reactions where the proton was removed in a stripping reaction. Missing-mass spectra for triple coincidence events with only one identified proton were fitted with two components as shown in Fig. 3 (c) to obtain the ratio of diffraction-stripping to stripping events. Similar to Fig. 3 (b) the yield of diffraction-stripping events increases with the proton energy, while the stripping yield  $(d\sigma^{\text{str}}/dE_p)/(d\sigma/dE_p)$  stays constant as a function of the energy of the detected proton  $E_p$ . This feature is independent of the type of the second detected particle. The ratio of diffraction-stripping to stripping amounts to  $\sigma_{\text{diff-str}}/\sigma_{\text{str}} = 0.7(2)$  for events where one of the two particles is a proton. This ratio is then used to extract the diffraction-stripping and stripping cross section from the events where both detected light particles were protons,  $\sigma_{\text{diff-str+str}}^{\text{PP}} = 0.17(2)$  mb, the broad component in Fig. 3 (a), assuming that the removal processes for the two protons are independent. Triple coincidence events, where none of the detected light particles is a proton ( $\sigma_{\text{obs}}^{\text{other}} = 0.18(2)$  mb), are assumed to arise from events where both protons were stripped.

The cross sections for the three mechanisms are summarized and compared to the theoretical predictions [4] (recalculated for the present incident beam energy) in Table II. The agreement with the theoretical expectations for the relative importance of each contribution is very good. Comparison of the absolute cross section values confirms the need for a reduction factor  $R_S(2N) = \sigma_{\text{exp}}/\sigma_{\text{theo}} = 0.488(6)$ , in agreement with the value  $R_S(2N) = 0.50(3)$  [4] deduced from the partial and inclusive cross sections reported in the previous  $^{26}\text{Ne}-\gamma$  coincidence experiment[1].



TABLE II: Cross sections of the three mechanisms contributing to the two-proton removal reaction and comparison with theory. For the comparison of the cross sections the theoretical values have been multiplied with the factor  $R_S(2N) = 0.488(6)$ . The relative contribution of each mechanism is consistent with theory.

	diff	diff-str	str	tot.
$\sigma_{\text{obs}}$ [mb]	0.07(2)	0.27(14)	0.54(14)	0.88(2)
$\sigma_{\text{extr}}$ [mb]	0.11(3)	0.44(23)	0.87(23)	1.43(5)
fraction [%]	8(2)	31(16)	61(16)	
$\sigma^{\text{inc}}$ [mb]				1.475(18)
$\sigma_{\text{theo incl.}}$ [mb]	0.19	1.13	1.70	3.02
$\sigma_{\text{theo}} \cdot R_S(2N)$ [mb]	0.09	0.55	0.83	1.475
fraction <sub>theo</sub> [%]	6.3	37.4	56.3	

#### IV. SUMMARY

In summary, first coincidence measurements of fast, light charged particles and the heavy projectile-like reaction residues following the removal of two well-bound protons from  $^{28}\text{Mg}$ , have allowed the relative importance of the stripping, diffraction-stripping and diffraction two-

proton removal mechanisms to be determined. The experimental results are consistent with the expectations for the relative importance of each mechanism calculated using the eikonal reaction framework [4] that assumes a sudden, one-step removal of the two protons from the fast projectile. The measured cross sections thus confront these specific reaction-model predictions [4, 5] at a more detailed level. The measurements are also consistent with the previously-determined reduction factor  $R_S(2N)$  for two-proton knockout from  $^{28}\text{Mg}$  and for two-nucleon removals from other *sd*-shell systems. These results further support the applicability and effectiveness of this reaction channel, that populates residues even more exotic than the projectile, for the production of and extraction of spectroscopic information in some of the most exotic nuclei currently accessible.

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