Excitation functions for total reaction cross sections, $\sigma_R$, were measured for the light, mainly proton-rich nuclei $^6$Li, $^7$Be, $^{10}$B, $^{9,10,11}$C, $^{12}$N, $^{13,15}$O and $^{17}$Ne incident on a Si telescope at energies between 15 and 53 MeV/nucleon. The telescope served as target, energy degrader and detector. Proton-removal cross sections, $\sigma_2p$, for $^{17}$Ne and $\sigma_p$ for most of the other projectiles, were also measured. The strong absorption model reproduces the $A$-dependence of $\sigma_R$, but not the detailed structure. Glauber multiple scattering theory and the JLM folding model provided improved descriptions of the measured $\sigma_R$ values. \textit{rms} radii, extracted from the measured $\sigma_R$ using the optical limit of Glauber theory, are in good agreement with those obtained from high energy data. One-proton removal reactions are described using an extended Glauber model, incorporating second order nonelkonal corrections, realistic single particle densities, and spectroscopic factors from shell model calculations.

PACS numbers: 24.10.-i, 25.60.-t, 25.60.Dz, 25.60.Gc, 25.70.Mn

I. INTRODUCTION

The interesting properties of radioactive nuclei produced in the laboratory include their lifetimes, sizes and distributions of nuclear matter, shell structure, excited states, and decay modes. Often, the one-particle separation energies are small, of the order of 1 MeV or less.
These small separation energies lead to a wealth of phenomena including soft collective modes, exotic transition strengths between low-lying states, changes in shell structure, long-tailed density distributions, and, perhaps most dramatically, halo nuclei. In one-particle removal reactions, the parallel and transverse momentum distributions of the core-like fragments are very narrow as compared with those of normal nuclei, indicating increased nuclear size. The total reaction and breakup cross sections are large, also reflecting the increased nuclear size. Spontaneous $2\pi$ radioactivity has been observed recently near the proton drip line\cite{1,2}. The increased density in the tails of the matter distribution generates a competition between the increased refractive power of the real optical potential and the increased absorption due to the imaginary part, leading to exotic shapes in heavy ion elastic scattering angular distributions.

Total reaction cross sections, $\sigma_R$, and proton-removal cross sections, $\sigma_p$, contain complementary information about the size and matter distributions of atomic nuclei. Various reactions at all impact parameters contribute to $\sigma_R$, which therefore reflects mainly the rms nuclear radius. Breakup, however, is a peripheral process, hence $\sigma_p$ is sensitive mainly to the surface distribution. Therefore these combined data are needed to better describe the matter distribution, and the best test of theory is obtained by fitting them simultaneously.

Measurements of both $\sigma_R$ and $\sigma_p$ can be used to identify proton-halo nuclei. Among the light nuclei, $^8$B has been identified as a proton-halo nucleus. The evidence includes its enhanced $\sigma_R$ at low energies \cite{2}, as well as a narrow longitudinal momentum distribution of the $^7$Be core following proton removal. \cite{1,2,3}

We report $\sigma_R$ measurements for the stable and short-lived light nuclei $^6$Li, $^7$Be, $^{10}$B, $^{9,10,11}$C, $^{12}$N, $^{13,15}$O, and $^{17}$Ne incident on Si targets at energies ranging from 15 to 53 MeV/nucleon. Most of these nuclei are proton-rich; some are on the proton drip line, and therefore may be proton-halo candidates. The measurements were made by aiming these projectiles at a stack of thin Si elements which we call D1 and D2, were position-sensitive detectors (PSD’s), with thickness 0.2 mm, lateral dimensions 2.5 cm x 2.5 cm, and 60 cm separation. They measured proton coordinates normal to the beam axis, defining the active areas from 300 to 600 mm$^2$. They stopped all non-reacting projectiles. Since the projectile’s energy decreases as it travels through the telescope, we obtained reaction events by identifying the detector in which a reaction occurred; i.e., the first detector to give a signal different from projectile signals.

To measure $\sigma_p$, the heavy fragments from proton removal reactions were observed in particle identification spectra from two detectors – the one which stops the fragment and the one which precedes it – following those in which the breakup reactions occur \cite{7}.

An 80 MeV/nucleon $^{20}$Ne beam at the National Superconducting Cyclotron Laboratory was fragmented on a 300 mg/cm$^2$ $^9$Be target which produced secondary beams. These secondary beams were transported by the A1200 analyzing system \cite{12} to the Si detector telescope. In this system the beams were partially purified by polyethylene wedges, and their energy dispersions were limited to $\leq$1% FWHM by analyzing slits. For example, one A1200 setting delivered usable quantities of $^{11}$C, $^{12}$N, and $^{13}$O at energies of 41, 46, and 51 MeV/nucleon, respectively.

The Si target-detector telescope is shown schematically as an inset to Figure 1. The first two detectors, which we call D1 and D2, were position-sensitive detectors (PSD’s), with thickness 0.2 mm, lateral dimensions 2.5 cm x 2.5 cm, and 60 cm separation. They measured projectile coordinates normal to the beam axis, defining beam of 5 mm radius. Energy losses in these detectors identified the desired projectiles, but allowed some contaminants as we discuss later. The next five detectors, called D3 through D7, were about 0.5 mm thick and had active areas from 300 to 600 mm$^2$. They stopped all non-
reacting projectiles with A ≥ 11 and served as targets for reactions, including breakup. The final Li-drifted detector, D8, had 5 mm thickness and about 4 cm diameter. It stopped projectiles with A < 10 and the longer-ranged breakup fragments. All detectors except D1 were close-packed. Detectors D9 and D10 were not used in this experiment, but were utilized in a concurrent measurement of σR’s in the Be isotopes [13].

The scatter plot of Fig. 1 illustrates our secondary beam composition. It shows ΔE2, the energy deposited in D2, vs. the total energy loss in the telescope, for properly-aimed projectiles tentatively identified as 15O by their energy loss in D1. The non-reacting projectiles are the most dense group, labeled 15O. Events in the horizontal tail to the left react downstream of D2, and the few to the right are either pileup or positive Q-value reactions. Events in the vertical tail are non-reacting projectiles with significant energy straggling in D2.

Several contaminant groups, with magnetic rigidities in the A1200 system identical to that of 48 MeV/nucleon 15O, also are observed in Fig. 1. Most of these, e.g. 16,17O and 17,20Ne, are so well resolved that a gate on ΔE2 removes them completely. The treatment of the remaining 15N contaminant is described in the next section.

### III. EVENT SELECTION AND DATA ANALYSIS

#### A. σR Measurements

Spectra of total energy deposited in the Si telescope by incident 48 MeV/nucleon 15O projectiles appear in Fig. 2. Each of these four spectra shows a prominent peak for non-reacting projectiles and, below this peak, a continuum due to reactions.

Events in the spectrum labeled D1–2 are from projectiles with acceptable positions and normal 15O energy losses in Detectors D1 and D2. The 15O reactions beneath the 15N contaminant peak are extracted by assuming a linear energy dependence of the 15O reaction yield near that peak. The contribution from small Q-value reactions is included by extrapolating the 15O reaction yield just below the full energy peak to its center. The probability η2 of a reaction occurring anywhere downstream of Detector D2 then equals the ratio of reactions to total events in this spectrum, which are mainly in the sharp peak. The spectrum labeled D1–3 has an additional gate requiring normal 15O ionization in D3, and therefore gives the probability η3 for a reaction to occur...
there are about 1700 non-reacting $^{15}$O projectiles drops in energy from 44 to 38 MeV/nucleon in Detector D3, the average cross section for this energy range is

$$\sigma_R = (\eta_2 - \eta_3)/N_3$$  \hspace{1cm} (1)

where Detector D3 has N$_3$ target nuclei per unit area. Similarly, the $\sigma_R$’s for the energy ranges 38 to 31 MeV/nucleon and 31 to 22 MeV/nucleon are determined by $(\eta_3 - \eta_4)/N_4$ and $(\eta_4 - \eta_5)/N_5$, respectively. Corrections were made for attenuation of the beam in the individual detectors; these were less than 1% in all cases.

Our $\sigma_R$ data are presented in Table I. The main experimental uncertainties are statistical in origin: the counts in the reaction region, subtraction of contaminant events, and extrapolation to the non-reacting-projectile peak center in Fig. 2. Events above the peak are believed to be mainly pileup. If treated similarly to those below the peak, they would add about 1.5%, or .02 b, to the $\sigma_R$’s quoted in Table I. Given the uncertain origin of these events, we make no correction to $\sigma_R$ but add 2% uncertainty in quadrature to the experimental uncertainties. A further 2% uncertainty in the detector thicknesses is also included.

The contaminants produced very few reactions which were counted in the reaction continuum. For example, there are about 1700 non-reacting $^{15}$N events in the D$_{1-2}$ spectrum of Fig. 2 compared with 3.2x10$^6$ $^{15}$O’s. Hence the reactions by contaminants add about 0.05% to the measured $\sigma_R$’s. No correction was made for this effect since it is so small and the contaminants’ reaction cross sections are not well known.

### B. $\sigma_p$ Measurements

The heavy fragments from proton removal generally have longer ranges than the projectiles which produce them. For example, all projectiles with A $\geq$ 11 stopped in Detector D7, but most produced some fragments which stopped in D8 along with others which stopped in D7. The exception was $^{12}$O which had detectable yield only for $^{12}$N stopping in D7. Projectiles with A$\leq$10, and all of their fragments, stopped in D8. Particle identification (PID) was used to select fragments of interest. The PID parameter for fragments stopping in Detector 7 is obtained from the energy losses $\Delta E_6$ and $\Delta E_7$, through the equation

$$PID = A[(\Delta E_6 + \Delta E_7)^p - (\Delta E_7)^p],$$  \hspace{1cm} (2)

where $p = 1.73$ and the arbitrary constant $A$ is chosen to place the peaks of interest in convenient channels. A similar equation, relating energy losses $\Delta E_7$ and $\Delta E_8$, identifies those fragments stopping in D8.

Fragment identification was basically restricted to those produced in Detectors D3 through D5. A tight $\Delta E_2$ gate limited the production region in D2 to about its last 0.03 mm, which increased the effective production target thickness. Fragments produced earlier in D2 were rejected because of their decreased ionization. Production in D6 and beyond was excluded by counting only events with significantly lower $\Delta E_5$ than that of non-reacting projectiles. This rejected some events produced in D5 near its rear face, and we made a model correction for this loss.

As an example, we discuss the boron isotopes produced by incident 37 MeV/nucleon $^{11}$C. A PID spectrum for fragments stopping in D7 appears in Fig. 3. The dominant isotope produced is $^{10}$B, with lesser amounts of $^{11}$B (through charge exchange) and $^8$B (via some more complex process). The gap between the $^8$B and $^{10}$B groups reflects the absence of $^9$B, which is unbound.

Several corrections were made to the observed fragment yields. The largest of these was for rejection of fragments produced in D5, near its rear face, by the software gate on $\Delta E_5$ mentioned earlier. This correction required the fragment momentum distribution in the kinematic center of mass system (c.m) of the incident projectile, which was calculated from Goldhaber’s [7, 14] theory. Typically, 10% of the fragments stopping in D7, but none of those stopping in D8, were rejected. No fragments produced before D5 were rejected by this gate; thus, the overall event loss it caused was typically 3%. Since fragment production in D2 increased the effective target thickness by about 2%, the observed yield was reduced by this amount. The loss of projectiles by reactions in D3 through D5, added to that of produced fragments lost to secondary reactions and hence misidentified, was about 1%. Possible corrections for fragments transmitted through D8 or stopping short of D7 were found to be negligible.

The beam contaminants mentioned earlier had no effect on these measurements due to their short range. For example, the 37 MeV/nucleon $^{15}$N contaminant in the 48 MeV/nucleon $^{15}$O beam (see Figs. 1 and 2) stops in Detector D6. In contrast, the $^{14}$N fragments produced from $^{15}$O breakup reached at least D7.

The ratio of the combined corrected fragment yield to the incident flux (projectiles with acceptable positions and energy losses in D1 and D2) gave the breakup cross section; these are presented in Table I. The uncertainties listed therein were found by adding in quadrature the statistical uncertainties and an uncertainty of 1/3 of the combined corrections to the data.

### IV. THEORETICAL PREDICTIONS, AND COMPARISON WITH MEASUREMENTS

#### A. Reaction cross sections

Experimental reaction cross section data are shown in Fig. 4. We first compare these data with the predictions of the strong absorption model of Kox [15]. In this model
the reaction cross section is

$$\sigma_R(E) = \pi r_0^2 \left( \frac{A_{p(1)}^{1/3}}{A_{t(1)}^{1/3}} + a \frac{A_{p(1)}^{1/3} A_{t(1)}^{1/3}}{A_{p(1)}^{1/3} + A_{t(1)}^{1/3}} - C(E) \right)^2 \times \left( 1 - \frac{V_c}{E_{c.m.}} \right)$$

where $A_{p(t)}$ are the projectile (target) mass numbers, $a = 1.85$ is a mass symmetry parameter related to the volume overlap of projectile and target, and $C(E)$ is a correction related to the transparency of the optical potential. We adopt here the linear approximation of Mittig et al.\cite{16}, $C(E) = 0.31 + 0.0147 E/A$ which gives reasonable results for the range of energies studied here. Bending of trajectories in the target Coulomb field is taken into account by the last factor in Eq. 3. There, the Coulomb potential is evaluated at $R_c = \left[ 1.07 \left( A_{p(1)}^{1/3} + A_{t(1)}^{1/3} \right) + 2.72 \right]$ fm.

The Kox formula gives excellent results for stable nuclei when the reduced strong absorption radius is fixed at $r_0 = 1.1$ fm, and therefore any significant departure from its predictions may disclose a halo structure. The calculations shown in Fig. 4 were done using the standard value for $r_0$, except for $^6$Li and $^9$C where a somewhat larger value ($r_0 = 1.15$ fm) was needed to fit the data. This variation must relate to the weak binding of the last two nucleons in each of these nuclei. It should be noted that the variation $\Delta r_0 = 0.05$ fm adds 130 mb to $\sigma_R$ for $^6$Li at 30 MeV/nucleon.

In Figure 5, we display the A-dependence of the Kox $\sigma_R$ predictions, using $r_0 = 1.10$ fm for all projectiles, at an energy of 35 MeV/nucleon. To compare them with our measurements, predictions for all projectiles were individually renormalized to best fit the energy dependence of each projectile’s $\sigma_R$ data. The renormalized calculations at 35 MeV/nucleon are plotted as interpolated “data” in Figure 5. The smooth A dependence of the predictions reproduces the data on average, but is unable to explain the scatter of the reaction cross sections observed in the experiment. This observation suggests that a more sophisticated theory is needed to explain these data.

We next use the optical limit (OL) of the Glauber multiple scattering theory. The reaction cross section is given by

$$\sigma_R = 2\pi \int_0^\infty b[1 - T(b)] db,$$

where $b$ is the impact parameter, and the transparency function (or elastic survival probability) $T(b)$ is given by

$$T(b) = \exp[-\chi(b)].$$

The quantity $[1 - T(b)]$ is called the opacity or nuclear
FIG. 3: Particle identification spectra for bound B isotopes produced in Detectors D3 through D5 and identified in D6 and D7, with 41 MeV/nucleon $^{11}$C incident upon the telescope. Note the absence of a group due to $^9$B, which is unbound.

The scattering phase is given by
\[ \chi(b) = \sum_{\alpha, \beta = p, n} \sigma_{\alpha\beta}^{NN}(E) \int db_1 db_2 \tilde{\rho}_{\alpha}(b_1) \tilde{\rho}_{\beta}(b_2) \delta(b_1 + b_2 - b) \]
where the sum runs over all NN isospin channels. Here we assume a zero-range nuclear force and charge symmetry for the free NN cross sections ($\sigma_{pp} = \sigma_{nn}$). These are taken from the parametrization of John et al. [17]. We ignore in-medium effects, Pauli blocking, and Fermi motion, and assume a purely imaginary forward NN scattering amplitude. In principle, one should correct Eq. 4 for Coulomb dissociation effects. Estimation of this mechanism (see next subsection) leads to the conclusion that its contributions are negligibly small. They amount to 2 mb for $^7$Be and 20 mb for $^{12}$N Coulomb breakup at 35 MeV/nucleon, well within the experimental uncertainties. The profile functions $\tilde{\rho}$ needed in Eq. 6 are calculated by Abel transformation of the ordinary particle densities $\rho$ in coordinate space,
\[ \tilde{\rho}(b) = \int_{-\infty}^{+\infty} \rho(\sqrt{b^2 + z^2}) dz \]
Correction for bending of the trajectories in the target Coulomb field is introduced as follows. Eq. 4 is rewritten as
\[ \sigma_R = 2\pi \int_0^\infty b[1 - T(b')]db' \]
where $b' = (1/k) \left( \eta + \sqrt{\eta^2 + k^2 b'^2} \right)$ is the impact parameter for a grazing Coulomb trajectory, $\eta$ is the Sommerfeld parameter, and $k$ the wave number. After some algebra one obtains
\[ b^2 = b'^2 \left( 1 - \frac{V_c(b')}{E_{c.m.}} \right) \]
Using $V_c(b') \approx V_c(R_c)$ with $R_c$ defined above, one obtains
\[ \sigma_R = 2\pi \left( 1 - \frac{V_c(R_c)}{E_{c.m.}} \right) \int_0^\infty b'[1 - T(b')]db' \]
which also justifies the correction made in Eq. (3).

The single particle densities used in this analysis were obtained from a standard spherical HF+BCS calculation using the density functional of Beiner and Lombard [18]. The surface strength of the functional has been slightly adjusted to reproduce the known experimental binding energies. The $rms$ radii from HF calculations are listed in Table III. They show a surprisingly good agreement with experimental data from high energy reactions [19] and those obtained from the present $\sigma_R$ data, as described below, especially for the loosely bound nuclei $^7$Be, $^9$C, $^{12}$N, $^{13}$O and $^{17}$Ne. The results with the OL model are displayed in Figs. 4 and 5. Clearly, the mass dependence of the reaction cross section is well reproduced since this approximation incorporates realistic densities.
In the remainder of this section we discuss the ability of the JLM folding model \cite{20} to describe reaction cross sections as a further check of our densities. We adopt their nuclear matter approach which incorporates a complex, energy- and density-dependent parametrization of the effective interaction obtained in the Brueckner Hartree-Fock approximation from the Reid hard-core NN potential. Studies of elastic scattering of $p$-shell nuclei \cite{21, 22} indicate that the absorptive component of the JLM potential is realistic for loosely bound nuclei and needs no renormalization ($N_w \approx 1$, see below), while the real part needs a significant renormalization. Here we extend these studies much closer to the proton drip line.

In the JLM model the complex form factor for the optical potential is given by

\begin{equation}
U(R) = \int d\vec{r}_p d\vec{r}_t \rho_p(r_p)\rho_t(r_t)v(\rho, E, s) \quad (11)
\end{equation}

where $v$ is the (complex) NN interaction, $\rho_p(t)$ are the single particle densities of the interacting partners, $s = \cdots$
\[ \mathbf{r}_p + \mathbf{R} - \mathbf{r}_t \] is the NN separation distance between interacting nucleons and \( \rho \) is the overlap density. The effective NN interaction contains an isovector component, which gives a negligibly small contribution for \( p \)-shell nuclei. However, it is included here for convenience in conjunction with appropriate single particle isovector densities. The coupling of the entrance channel to the breakup and particle transfer reactions has been described by a dynamic polarization potential (DPP) which is strong and has complicated dependence on radius, mass, and energy \([23]\). To simulate the radial dependence of a DPP, and to increase the flexibility of the folding potential we introduce a smearing function \( h(r) \) to obtain our final folding potential,

\[
\tilde{U}(R) = \int d\mathbf{R}' U(\mathbf{R}') h(|\mathbf{R} - \mathbf{R}'|)
\]

The smearing function \( h(r) \) is taken as a normalized Gaussian \([20, 22]\),

\[
h(r) = \frac{1}{\sqrt{\pi} t^{3/2}} \exp(-r^2/t^2)
\]

which behaves as a \( \delta \)-function for \( t \to 0 \), while for finite \( t \) values it modifies the rms radius of the folding form factor by \( r_h^2 = (3/2)t^2 \), leaving the volume integral unchanged. It turns out that the smearing procedure described above is essential in simulating the complicated radial dependence of the dynamic polarization potential \([21]\). To be consistent with the JLM model we take the overlap density in Eq. 11 to be given by

\[
\rho = \left[ \rho_p(\mathbf{r}_p + \frac{1}{2}\mathbf{s})\rho_t(\mathbf{r}_t - \frac{1}{2}\mathbf{s}) \right]^{1/2}
\]

This approximation is physically reasonable since the overlap density approaches zero when one of the interacting nucleons is far from the core, and approaches the nuclear matter saturation value for complete overlap. We recall that the JLM model was developed to describe the optical potential for a nucleon traversing nuclear matter, and its density dependence is defined for densities not exceeding the saturation value in nuclear matter.

The model contains four parameters: two normalization constants \( N_v, N_w \) and two range parameters \( t_v, t_w \).
They have been fixed here close to standard values for p-shell nuclei 21, 22: \( N_s=0.4, N_w=0.85 \) and \( t_v = t_w = 1.2 \) fm. We assume that the energy dependence is weak, and use this set of parameters at all energies and for all projectiles. We are merely interested in a general assessment of the JLM model rather than fitting a particular cross section. The results of this approach are shown with continuous lines in Figs. 4 and 5. Fig. 6 also includes the optical model cross sections obtained by fitting known elastic scattering distributions 24, 25. One observes an even better description of the scatter effect in the reaction cross sections.

B. Nuclear radii

It is interesting to use reaction cross section data to infer nuclear sizes. At the energies of our experiment, the total NN reaction cross section is large, the mean free path is small, and therefore the heavy ion reaction cross section is strongly influenced by NN collisions at the surface. We chose to describe the tails of the nuclear matter densities by a Gaussian 22:

\[
\rho_i(r) = \rho_{i0} \exp(-r^2/a_i^2), \quad i = p, t, \tag{15}
\]

with the normalization,

\[
\rho_{i0} = \frac{A_i}{(\sqrt{\pi}a_i)^3}. \tag{16}
\]

The slope parameter \( a_i \) is related to the nuclear size by

\[
< r_i^2 > = \frac{3}{2} a_i^2. \tag{17}
\]

We let \( a^2 = a_p^2 + a_t^2 \) and

\[
\chi_0 = \frac{\sigma_{NN} a^2}{N\rho_0} \frac{\rho_{p0} \rho_{t0}}{a^2} \tag{18}
\]

where \( \sigma_{NN} \) is the isospin-averaged NN cross section. Under these assumptions, Eq. 14 can be solved analytically,

\[
\sigma_R = \pi a^2 \left( C + \ln \chi_0 + E_1(\chi_0) \right) \left( 1 - \frac{V_b}{E_{c.m.}} \right) \tag{19}
\]

where \( C = 0.5772 \) is the Euler constant and \( E_1(\chi) \) is the exponential integral. Eq. 19 shows essentially the geometric character of the reaction cross section since the leading term is \( \sigma_R \approx \pi (r_p^2 + r_t^2) \). The leading term in the Kox formula is \( \sigma_R \approx \pi (r_p + r_t)^2 \). The energy dependence is governed entirely by \( \sigma_{NN} \). To extract nuclear sizes from experimental data, we use Eq. 19, with the target \( rms \) radius fixed to \( r_i = 3.05 \) fm which we obtained from HF calculations. The compilation of Angeli 22 for \( rms \) charge radii indicates a value of \( r_{c,n} = 3.12 \) fm for \( ^{28}\text{Si} \). We calculate an upper limit of 2% uncertainty from this difference in our theoretical estimations. In practice, the parameter \( a_p \) is gridded in small steps until the calculated cross section equals the experimental value. The results are listed in Table III and displayed in Fig. 6. These values are consistent with those extracted from high energy data within their uncertainties. The values and uncertainties quoted in the table include the weighted averages over various energies measured here, and statistical uncertainties. No provision has been taken to correct values in Table III for nucleon finite size. Assuming a nucleon \( rms \) value of \( r_n^2 \approx 0.8 \) fm\(^2\), this would increase values in Table III by \( \approx 5\% \).

The sensitivity of the cross section to the functional form of the single-particle density is studied using harmonic oscillator wave functions appropriate for the \( pd \)-shell nuclei with \( s \) and \( d \) state admixtures.

\[
\rho_{r}(r) = \frac{1}{(\sqrt{\pi}b_r)^3} \left( n_s + \frac{2}{3} n_p x^2 + \frac{4}{15} n_d x^4 \right) \exp(-x^2) \tag{20}
\]

where \( n_s, n_p, n_d \) are occupation numbers in the \( s, p, d \) shells, \( b_r \) is the range parameter and \( x = r/b_r \). The finite range of the nuclear force is included in Eq. 10 by replacing the \( \delta \) force by a finite range NN interaction

\[
v(b) = \frac{1}{\pi \mu^2} \exp(-b^2/\mu^2) \tag{21}
\]

with the interaction range \( \mu = 1 \) fm 28. The normalization in Eq. 21 ensures that the reaction volume overlap in Eq. 6 is not changed, but the smearing enhances the weight of the density tail and reduces the contribution from the central part of the density. In addition, the number of NN inelastic scatterings in the overlap volume is weighted differently by \( \sigma_{pp} \neq \sigma_{np} \). As a result, the \( rms \) radii extracted with this method (shown in Table III) are slightly smaller than with the Karol model. Woods-Saxon (WS) shapes are more appropriate for testing the role played by long tails in the projectile neutron and/or proton densities

\[
\rho_{r}(r) = \rho_{r0}/ \left[ 1 + \exp \left( \frac{r-R_r}{a_r} \right) \right], \quad r = p, n \tag{22}
\]

where the \( \rho_{r0} \) are normalization constants. Equations 17 have been solved numerically. The half-radius parameter \( R_r \) is the most sensitive in extracting the nuclear \( rms \) radius. No anomalies were found in proton or neutron surface thickness when using \( a_p \approx a_n \approx 0.5 \) fm for most nuclei, and slightly larger values for \( ^9\text{C}, ^{12}\text{N} \) and \( ^{17}\text{Ne} \). The uncertainties shown in Table III are evaluated with the bootstrap method of Efron 29, which has the merit of weakening the influence of systematic errors in the data, and leads to meaningful ranges in the extracted parameters. All these calculations lead to mutually consistent \( rms \) radii for the nuclei studied here (Table III).

C. One-proton removal

We use the core spectator model and Glauber multiple scattering theory to calculate one-proton breakup cross
sections. This model has been tested extensively on a number of one-neutron removal reactions of neutron-rich nuclei in the \(p sd\) shell. We approximate the ground state of the projectile \((J^p)\) by a superposition of configurations of the form \([I_c^p \otimes nlj]^J^p\), where \(I_c\) denotes the core states and \(nlj\) are the quantum numbers specifying the single particle wave function of the outermost proton. The s.p. wave functions were obtained for a Woods-Saxon potential using the effective separation energy recipe \(S_{eff}^p = S_p + E_{exc}^c\), where \(E_{exc}^c\) is the excitation energy of the core state. The depth of the potential was varied in such a way that the known one-proton separation energy was reproduced. The radius of the WS potential was fixed to values close to the \(rms\) radius of the core (Table III) and the diffuseness was fixed to \(a = 0.5\) fm for all cases.

Fine tuning of these parameters could significantly improve the theoretical results since they determine the asymptotic normalization coefficient of the outermost proton. We neglect dynamical excitation of core states in the reaction. In this approximation, the reaction can populate core states only to the extent that there is a nonzero spectroscopic factor \(C^2 S(I_c, nlj)\) in the projectile ground state. The various configurations are assumed to contribute incoherently to the total breakup cross section for a given core state,

\[
\sigma_p(I_c^p) = \sum_{nlj} C^2 S(I_c^p, nlj) \sigma_{sp}(nlj, S_{eff}^{p,f}).
\]  

(23)

The total breakup cross section \(\sigma_p\) is then the sum over all particle-bound states of the core. In the present experiment, the core states were not identified and the removed proton was not detected. Therefore, the dynamical factor \(\sigma_{sp}\) in Eq. (23) includes contributions from stripping, nuclear dissociation and Coulomb dissociation. Other more violent channels, such as core breakup, have been ignored. The nuclear mechanisms have been described using transition operators defined in terms of scattering functions (S-matrix) for p-target and core-target interactions generated in the JLM folding model as described above. Scattering functions in impact parameter representation have been calculated in the eikonal approxima-
tion, including nonekonical corrections up to second order. 
Coulomb dissociation has been calculated in the first or-
der of perturbation theory. Both $E1$ and $E2$ amplitudes 
have been included. The interference of these amplitudes 
does not contribute to the inclusive removal cross section.

The spectroscopic factors $C^2S(I_n, nlj)$ employed here 
were calculated with the shell model code OXBASH [31] 
using the WBP [32] interaction within a $1s - 1p - 2s1d - 
1f2p$ model space. Excitations up to $4\hbar\omega$ have been 
included in this single particle model space for most of the 
cases. Inclusion of higher $n\hbar\omega$ excitations with this 
effective interaction was shown to better describe some exper-
imental observables [33]. Spurious center-of-mass compo-
nents of the projectile have been suppressed by the usual 
method [34] of adding a center-of-mass hamiltonian to 
the nuclear interaction. In all cases, the experimentally 
established spin-parity and core excitation energies have 
been used. The shell model spectroscopic factors have 
been multiplied by the center-of-mass correction factor 
$A_p/(A_p - 1)$, following Refs. [35, 36].

The projectile ground state spin-parity ($J^\pi$), core spin-
parity and excitation energies ($E_{zz}$, $I^\pi_g$), the stripping, 
diffractive dissociation and Coulomb dissociation cross 
section, as well as the shell model spectroscopic factors 
are listed in Table IV. The total inclusive cross 
section $\sigma^{Glauber}_{p}$ was corrected for center-of-mass effects 
as explained above. All calculations were done at 35 
MeV/nucleon.

Comparison with experimental values in Table I shows 
reasonable agreement. It should be noted that the ex-
tended Glauber model is designed to describe one nucleon 
removal reactions for loosely bound nuclei. The wave 
function of the outermost nucleon is assumed to pene-
trate substantially into the classically forbidden region, 
since most of the reaction probability is localized at the 
surface. The interaction should be strongly absorptive. 
In addition, the core is assumed to be compact and well 
decoupled from the outermost nucleon. A special case is 
$^{10}$B which has a quite large one-proton separation en-
ergy ($S_p \approx 6.8$ MeV), and a relatively fragile core, $^9$Be. 
In this case the reaction is not completely peripheral, with 
significant contributions arising from impact parameters 
b \( \leq R_c \), where $R_c$ is the core radius. The calculated 
breakup cross section exceeds the experimental value by 
more than 50%. Only by excluding contributions from 
the nuclear interior can one obtain a reasonable value 
(Table IV).

D. Discussion of Results

The reaction cross sections for $^6$Li measured in this 
experiment and at higher energy [11] show in Fig. 4 a 
smooth energy dependence, falling at 50 MeV/nucleon, 
which is well fitted by the Kox model and slightly un-
derpredicted by the Glauber models. For $^7$Be we see a 
flat energy dependence, with all models slightly under-
Predicting the 40 MeV/nucleon datum.

Figures 4 and 5 show a large reaction cross section for 
the $^9$C projectile. Both Glauber (OL) and JLM models 
Predict this increase, in reasonable agreement with the 
experiment. The $rms$ radius obtained from our present 
data exceeds by about 12% the value obtained from high 
energy data [10], and it is close to that obtained for $^{17}$Ne, 
another loosely bound nucleus. The smaller Coulomb 
barrier in $^{9}$C enhances the penetrability of the outermost 
proton much beyond the range of nuclear forces and this 
compensates the larger interaction volume provided by 
$^{17}$Ne. Unfortunately, the uncertainty is relatively large 
and the halo structure of this nucleus cannot be firmly 
established. More accurate experimental data are needed 
to clarify this point.

The reaction cross sections for $^{10}$B, $^{10}$C, and $^{11}$C are 
definitely smaller than for $^9$C and not much larger than 
those of $^6$Li and $^7$Be. The extracted $rms$ radius of $^{11}$C is 
quite small though in agreement with high energy data.

An independent measurement by Liatard et al. [37] 
indicates a much larger value, 2.46±0.30 fm, in agreement 
with our HF calculation of 2.48 fm (see Table III). $^{12}$N 
seems to behave normally. Both Glauber (OL) and JLM 
models give an excellent description of the cross section. 
The extracted radii seem to be in good agreement with 
HF calculations (see Table III).

Figure 5 shows that $\sigma_B$ stays nearly constant from $^{12}$N 
through $^{15}$O, as predicted by the JLM and OL (but not 
the Kox) models. For well-bound projectiles we expect 
an increase with increasing A. However, $S_p$ is 0.6, 1.5 
and 7.3 MeV for $^{12}$N, $^{13}$O and $^{15}$O respectively, and 
the weaker binding of the two lighter nuclei increases the 
range of their valence protons. The two effects appear 
to roughly compensate for each other.

Among the nuclei we studied, $^{12}$N has by far the largest 
one proton removal reaction cross section. Furthermore, 
the $p$-removal process for this case is related to $^{11}$C+p 
radiative capture. Depending on their initial CNO abun-
dances, this reaction may have been important in some 
super-massive stars in the early universe, allowing the 
stars to explode as supernovae rather than collapsing 
as black holes before ejecting any mass. [38, 39]. The 
super-massive stars in the early universe, allowing the 
destruction of black holes before ejecting any mass.

The asymptotic normalization coefficient (ANC) for $^{12}$N \( \rightarrow 
^{11}$C+p has been measured recently using transfer reac-
tions [40]. However, these reaction-rate data are ambigu-
ous and therefore it is desirable to remeasure the ANC 
by breakup, as an independent check. The one proton 
separation energy is small ($S_p = 0.6$ MeV), and thus $^{12}$N 
could be a proton halo candidate. The Glauber model 
nicely reproduces the measured $\sigma_p$. However, the shell 
model calculations suggest a very fragmented structure 
for the g.s. wave function, significant contributions arising 
from ($g.s, 3/2^-\otimes 1p_{1/2}$), ($g.s, 3/2^-\otimes 1p_{3/2}$) ($E_x=2.0$ 
MeV, $1/2^-\otimes 1p_{3/2}$) and ($E_x=4.8$ MeV, $3/2^-\otimes 1p_{1/2}$). 
The ANC's have been measured [40], for the core ground 
state components; they are $C^2_{1p_{1/2}} = 1.4 \pm 0.2$ fm$^{-1}$ 
and $C^2_{1p_{3/2}} = 0.33 \pm 0.05$ fm$^{-1}$. Since the single particle nor-
malization coefficients are almost identical for the $1p_{1/2}$ 
and $1p_{3/2}$ wave functions, one should have approxima-
tively $S_{1p_{1/2}}/S_{1p_{3/2}} \approx C_{1p_{1/2}}^2/C_{1p_{3/2}}^2$, a relation that is satisfied for the states mentioned above for which the experimental values of the ANC are known, when one uses the corresponding shell model spectroscopic factors listed in Table IV. The reaction cross section measurements showed no anomaly for this nucleus. The calculated parallel and transverse core fragment momentum distributions are narrow (FWHM$_z \sim 86$ MeV/c, FWHM$_r \sim 120$ MeV/c) comparable to that found for a well established halo nucleus, such as $^8$B [4]. The halo character of $^{12}$N could not be firmly established on the basis of the present data. More precise reaction and breakup cross section data are needed as well as a clear separation of contributions from core excited states.

For halo nuclei, one can assume that the core is decoupled from the halo nucleon, and the following decomposition of the absorption operator (Eq. 4) holds

$$1 - T \approx 1 - T_c T_h = (1 - T_c) + T_c (1 - T_h)$$  

(24)

Here, the first bracketed term on the right describes the core absorption (in the absence of the halo particle), while the second describes the absorption of the halo particle, weighted by the core survival probability. One can associate this last term with the stripping component of the total breakup cross section $\sigma_p$. Assuming that the diffractive dissociation and Coulomb dissociation components are small, one can approximate $\sigma_R = \sigma_R^c + \sigma_p$. The difference of the $\sigma_R$ is given for $^{11}$C and $^{12}$N in the middle energy bins of Table II (at energies 28 and 33 MeV/nucleon, respectively) is 110 ± 86 mb. This agrees with the breakup cross section of 120 ± 6 mb given in Table II though with a large uncertainty.

$^{15}$O has a one-proton separation energy $S_p$ four times larger than $^{13}$O, yet the $^{15}$O breakup cross section is two times larger. We expect a larger $S_p$ to give a smaller $\sigma_p$ and so the Glauber model, which is very sensitive to the separation energy, is not able to reproduce this behaviour. This anomaly probably results from competition with 2$p$-breakup; we found that the $^{13}$O breakup produces more C than $^{12}$N, though the C yield is isotopically unresolved. Other similar cases were observed for nuclei which have one nucleon outside a fragile core. For example, $^{12}$Be, which has one neutron loosely bound to a neutron halo nucleus $^{11}$Be, has a smaller $\sigma_n$ than $\sigma_{2n}$ [15]. $^9$C behaves similarly for proton removal [7].

V. CONCLUSIONS

We have measured reaction cross sections $\sigma_R$ and one-proton removal cross sections $\sigma_p$ for a range of stable and short-lived nuclei close to the proton drip line. These $\sigma_R$ extend our earlier measurements to projectiles of higher A and Z. Comparison with earlier, higher energy data for $^6$Li and $^7$Be shows a reasonable energy dependence. The optical limit of the multiple scattering Glauber model, and double folding optical potentials derived from the NN effective interaction in nuclear matter, are about equally successful in describing the data, including their energy- and mass-dependence. However, more accurate data would be needed to distinguish between them or to test sensitively for nuclei with weak halos.

One proton removal cross sections vary widely. These reactions were described within an extended Glauber model by incorporating fundamental NN interactions and spectroscopic factors from the shell model. The large $\sigma_p$ in the $^{12}$N case suggests a possible weak halo, although the wave function is fragmented into many components. An anomaly has been found in the A=12-15 region, where the one-proton removal cross sections and total reaction cross sections do not behave as expected from proton separation-energy systematics. More experimental and theoretical effort should be devoted to a better understanding of the competition between $-1p$ and $-2p$ channels for nuclei, such as $^{13}$O, where the last proton’s separation energy exceeds that of the next one (i.e., $S_p > \frac{1}{2} S_{2p}$).

VI. ACKNOWLEDGMENTS

We benefitted from useful discussions with Shalom Shlomo. We thank J. J. Kruse, M. Y. Lee, T. W. O’Donnell, P. Schwandt, H. Thirumurthy, J. Wang, J. Woodroffe, and J. A. Zimmerman for assistance with these measurements. One of us (F.C.) acknowledges support by the Texas A&M University Cyclotron Institute. Additional support from the following National Science Foundation grants PHY-9971836 (UM-Dearborn), PHY02-44989 (Notre Dame and UM-Ann Arbor, PHY0244453 (Central Michigan University) is acknowledged. B. Davids also acknowledges additional support from the Natural Sciences and Engineering Research Council of Canada.
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### VII. TABLES

**TABLE I: Total reaction cross sections, $\sigma_R$, for ten light isotopes on Si, averaged between the listed energies.**

| System | Energy interval (MeV/nucleon) | $\sigma_R$ (b) |
|--------|-----------------------------|---------------|
| $^7$Li+Si | 15.1-19.4 | 1.55±0.06 |
|  | 19.4-23.1 | 1.54±0.06 |
| $^7$Be+Si | 21.0-26.2 | 1.54±0.09 |
|  | 26.2-30.6 | 1.44±0.10 |
|  | 30.6-34.7 | 1.54±0.10 |
| $^{10}$B+Si | 25.0-30.0 | 1.58±0.06 |
|  | 30.0-34.3 | 1.65±0.07 |
|  | 34.3-38.4 | 1.58±0.07 |
| $^9$C+Si | 27.7-34.9 | 1.75±0.18 |
|  | 34.9-41.0 | 1.65±0.19 |
|  | 41.0-46.6 | 1.69±0.20 |
| $^{10}$C+Si | 22.6-30.0 | 1.53±0.06 |
|  | 30.0-36.2 | 1.69±0.07 |
|  | 36.2-41.7 | 1.57±0.07 |
|  | 41.7-46.4 | 1.52±0.07 |
| $^{11}$C+Si | 17.3-25.3 | 1.61±0.05 |
|  | 25.3-31.7 | 1.64±0.05 |
|  | 31.7-37.0 | 1.54±0.05 |
| $^{12}$N+Si | 20.3-29.2 | 1.74±0.07 |
|  | 29.2-36.4 | 1.75±0.07 |
|  | 36.4-42.2 | 1.68±0.08 |
| $^{13}$O+Si | 22.5-32.3 | 1.74±0.11 |
|  | 32.3-40.4 | 1.77±0.12 |
|  | 40.4-46.8 | 1.69±0.13 |
| $^{15}$O+Si | 22.1-30.8 | 1.77±0.06 |
|  | 30.8-38.1 | 1.81±0.06 |
|  | 38.1-44.0 | 1.62±0.06 |
| $^{17}$Ne+Si | 27.5-37.7 | 1.99±0.09 |
|  | 37.7-46.3 | 1.92±0.10 |
|  | 46.3-53.3 | 1.84±0.10 |

**TABLE II: Proton-removal cross sections for light nuclei on Si, averaged between the specified energies. The Glauber theoretical predictions are described in Section IV C.**

| Projectile, cross section | Fragment | Energy interval (MeV/nucleon) | Measurement (mb) | Glauber (mb) |
|---------------------------|----------|-------------------------------|----------------|-------------|
| $^7$Be, $\sigma_{1p}$    | $^6$Li   | 26-38                         | 90±6           | 117         |
| $^{10}$B, $\sigma_{1p}$  | $^9$Be   | 30-42                         | 41±3           | 62          |
| $^{11}$C, $\sigma_{1p}$  | $^{10}$B | 17-37                         | 53±2           | 78          |
| $^{12}$N, $\sigma_{1p}$  | $^{11}$C | 20-42                         | 120±6          | 130         |
| $^{13}$O, $\sigma_{1p}$  | $^{12}$N | 23-49                         | 31±5           | 56          |
| $^{15}$O, $\sigma_{1p}$  | $^{14}$N | 22-44                         | 64±3           | 46          |
| $^{17}$Ne, $\sigma_{2p}$ | $^{15}$O | 28-53                         | 223±18         |             |
TABLE III: Proton ($r_\pi$), neutron ($r_\nu$), and matter ($r_m$) rms radii from HF calculations are given in Columns 2 through 4. Column 5 gives experimental values extracted from high-energy reaction cross sections [19]. The last three columns show experimental values extracted from our present data, using Glauber theory (OL) and assuming gaussian, harmonic oscillator, and Woods-Saxon densities.

| Nucleus | $r_\pi$ | $r_\nu$ | $r_m$ | $r_m$(exp) [19] | $r_m$(gauss) | $r_m$(HO) | $r_m$(WS) |
|---------|---------|---------|-------|---------------|---------------|------------|-----------|
| $^6$Li  | 2.33    | 2.31    | 2.32  | 2.32±0.03     | 2.28±0.10     | 2.23±0.11  | 2.30±0.12 |
| $^7$Be  | 2.49    | 2.24    | 2.39  | 2.31±0.02     | 2.28±0.20     | 2.20±0.19  | 2.28±0.20 |
| $^{10}$B| 2.46    | 2.46    | 2.46  | 2.40±0.06     | 2.29±0.13     | 2.24±0.13  | 2.27±0.13 |
| $^9$C   | 2.76    | 2.25    | 2.60  | 2.42±0.03     | 2.75±0.34     | 2.71±0.26  | 2.69±0.25 |
| $^{10}$C| 2.57    | 2.31    | 2.47  | 2.27±0.03     | 2.32±0.14     | 2.29±0.14  | 2.31±0.14 |
| $^{11}$C| 2.53    | 2.41    | 2.48  | 2.26±0.06     | 2.20±0.10     | 2.18±0.11  | 2.23±0.10 |
| $^{12}$N| 2.70    | 2.45    | 2.60  | 2.47±0.07     | 2.51±0.13     | 2.49±0.12  | 2.60±0.12 |
| $^{13}$O| 2.81    | 2.47    | 2.69  | 2.53±0.05     | 2.54±0.21     | 2.54±0.20  | 2.59±0.20 |
| $^{15}$O| 2.69    | 2.58    | 2.64  | 2.44±0.04     | 2.40±0.10     | 2.40±0.10  | 2.45±0.10 |
| $^{17}$Ne| 2.98   | 2.61    | 2.83  | 2.75±0.07     | 2.82±0.15     | 2.84±0.14  | 2.89±0.14 |
TABLE IV: Calculated spectroscopic factors (C^2S) and cross sections \( \sigma(I_e^c) \) to the core excited states \( (E_{ex},I_e^c) \) populated in single proton removal from the projectile \( (^A Z,J^\pi) \) by the silicon target. The contribution arising from stripping \( \sigma_{abs} \), diffractive dissociation \( (\sigma_{diff}) \) and Coulomb dissociation \( (\sigma_{coul}) \) are detailed. The total inclusive cross section \( \sigma_p^{Glauber} \) is corrected for center-of-mass effects as explained in the main text.

| ^A Z | J^\pi | E_{ex} [MeV] | I_e^c | n/lj | C^2S | \sigma_{abs} [mb] | \sigma_{diff} [mb] | \sigma_{coul} [mb] | \sigma(I_e^c) [mb] |
|------|-------|-------------|-------|------|------|-----------------|-----------------|-----------------|-----------------|
| 7Be  | 3/2^-| g.s.        |       | 1p_3/2 | 0.368 | 20.3 | 16.9 | 1.0 | 38.2 |
|      |       | 1p_1/2     | 0.306 | 16.0 | 13.1 | 0.8 | 29.9 |
|      |       | 2.186 3^+  | 1p_3/2 | 0.365 | 18.0 | 14.3 | 0.5 | 32.8 |
|      |       |            |       |      |      |      |      |      | \( \sigma_p^{Glauber} = 117 \text{ mb} \) |
| 10B  | 3^+  | g.s. 3/2^- | 1p_3/2 | 1.097 | 29.3 | 24.6 | 2.30 | 56.2 |
|      |       |            |       |      |      |      |      |      | \( \sigma_p^{Glauber} = 62 \text{ mb} \) |
| 11C  | 3/2^-| g.s. 1^-   | 1p_3/2 | 0.927 | 16.8 | 13.5 | 0.8 | 31.1 |
|      |       | 0.718 1^+  | 1p_3/2 | 0.756 | 13.2 | 10.5 | 0.5 | 24.2 |
|      |       | 1p_1/2     | 0.532 | 8.6  | 6.8  | 0.3 | 15.8 |
|      |       |            |       |      |      |      |      |      | \( \sigma_p^{Glauber} = 78 \text{ mb} \) |
| 14N  | 3/2^-| g.s. 1^-   | 1p_3/2 | 0.073 | 3.3  | 3.4  | 2.0  | 8.8  |
|      |       | 1p_1/2     | 0.518 | 21.6 | 22.5 | 13.5 | 57.7 |
|      |       | 2p_1/2     | 0.001 | 0.07 | 0.07 | 0.04 | 0.2  |
|      |       | 2p_3/2     | 0.002 | 0.13 | 0.14 | 0.08 | 0.35 |
|      |       | 2.000 1/2^-| 1p_3/2 | 0.302 | 8.9  | 8.5  | 2.3  | 19.7 |
|      |       | 1p_1/2     | 0.038 | 1.0  | 0.9  | 0.3  | 2.2  |
|      |       | 4.318 5/2^-| 1p_3/2 | 0.130 | 2.9  | 2.6  | 0.40 | 5.9  |
|      |       | 4.800 3/2^-| 1p_3/2 | 0.085 | 1.8  | 1.6  | 0.2  | 3.6  |
|      |       |            | 1p_1/2 | 0.538 | 10.8 | 9.2  | 1.2  | 21.2 |
|      |       |            | 2p_3/2 | 0.001 | 0.04 | 0.03 | 0.07 |      |
|      |       |            | 2p_1/2 | 0.002 | 0.08 | 0.06 | 0.01 | 0.14 |
|      |       |            |       |      |      |      |      |      | \( \sigma_p^{Glauber} = 130 \text{ mb} \) |
| 15O  | 3/2^-| g.s. 1^-   | 1p_3/2 | 0.086 | 3.4  | 3.4  | 1.03 | 7.83 |
|      |       | 1p_1/2     | 0.537 | 19.3 | 19.1 | 5.84 | 44.24 |
|      |       |            |       |      |      |      |      |      | \( \sigma_p^{Glauber} = 56 \text{ mb} \) |
| 16O  | 1/2^-| g.s. 1^-   | 1p_3/2 | 0.372 | 6.5  | 5.5  | 0.65 | 12.65 |
|      |       | 1p_1/2     | 0.606 | 9.7  | 8.1  | 0.98 | 30.45 |
|      |       |            |       |      |      |      |      |      | \( \sigma_p^{Glauber} = 46 \text{ mb} \) |