$^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ CROSS SECTION STUDY
WITH THE NOTRE DAME 5U ACCELERATOR

A Dissertation

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Stephanie Lyons

Michael C. Wiescher, Director

Graduate Program in Physics
Notre Dame, Indiana
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Abstract

by

Stephanie Lyons

In stars whose temperature is greater than 0.05 GK, hydrogen burning can proceed via the NeNa cycle, which is important for the nucleosynthesis of Ne, Na, and Mg isotopes. The first reaction in this cycle is $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$, which also has the slowest proton capture reaction rate [23], thereby influencing the rest of the cycle. The stellar reaction rate for $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ is dominated by direct capture and the high energy tail of a sub-threshold resonance. The aim of this work is to understand the direct-capture component of this reaction. Using Notre Dame's recently commissioned 5U-4 accelerator, the $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ cross-section has been measured relative to the 1169 keV resonance at low energies using the Rhinoceros gas target. The resonance strength of the 1169 keV resonance was also independently determined. Finally, the cross sections were analyzed with the Notre Dame's R-matrix code AZURE[4].
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CHAPTER 1
INTRODUCTION AND THEORY

In working towards understanding the direct capture to ground state component of the $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$, a review of the astrophysical importance of this reaction and possible sites for this reaction will be discussed to facilitate understanding. But first the astrophysics and reaction theory formalism that will assist in the understanding of this work will be discussed.

1.1 Astrophysics

1.1.1 Stellar evolution

The hydrogen burning stage of a star’s life is the first phase and typically the longest. During this phase the star will convert most of the hydrogen into helium in the core. Once the hydrogen is almost all consumed, the equilibrium of the energy released from the thermonuclear reactions and gravitational potential energy is lost and gravitational force causes the star to contract. Once the temperature and pressure in the core of the star get high enough, helium burning may begin taking place, once again establishing a balance and halting further contraction.

Helium burning is the process of helium nuclei fusing to create carbon. While the core of the star at this point is burning helium, the remaining hydrogen continues hydrogen burning in a shell layer around the core. The process of ther-
mononuclear burning followed by gravitational contraction continues through several burning stages as long as there is sufficient fuel available in the core after each burning cycle, which leaves the star with an onion-like structure. For example, that at the end of helium burning, if there is a sufficient amount of carbon in the core, carbon burning, the process of carbon fusion, may ignite after the star contracts again. Helium burning would then continue in a helium shell around the core, and hydrogen burning would occur in a shell of hydrogen outside of the helium burning shell.

The burning phases of a star can continue all the way up to iron. At this point, it’s no longer possible to generate energy from nuclear fusion in the core. Figure 1.1 shows the average binding energy per nucleon in MeV versus the total number of nucleons contained in the nucleus. The peak of this graph is the “iron group” nuclei, which are the most tightly bound nuclei. The fusion of iron would take away energy rather than provide it, making it an energetically unfavorable process.

When the star no longer has any nuclear fuel, it begins to gravitationally collapse. During the collapse, photo-disintegration of the iron nuclei and electron capture occur, which consume energy and catalyze the collapse. This rapid collapse leads to a massive explosion, known as a Type II supernova. Explosive nucleosynthesis can occur during supernovae explosions. The remnants of a Type II supernova are neutron stars or black holes. The ejection of material from the supernova explosion into the interstellar medium contributes to the cycle of stellar formation.

While the above description is a possible stellar evolution scenario for stars that are massive enough to sustain many burning cycles, less massive stars evolve
Figure 1.1. Binding energy plotted as a function of nucleon number. Energy yield from fusion may occur up to iron, where fusing two iron nuclei is no longer energetically favorable. Energy yield from fission occurs on nuclei heavier than iron.

differently. Once hydrogen burning can no longer sustain equilibrium with the gravitational collapse, the star begins to contract. During the first contraction, hydrogen burning ignites on the shell surrounding the helium core. This intense shell hydrogen burning results in more energy being generated in the core than is able to radiate away. As a result, the outer layers expand and cool. So while the star is brighter, its surface is cooler, or redder, thus these stars are called red giants. The helium core may also begin helium burning as the temperature increases from the hydrogen burning in the shell. The star will eventually run out of fuel causing it to contract. The star may at some point eject its envelope,
becoming a planetary nebula. From there the star will dim and become a white
dwarf. White dwarfs are highly abundant stellar objects due to the fact that most
stars end their life as this type of star. However, due their dim nature they are
also difficult to observe.

1.1.2 Stellar hydrogen burning

Now that an understanding of the evolution of stars has been covered, a de-
scription of the nucleosynthetic processes that take place during these events will
be discussed. If a star is formed mainly of hydrogen or is less than 1.5 M\(_\odot\),
then the hydrogen burning phase will take place primary via the proton-proton
chain, which will produce the thermonuclear energy in the star. The pp-chain is
a series of hydrogen fusion reactions that combine 4 protons into helium, and in
doing produces 26 MeV of energy. In stars similar to our Sun, hydrogen burn-
ing proceeds mainly through the pp-chain, which little contribution from heavier
elements. However, in more massive stars which contain heavier elements and
burn at higher temperatures, heavier elements may act as a catalyst for hydrogen
burning. The carbon-nitrogen-oxygen cycles, or CNO cycles, contribute mainly
to the energy generation in these stellar environments. The CNO cycles, similar
to the pp-chain, process hydrogen into helium. Unlike the pp-chain, the CNO
cycles begin and end with \(^{12}\text{C}\), meaning that the carbon is not depleted, but re-
mains available for further processing of hydrogen. Figure 1.2 shows two possible
nucleosynthetic pathways of the CNO cycle. The second possible nucleosynthesis
pathway, CNO II, is shown by including the teal colors isotopes into the network.

If hydrogen burning takes place in a much hotter environment, such as in novae
or red giant stars, the CNO cycle can proceed via rapid proton capture to push
Figure 1.2. Details of the nucleosynthesis from the CNO cycle $I$ (white isotopes only) and $II$ (teal isotopes included). The cycle begins with the proton capture on $^{12}\text{C}$ and ends with proton capture and subsequent $\alpha$-decay on $^{15}\text{N}$, getting back to $^{12}\text{C}$. The cycle is a series of proton-captures and $\beta$-decays that process hydrogen into helium.
beyond nuclei that would otherwise $\beta$-decay. Figure 1.3 shows this process, known as the hot-CNO cycle or HCNO cycle. In a hotter environment, proton-capture can exceed the rate of $\beta$-decay and push to heavier nuclei. This cycle also opens the possibility of further nucleosynthesis on heavier nuclei.

1.1.3 NeNa cycle

Another hydrogen burning cycle is the NeNa cycle. This cycle requires even higher temperatures than those required to synthesize helium via the CNO cycle. The NeNa cycle, shown in Figure 1.4, begins with $^{20}\text{Ne}$, which can be formed in stellar environments through various phases of burning. As shown in Figure 1.3, $^{20}\text{Ne}$ can be produced from the HCNO cycle via proton capture on $^{19}\text{F}$ or via $\beta$-decay of $^{20}\text{Na}$. Additionally, $^{20}\text{Ne}$ can be formed during advanced stages of burning. During helium burning, $^{20}\text{Ne}$ may be formed by alpha-capture onto $^{12}\text{C}$ which is formed through the triple-$\alpha$ process, followed by another alpha-capture onto the formed $^{16}\text{O}$. The break-out reactions as well as the alpha capture on $^{16}\text{O}$ are limiting due to the low cross-sections. During carbon-burning, $^{20}\text{Ne}$ may be formed via $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$, though this reaction may only occur in stars massive enough to burn carbon.

If a star is massive enough to complete the carbon burning stage, but cannot continue into the Ne-burning phase, it may form a white dwarf that is enriched in oxygen and neon. If this white dwarf is part of a binary system, the NeNa cycle can take place as hydrogen-rich material is accreted onto the surface of the white dwarf. As compression increases from the material being accreted, the material heats to the point of ignition. This can cause the necessary drive to produce the thermonuclear runaway that produces classical novae. Additionally, convection...
Figure 1.3. Nucleosynthesis pathways from the hot-CNO cycle that in hotter temperature environments ($10^8 - 10^9$ K or higher), such as in supermassive stars, novae and supernovae outbursts, and accreting neutron stars. Compared to Figure 1.2 the possibility of further nucleosynthesis becomes evident. Notice the possible production of $^{20}$Ne.
Figure 1.4. Nucleosynthesis pathways of the NeNa cycle. The color coding denotes the two possible pathways for the cycle. The pink isotopes denote the cycle pathway where the $\beta^+$ decay dominates, leading to the production of more Ne isotopes. The teal isotopes denote the pathway where proton capture dominates. Isotopes colored with both are involved in both possibilities.

causes material from beneath the surface of the white dwarf to be dredged-up, causing an enhancement in heavier isotopes available for nucleosynthesis within the accretion disk [31]. Novae occurring in ONe white dwarfs explain the high concentrations of Ne as well as other heavier isotopes found in spectra from well-observed novae [24]. It should be noted that ONe novae make-up 25-57% of all novae [31]. These novae are also of interest because they may be the sites of nucleosynthesis for $^{22}$Na and $^{26}$Al, which are two radioactive nuclei that produce signature gamma-rays in our universe [24, 47].

Another astrophysical location for the formation of $^{22}$Na and $^{26}$Al is in globular cluster red giant stars. Variations in abundances of the carbon, nitrogen, oxygen, sodium, and aluminum, which were unexplained by canonical stellar evolution models, were observed in clusters of RGB stars [12, 40]. One potential answer comes from mixing from the hydrogen shell into the envelope of the star [44].
heavier elements that are synthesized in the core of the star are brought to the H-shell during the standard first dredge-up in RGBs[12]. From there, the CNO-, NeNa, and MgAl cycles may take place in a various regions of interplay between the H-shell and the envelope depending on the temperatures achieved. The higher levels of Na and Al observed in the RGB clusters can then be explained by the nucleosynthesis taking place in regions outside of the core of RGB stars. Additional evidence for mixing comes from a decrease in carbon abundances coupled with an increase in the luminosity in low-intermediate metalicity clusters [13]. From the various studies of RGB stars, the NeNa cycle is proven to be of great importance to explaining the abundance of various observables.

1.1.4 The particular importance of $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$

It should be clear at this point that the NeNa cycle is of importance to further our understanding of the stellar objects we observe. This thesis work focuses on the determination of the reaction rate and cross-section of the first reaction in the NeNa cycle, $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$. Along with being the first reaction in the cycle, it is also predicted to have the slowest reaction rate, by an order of magnitude, compared to the rest of the reactions in the cycle as shown in Table 1.1 [23].

Because $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ is the slowest reaction, it sets the timescale of the cycle and ultimately the final abundances of the isotopes that are synthesized. This dependence on $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ also makes it a limiting factor for the $^{22}\text{Na}$ production in novae and RGB stars.
## TABLE 1.1

### REACTION RATES AND HALF LIVES OF THE NENA CYCLE

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Recommended Reaction Rate</th>
<th>$\beta^+$ Decay</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$</td>
<td>$5.91 \times 10^{-6}$</td>
<td>$^{21}\text{Na}$</td>
<td>23 s</td>
</tr>
<tr>
<td>$^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$</td>
<td>$1.99 \times 10^{-2}$</td>
<td>$^{22}\text{Mg}$</td>
<td>3.9 s</td>
</tr>
<tr>
<td>$^{21}\text{Ne}(p,\gamma)^{22}\text{Na}$</td>
<td>$1.08 \times 10^{-1}$</td>
<td>$^{22}\text{Na}$</td>
<td>2.6 y</td>
</tr>
<tr>
<td>$^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$</td>
<td>$2.76 \times 10^{-2}$</td>
<td>$^{23}\text{Mg}$</td>
<td>11 s</td>
</tr>
<tr>
<td>$^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$</td>
<td>$3.68 \times 10^{-5}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{23}\text{Na}(p,\alpha)^{20}\text{Ne}$</td>
<td>$1.47 \times 10^{-2}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Reaction rates taken from Illiadis (2001) (at $T=2 \times 10^8\text{K}$) and $\beta$-decay half-lives from the Chart of the Nuclides [23].
1.2 Understanding Stellar Reactions

The previous sections demonstrated the importance of understanding $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$. Understanding these systems in the laboratory can be challenging, and so some of general ideas and concepts will be presented for use in subsequent chapters.

1.2.1 Cross sections and reaction rates

To study stellar environments, it is pertinent to understand how frequently a reaction will take place. This helps to infer which reactions are the strongest and how they contribute to the energetics of the star. The probability that a reaction will occur is called the cross section. From a classical perspective, the cross section is merely the probability of the two nuclei interacting with each other can be determined by the combined area of the two nuclei,

$$
\sigma = \pi (R_A + R_a)^2 \quad (1.1)
$$

where $R_A$ and $R_a$ are the radii of the target and projectile nuclei, respectively. Given that a nucleus has a radius,

$$
R = R_0 A^{1/3} \quad (1.2)
$$

where $R_0 = 1.25 \times 10^{-15} m$ and $A$ is the atomic number of the nucleus. For $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ the classically derived cross section is:
\[ R_{20Ne} = 3.5 \times 10^{-13} \text{cm} \]
\[ R_p = 1.25 \times 10^{-13} \text{cm} \]
\[ \sigma = \pi (4.5 \times 10^{-13} \text{cm})^2 = 0.64 \times 10^{-24} \text{cm}^2 = 0.64 \text{ barns} \]

It would be nice if all cross sections could be calculated purely geometrically. However, in reality, the cross section cannot be determined classically because nuclear reactions are quantum mechanical systems. Replacing the geometrical expression with one describing the wave nature of particles involved, the cross section becomes,

\[ \sigma = \pi \lambda^2 = \pi \left( m_a + m_A \right) \frac{\hbar}{m_A \left( 2m_aE \right)^{1/2}} \]

where \( \lambda \) is the deBroglie wavelength, \( m_a \) and \( m_A \) are the projectile and target mass, respectively, and \( E \) is the lab energy. From the above equation, it becomes clear that the cross section is an energy dependent quantity. Other factors may also contribute to the energy dependence of the cross section, such as angular momentum and the nature of the force involved in the reaction. From the energy dependence of the cross section, it is also easy to understand that the cross section is also, therefore, velocity dependent. Due to the stellar environment this describes, it should be noted that the dependency is upon the relative velocity.

The cross section gives valuable information regarding the likelihood of the interaction taking place in a stellar environment. It influences the rate at which the reactions occur. This rate is called the reaction rate, and it determines the
production and consumption of the nuclei in question. In stellar models the reaction rates of the various reactions lead to the isotopic abundance evolution within the stellar environment being simulated and without an accurate understanding of these reaction rates, an accurate picture cannot be determined. The reaction rate is defined mathematically,

\[ r = N_A N_a v \sigma (v) \quad (1.5) \]

where \( N_A \) and \( N_a \) are the number of projectiles and target particles per unit volume, \( v \) is the velocity of the projectiles and \( \sigma (v) \) is the cross section, in terms of velocity, of the reaction. In a laboratory setting, where the beam energy determines the velocity of the particles being impinged upon a target that is at rest, this seems a simple consideration. However, in a stellar environment where both of the particles would be moving, this becomes more complex. Inside a star, the particles would not just have a single velocity, but they have range of velocities, which can be described by a probability distribution, defined as,

\[ \int_0^\infty \phi (v) dv = 1 \quad (1.6) \]

where \( \phi (v) dv \) is the probability that the relative velocity of the particles in the reaction is between \( v \) and \( dv \). This quantity is then added to the reaction rate,

\[ r = N_A N_a \int_0^\infty \phi (v) v \sigma (v) dv \quad (1.7) \]
The value of reaction rate per particle pair is also often used. This is denoted \( \langle \sigma v \rangle \) and is merely the reaction rate divided by \( N_A N_a \), which is just defined as the cross section integrated over the velocities of the interacting particles.

To further describe the reaction rate, the probability distribution of the velocities can be described by the Maxwell-Boltzmann velocity distribution 1.8, which describes a gas in thermodynamic equilibrium.

\[
\phi(v) = 4\pi v^2 \left( \frac{m}{2\pi kT} \right)^{3/2} \exp \left( -\frac{mv^2}{2kT} \right)
\]  

where \( T \) is temperature of the gas, and \( m \) is the mass of the nucleus of interest. The energy dependence of the probability function can be seen in the numerator of the exponential term. The velocity distribution is described by Equation 1.8 for both of the particle in the reaction. Therefore, the reaction rate per particle pair requires a double integral over both.

\[
\langle \sigma v \rangle = \int_0^\infty \int_0^\infty \phi(v_A)\phi(v_a)v\sigma(v)dv_A dv_a
\]  

This can be written in terms of relative velocity, \( (v) \), and center of mass velocity, \( (V) \), which transforms the velocity distributions into,

\[
\phi(V) = 4\pi V^2 \left( \frac{M}{2\pi kT} \right)^{3/2} \exp \left( -\frac{Mv^2}{2kT} \right)
\]

\[
\phi(v) = 4\pi v^2 \left( \frac{\mu}{2\pi kT} \right)^{3/2} \exp \left( -\frac{\mu v^2}{2kT} \right)
\]
where $M$ is total mass $(m_A + m + a)$, and $\mu = \frac{m_A m_a}{(m_A + m_a)}$ is the reduced mass. Inserting these expressions for the velocity distributions back into Equ.1.9, it can be seen that the cross section is dependent only upon the relative velocity, and the center of mass velocity distribution can immediately be integrated, leaving the reaction rate per particle pair,

$$\langle \sigma v \rangle = \left( -\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_{0}^{\infty} \sigma(E)E \exp\left(-\frac{E}{kT}\right) dE$$

(1.12)

where $E = \frac{1}{2} \mu v^2$. From Equation 1.9, the reaction rate is determined for a given temperature, $T$. This expression also contains the energy dependent cross section, which reflects the reaction mechanisms, non-resonant and resonant, involved in the process of interest.

1.2.2 Non-resonant reactions

Non-resonant, or direct capture reactions occur, when the projectile goes directly into the final nucleus, emitting excess energy as a gamma ray of energy $E_\gamma = E + Q + E_i$. Direct capture reactions take place in a single step and therefore take place quickly. Non-resonant reactions can occur at any energy and vary smoothly with energy. To begin looking at this process we first we can examine how particles interact both classically and quantum mechanically.

Classically, as two particles approach each other, they are repulsed from each other via the Coulomb force. So to interact they must overcome the Coulomb potential. This means that the energy of the incoming particle has to be greater than the potential that it feels from the target particle. If the particles were able to get close enough, the attractive nuclear force would take over and the reaction
would take place. Classically, if the energy was high enough to overcome the Coulomb barrier, the reaction could always take place. In a stellar environment, the temperature determined the energy available via \( E = kT \). This would imply that if the temperature of the star were hot enough, all of the reactions would be able to take place at the same time. However, this would lead to a very short-lived star, and because stars live for long time periods, there must be another solution.

From quantum mechanics, a particle with energy less than the Coulomb barrier has a small, but finite probability to tunnel through the barrier to the point where the nuclear force can take over. The relevant solution to the Schrödinger equation gives the following equation for the tunneling probability,

\[
P = \exp \left[ -2RC \sqrt{\frac{2\mu}{\hbar^2}} (E_C - E) \left( \text{arctan} \left( \frac{RC}{Rn} \right) - 1 \right)^{-1/2} \right]
\]

where \( RC \) is the classical turning point from the Coulomb barrier, \( Rn \) is the nuclear radius, \( E_C \) is maximum energy of the Coulomb barrier. In the case where \( RC \gg Rn \) (or \( E \ll E_C \)), the tunneling probability can be approximated by

\[
P = \exp(-2\pi\eta) \text{ where } \eta = \frac{Z_1 Z_2 e^2}{\hbar \nu}
\]

This is commonly referred to as the Gamow factor. As shown in Figure 1.5 the peak arises from the interference of the Maxwell-Boltzmann expression and the quantum mechanical tunneling probability.

Due to the exponential behavior of the tunneling probability, the cross section for charged particle reaction plummets for energies below the Coulomb barrier.
Figure 1.5. Plots of the two components that lead to the Gamow peak energy window.

From the previous description of the cross section, it is also dependent on the deBroglie wavelength, as well as several nuclear effects. Combining these contributions to the cross section another definition can be derived.

\[ \sigma(E) = \frac{1}{E} \exp(-2\pi\eta)S(E) \]  \hspace{1cm} (1.15)

This expression contains the energy dependence of the deBroglie wavelength \((1/E)\), the exponential behavior from the Coulomb potential, and all nuclear effects, which are put into the \(S(E)\) term. \(S(E)\) is referred to as the astrophysical S-factor, which varies smoothly in a non-resonant regime. This expression can also be used in Equation 1.9, to give the reaction rate per particle pair in terms of the S-factor.
\[
\langle \sigma v \rangle = \left( -\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp \left( -\frac{E}{kT} - \frac{b}{\sqrt{E}} \right) dE
\]

\[b = (2\mu)^{1/2} e^2 \frac{Z_A Z_a}{h}\]

The \(b\) term comes from the penetrability. Also by taking the derivative of the integral and setting it equal to zero, the maximum value of the Gamow peak can be determined. This is the effective mean energy for a reaction at a given temperature, \(T\).

\[
E_0 = \left( \frac{bkT}{2} \right)^{2/3} = 1.22(Z_A^2 Z_a^2 \mu T_0)^{1/3}[keV]
\]

1.2.3 Resonant reactions

In contrast to non-resonant reactions, resonant reactions occur at very specific energies, which are determined by the excited states in the resultant compound nucleus. When the entrance channel energy matches up with the level energy of an excited state, the projectile can go into that state from which it then decays. In contrast to direct-capture, this process takes place in two steps. Resonant reactions are particularly important in nuclear physics because they reveal level structure information about the final nucleus. Additionally, resonances often cause a dramatic increase in the cross section, sometimes by orders of magnitude, which makes them easier to measure than non-resonant cross sections. Because resonances are limited to narrow energy ranges, the cross sections are strongly dependent on energy:
\[
\sigma(E) \propto \frac{\Gamma_a \Gamma_b}{(E - E_R)^2 + (\Gamma/2)^2}
\]  

(1.18)

where \( \Gamma = \Gamma_a + \Gamma_b + \ldots \) etc. is the total width of the resonance. Taking to consideration the angular momentum of the excited state in the compound nucleus, as well as the spins of the target and projectile nuclei, the cross section becomes:

\[
\sigma(E) = \pi \lambda^2 \frac{2J + 1}{(2J_1 + 1)(2J_2 + 1)} \left( 1 + \delta_{12} \right) \frac{\Gamma_a \Gamma_b}{(E - E_R)^2 + (\Gamma/2)^2}
\]

\[
\omega = \frac{2J + 1}{(2J_1 + 1)(2J_2 + 1)} \left( 1 + \delta_{12} \right)
\]  

(1.19)

The factor \( \omega \) is the statistical factor from the angular momentum consideration and it includes the factor, \( \delta_{12} \), to account for identical entrance particles. This expression for the cross section is called the Breit-Wigner formula. This expression is only valid for narrow, isolated resonances where the total width is much smaller than the resonance energy. Using the Breit-Wigner cross section, the reaction rate per particle pair can also be found.

\[
\langle \sigma \nu \rangle = \left( -\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma_{BW}(E) \exp\left( -\frac{E}{kT} \right) dE
\]  

(1.20)

In the case of a narrow resonance, both the Maxwell-Boltzmann function and the partial and total widths are essentially constant over resonance energy region can be taken out of the integral, which leaves the integral of the Breit-Wigner left to solve for the reaction rate.
The product of the statistical factor, $\omega$, and the ratio of the widths is referred to as the resonance strength, $\omega \gamma$. This value is proportional to the integrated cross section and is commonly used as reference to compare resonances. Using this expression in Equation 1.20,

$$\langle \sigma \nu \rangle = \left( \frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 (\omega \gamma)_R \exp \left( -\frac{E_R}{kT} \right) \tag{1.22}$$

Therefore, by measuring the resonance strength, width, and energy the reaction rate per particle pair can be calculated. Also of note, is that for narrow resonances the effective stellar burning temperature is determined by the resonance energy, rather than the Gamow peak, which determines the effective burning temperature for non-resonant reactions.

1.2.4 Yields

The measurable quantities from laboratory experiments that are used to determine cross sections will now be discussed. The cross sections have been shown to lead to the determination of reaction rates, which can give us information regarding various stellar processes. As previously discussed, a typical experimental measurement requires that particles of some energy, $E$, be impinged upon a target
in order to observe the reaction’s outcome via the appropriate type of detector. The probability that a projectile particle interacts with a target nucleus is known as the reaction yield, $Y$. The yield is given by

$$Y = N\sigma \Delta x$$  \hspace{1cm} (1.23)

where $N$ is the number of target nuclei per unit volume and $\Delta x$ is the thickness of the target. Unfortunately, determining the number of target nuclei is often difficult to do. However, the energy loss by the beam while passing through the target, $\Delta E$, can be measured. And the stopping power cross section, $\epsilon = \frac{dE}{\Delta x}$, can also be determined. The stopping power cross section is the energy lost per particle per unit area by the projectile in the medium of the target. Using the energy loss and stopping power, the yield for a thin target becomes,

$$Y = \sigma \frac{\Delta E}{\epsilon}$$  \hspace{1cm} (1.24)

The above equation for the yield only involves values that can all be determined experimentally. For thicker targets, this expression is then integrated over the target thickness, as shown in Equation 1.25.

$$Y(E_0) = \int \sigma(E) nd\tau = \int_{E_0 - \Delta E}^{E} \frac{\sigma(E)}{\epsilon(E)} dE$$  \hspace{1cm} (1.25)
In the case of a narrow resonance, the integration of the cross section is also included and results in the following expression,

\[ Y(E_0) = \frac{\lambda^2}{2\pi} \frac{M + m}{M} \frac{1}{\epsilon} \gamma \left[ \arctan \left( \frac{E_0 - E_R}{\Gamma/2} \right) - \arctan \left( \frac{E_0 - E_R - \Delta E}{\Gamma/2} \right) \right] \]  

This expression is called the thick target yield and takes into account the stopping power, resonance strength, as well as the mass ratio, where \( M \) is the mass of the target nuclei and \( m \) is the mass of the projectile. The resonance width, \( \Gamma \), and target thickness, \( \Delta E \), determine the shape of the thick target yield. If \( \Delta E \ll \Gamma \), the yield shape is Lorentzian, corresponding to the shape of the cross section. The maximum yield is located at the resonance energy, \( E_R \). On the other hand, if \( \Delta E \gg \Gamma \), then the shape of the yield is determined by the arctangent function, with a flat plateau (\( Y_{\text{max}} \)) at \( E_R + \Delta E/2 \) and the FWHM approximately equal to the resonance width.

But how is the yield determined from the measured quantities of the experiment? For this, recall that the yield is the likelihood of the reaction taking place, or the number of reactions per incident particle. This can be expressed as the number of measured reaction products divided by the number of beam particles impinged upon the target.

\[ Y = \frac{N_{\text{reactions}}}{N_{\text{beam}}} = \frac{N_{\text{counts}}}{N_{\text{beam}}B\eta W(\theta)} \]  

This ratio of reactions to projectiles typically requires the number of counts
from the reaction to be corrected for branching ratios \((B)\), detection efficiency \(\eta\), and angular distributions \(W(\theta)\). All of the correction factors can be determined through experimental tests. The above equation can be used to determine the resonance strength and cross section, as shown in Equation 3.1 1.29.

\[
\omega_{\gamma} = \frac{2}{\lambda_R} \frac{\epsilon_R}{\Delta E} \int_0^\infty Y(E_0) dE_0 = \frac{2}{\lambda_R} \frac{\epsilon_R}{\Delta E} \frac{1}{B\eta W(\theta)} \int_0^\infty \frac{N(E_0)}{N_{\text{beam}}} dE_0 \tag{1.28}
\]

\[
\sigma(E) = \frac{Y(E_0)}{n} = \frac{\epsilon}{\Delta E N_{\text{beam}} B\eta W(\theta)} N_{\text{counts}} \tag{1.29}
\]

The results would lead to an absolute determination of these values. While an absolute value is preferred, it is much easier and useful for removing systematic errors, to determine resonance strengths and cross sections relative to an absolute, known standard value for these. By taking the ratio of an unknown resonance strength or cross section with a known resonance strength or cross section, many of the parameters that are the same for both values cancel out. Additionally, a resonance strength or cross section can be found relative the other and vice versa. This is another common experimental tactic to eliminate the need for a precise knowledge of experimental variables that are difficult to measure precisely.

1.3 Previous Work

The astrophysical importance of the \(^{20}\text{Ne}(p,\gamma)^{21}\text{Na}\) reaction and necessary base of reaction formalism has been introduced. The experimentation described in the remainder of the dissertation was performed to improve our understanding of the
direct capture to ground state transition in $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$. This reaction was previously measured by Rolfs et al. [37]. This experiment, performed at California State University, used beams from a 4MV Van de Graaff accelerator and a recirculating gas target with high purity neon gas of natural isotopic abundance. Gamma rays were detected using Ge(Li) detectors at 0 and 90° and elastic scattering was measured using a ruggedized Si detector at 135°. The goal of this thesis work is to improve upon these measurements, as they are currently the only available measurements of this cross section in the literature.

In the following chapters I will discuss Notre Dame’s new 5U accelerator and the Rhinoceros gas target, which were used in the present cross section measurements. Additionally, an independent measurement of the 1169 keV resonance strength in $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ was performed. This value was used for determining the cross section of $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ relative to the 1169 keV resonance. The cross sections are then used in R-matrix fitting to determine the astrophysical S-factor and compared to Rolfs et al. [37]. The reaction rate for this reaction was also determined and compared compared to existing rated available in various reaction rate databases.
CHAPTER 2

THE 5U-4 ST.ANA ACCELERATOR

In preparation for the cross section measurements of the $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ reaction, the Nuclear Science Laboratory’s new accelerator needed to be installed and commissioned for experimental use. In this chapter, I will describe the 5U and discuss the initial tests that were performed in working towards completing the cross section measurements.

2.1 NSL Welcomes the 5U-4

In December 2011, the Stable beam Accelerator for Nuclear Astrophysics, or St. ANA 5U-4 accelerator was delivered to the University of Notre Dame’s Nuclear Science Laboratory (NSL). The 5U’s purpose was to provide beam to the target room that was already in place for use by the KN and JN accelerator, and specifically to St. George, which will require a variety of high intensity, heavy isotope beams. Due to the intensity of beams the 5U will be able to produce, this new accelerator was used to make the cross section measurements of $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ because of the small cross sections at low energies. Before the experiment could be performed, the 5U had to be built and commissioned. The cross section measurements presented were one of the first experiments performed using the 5U, and as such more detail will be paid to the specifics of the 5U in this chapter.
The building infrastructure to hold the four-story vertical machine was put in place in October of 2011. The steel tripod that supports the tank base was constructed and the accelerator tank was placed via crane onto the steel supports. Once the tank was secure, the pre-cast, high-density concrete walls of the building were brought in and placed around the tank. The rest of the building infrastructure was constructed and the roof was placed on the tower structure.

Once the building itself was complete, National Electrostatic Corporation, NEC, guided the construction of the accelerator inside the tank. This required a lift-system inside the accelerator tank to be built first so that the accelerator could be built from the bottom up. The 5U is a pelletron accelerator and works under the same principles as previous accelerators. So before going through the components of the 5U, it is suitable to now review the basic principles of how a Van de Graaff accelerator works.

### 2.2 How a Van de Graaff Accelerator Works

A Van de Graaff accelerator produces high voltage by transporting positive charge from ground to a Faraday cage with a field free interior, referred to as the terminal. In the 5U-4, charge transportation is achieved by four motor-driven pelletron chains, which are made of metal pellets connected by insulating nylon links. The method by which the charge is transported is the difference between a pelletron and more traditional belt driven Van de Graaff. Looking at one link in the chain we can understand how the high voltage of the terminal is achieved. The link is charged by a negatively charged inductor electrode, which pushes electrons off while the pellet is in contact with the grounded drive pulley, leaving each pellet positively charged. This small amount of positive charge is then transported to the
terminal where the reverse process occurs, charging the terminal [17]. This process occurs for each link on the four chains of the 5U-4 and the system can deliver up to 125 per chain. The high voltage of the terminal is given by the relation $V = Q/C$, where $Q$ is the transported charge and $C$ is the capacitance of the terminal [38, p.201]. Because irregularities in the links of the pelletron chain cause small variations in the charge delivered to the terminal. These fluctuations need to be compensated for in order to maintain a constant terminal voltage. This is done through a set of metal needles on a position adjustable arm from the terminal shell called corona points. When the corona points are positioned close enough to the terminal, a discharge begins at the points causing charge to flow from the terminal through the points. A variable resistor within the circuitry connected to the corona points is adjusted to increase or decrease the charge extracted from the terminal to maintain a constant terminal voltage.

The terminal voltage is monitored by a generating volt meter, or GVM, which is a set of two metal vanes: a stationary one, which is positioned behind the rotating vane. The GVM is positioned across from the terminal shell inside the tank, so it is exposed to the electric field at the terminal. The rotating vane momentarily cover and expose the stationary vanes thereby varying the capacitance of the GVM, which is used to determine the terminal voltage. This device is also used in an operating mode of the accelerator called GVM mode. In this mode, the GVM is compared to a voltage set by the experimenter and the error signal created is used to adjust the variable resistance in the corona points to cause the voltage to change until the reference and the GVM signals agree.

The high voltage on the terminal is used to accelerate the beam as it experiences a uniform voltage drop down the acceleration tube and column, which is
achieved through a resistor chain that connects the electrodes that are separated by insulating sections. The electrodes act as electrostatic lenses, providing some focusing properties. The tube and column are housed within a uniformly spaced stack of metallic rings, called equipotential rings, that are connected to a resistor chain. The corona rings help to improve stability of the high voltage by making sure the electric field is uniform. The radius of curvature of the corona rings and terminal shell are as large as possible to reduce field gradients. To prevent sparking, the entirety of the accelerator structure is housed in large pressure vessel, which is pressurized to 85 psi of an electrically insulating gas. SF$_6$ is used in the 5U-4.

Maintaining a constant voltage on the terminal requires a balance of the transported charge to the terminal with the charge losses from beam, corona discharge, and the resistors and can be given by Kirchhoff’s Rule, Equation 2.1 [38]. Increasing the charge on the chains raises the terminal voltage, while increasing the amount of charge losses decreases the voltage. From the equation, it is clear that the charging current limits beam intensity.

$$I_{chains} = I_{beam} + I_{cor} + I_{res}$$  \hspace{1cm} (2.1)

After leaving the accelerator the beam is analyzed by an electromagnetic dipole magnet, which bends it through a slit system, which provides another operation mode to maintain a stable voltage, called slit mode. If, for example, the voltage has decreased to below the desired value, the beam is bent more by the analyzing magnet and more intensity will appear on the low-energy slit. The difference in current on the high and low-energy slits is amplified and the produces an error
Figure 2.1. Diagram of a Van de Graaff accelerator. The charge transportation is shown here with a belt, whereas the 5U-4’s charge transportation is achieved via a pelletron chain [38].
signal that is used to adjust the variable resistor in the corona points to cause the terminal voltage to adjust. The error is minimized when the two slits are in equilibrium, which would indicate that the beam is going through the center. The mechanisms describing the voltage regulation of the accelerator can be seen in Figure 2.1.

2.3 A New Perspective

Now that the basic principles of how an accelerator works have been reviewed, some of the other design aspects and advantages the 5U provides for the next phase of nuclear astrophysics experimentation will be discussed.

Due to the weight of the terminal of the accelerator, it was required to construct it vertically. Because the ion source is housed inside the terminal of the accelerator, this would put a tremendous amount of weight on the terminal end of the accelerator. In the case of a horizontal design, gravity would have pulled the terminal down, thereby complicating the optics and making it impossible to get beam out of the accelerator. To solve this problem, the accelerator was placed vertically, which then utilized the 90° bend analyzing magnet to return the beam to horizontal so that the beam could be transported to the target room.

2.4 ECR Ion Source

The Electron-Cyclotron Resonance (ECR) ion source is an advantage of the 5U. The 5U uses a Pantechnik Nanogen 14.5 GHz ECR source. There are many advantages to an ECR source, but before these are described, it is important to first understand how these devices work.
2.4.1 How does the ECR source work?

As the name would indicate, an ECR ion source utilizes the electron cyclotron resonance to produce and maintain a plasma of the desired ion beam. ECR sources are designed as open-ended magnetic traps for electron plasmas. The configuration of the magnets is such that the magnetic field is a minimum at the center and increases radially outward, thus confining the plasma and stabilizing it. This magnetic configuration is achieved by combining an axial magnetic field with a multipole magnetic field. This configuration can be achieved with the use of electromagnetic coils, or, as in source in the 5U, permanent magnets. A diagram of the magnetic configuration is shown in Figure 2.2 [30, p. 213]. Positively charged ions and electrons are generated from the neutral gas of the desired beam that is put into the source [42]. The electron plasma is formed within the closed ECR surface. To selectively heat the electrons, an electromagnetic wave with a frequency equal to the cyclotron frequency of the electrons in the magnetic field is introduced to the plasma, as shown in Equation 2.2.

\[
\omega_{ce} = \frac{e|B|_{ecr}}{m_e} = \omega_{rf}
\] (2.2)

The ions are confined within this surface and ionized via collisions with the electrons. In this way the electrons that are used for the confinement are also used for enhancing the ionization. The electron density plays an important role in achieving the plasma [30, p.213]. To enhance the electron density, various electron sources can be utilized to enhance the performance of the source from electron guns to chamber wall coatings that produce supplementary electron emissions [33].
In the ECR source for the 5U, supplementary electrons are also emitted from a low voltage negatively biased probe, which can be tuned. From understanding of how the ECR source works, the main controls for gaining the desired ion beam from the source are the RF power and gas pressure in the source. From tuning these parameters, the ionization time can be matched to the confinement time for desired beam, thus optimizing the plasma to produce stable beams.

2.4.2 Advantages of an ECR source

Now that an understanding of the how the ECR source works has been established, the advantages of this type of source can be discussed. The ECR’s advantages over other ion sources is that it can produce ion beams of a wide range of the species with good stability, reliability, and longevity [33]. ECR sources are capable of delivering high intensity beams of high and intermediate charge...
states. Also because they do not have a cathode or filament, they require almost no maintenance. While they do have advantageous qualities, especially for use in nuclear physics, there are also some disadvantages. One of the main drawbacks is that the ions are produced via plasma confinement, and therefore not directly controlled \[33\]. This leads to another drawback of ECR sources, complicated tuning. This is a specific drawback in the Nuclear Science Laboratory since it is a student operated laboratory. Because the source requires specific tuning, there is a steep learning curve to being able to optimize the source.

2.5 Segmentation

The 5U’s specialized design also includes a segmented column. Each segment of the column represents a voltage of 1 MV totaling the full 5 MV capacity of the accelerator. Each of the segments can be shorted out separately with a stainless steel shorting rod, as shown in Figure 2.3. Nylon rods are also available to enable experimenters to choose which segments they would like to include.

This design is advantageous because setting temporary limits in such a way allows experimenters to achieve stable voltages down to $\sim$300kV with improved optics. This enables reactions at astrophysically important energies to be measured directly instead of relying on theoretical projections. Additionally, this provides operators the ability to bypass a segment that may be having problems and continue to use the accelerator. The main advantage of the segmented column is the improved beam optics at low energies. At low beam energies, the voltage gradient as the beam travels down the tube is too shallow and does not provide enough focusing to get the maximum beam output. However by shorting out sections of the column, in 1 MV segments, the voltage gradient increases and
Figure 2.3. NEC Schematic of the 5U. For scale, the outline of a person is in yellow. The pink highlighted region denotes 2 sections of the column. These are the individual segments, of 1MV each, that make up the 5MV single ended accelerator.
improves the focusing provided by the tube.

2.6 Stabilizer System

In addition to the standard controls of a pelletron accelerator that maintain a stable voltage, the 5U-4 has added design features that are meant to help with the voltage stability of the machine. The main feature that was added to the 5U was a liner. The liner is a large aluminum plate that is curved to the shape of the outer edge of the tank. The liner is positioned to stand a few millimeters from the surface of the tank edge to prevent discharging to the tank. It is placed across from the terminal shell of the 5U and is connected to HV, which can then adjust the terminal voltage quicker than the corona system. This leaves the high frequency voltage fluctuations, which can affect the beam resolution less than the typically larger low frequency fluctuations, which the liner helps to eliminate. The signal from the voltage on the liner is adjusted by the stabilizer system to maintain a stable terminal voltage. The amplification of the liner signal is controlled by the operator and therefore can be changed as part of the tune. The liner gain is typically left at 80% and the CPO gain is adjusted from 30% to 50-60% when the liner is turned on. The liner can be seen in Figure 2.3 at the top, wrapping around the terminal.

During commissioning experimentation, the energy resolution of the beam with both the liner on and off was measured to evaluate the effect of eliminating the low frequency fluctuations in the voltage of the accelerator. Results for these test are presented later in this chapter.
2.7 5U-4 Layout Overview

2.7.1 Beam production and acceleration

Now that some design aspects of the 5U have been discussed, the general layout of the accelerator and beamline will be reviewed. Starting at the top, the beam is created by the previously discussed ECR ion source, which is housed inside the terminal as shown in Figure 2.4. The beam is then extracted, focused and charge analyzed by several components housed in the terminal of the accelerator. The extractor, as its name would suggest, extracts the beam from the ion source, but not actively. As the ions in the plasma drift towards the exit of the ion source, they experience their first kick of acceleration (typical setting is 17kV) to transport the ion beam through the rest of the elements in the terminal. The beam is first analyzed by a 40° terminal bending magnet that selects for the desired momentum to charge ratio as set by the operator. The beam is then initially shaped by the focus and gap elements, which are electrostatic elements that help to focus the beam before it continues down the vertical acceleration tube.

At the end of the accelerator an electrostatic triplet focuses the beam to the analyzing magnet. It is particularly important that the beam is sent through the center of the triplet so that the triplet does not steer the beam as it focuses. This is achieved using the focus, gap, and magnet in the terminal. The triplet then focuses the beam through two sets of line defining slits: a water-cooled, high power set and a low power set. The intensity of the beam can be optimized just after the slits by a Faraday cup (Cup 1). The slits define the centerline through the 90° analyzing magnet, which defines the beams energy. The beam then goes through the analyzing slits, which are used for stabilization in slit mode and the intensity of the beam can once again be optimized to a Faraday cup (Cup 2) just
Figure 2.4. Schematic diagram of the 5U terminal. The devices described throughout the section have been annotated.
after the analyzing slits.

2.7.2 Main beamline overview

Once the beam has been analyzed, it’s tuned to the target room using an arrangement of electrostatic and magnetic elements. The beamline up to the switching magnet consists of two sets of magnetic quadrupoles, several sets of steerers, beam profile monitors, slits, and faraday cups. The beam first encounters two sets of magnetic steerers, denoted X1, X2 and Y1, Y2 in Figure 2.5. These elements provide a “kick”, or shift in either X or Y, to the beam in order to send it through the optical center of the quadrupole doublets, which focus the beam.

The doublets, denoted Q1-4, are sets of two quadrupole magnets that are arranged to focus the beam in both the X and Y direction. Quadrupoles are typically arranged in twos because as a quadrupole focuses the beam in one direction, it resultanty de-focuses in the opposite direction. Therefore by arranging them in doublets, the beam can be focused in both directions and the amount the beam is defocused can be reduced. Between the two doublets are more steerers, slits, and a Faraday cup. These components provide tuning information to the experimenter for intensity optimization. These components were added to the original design after several months of operation, when it became apparent that Q1 and Q2 were on a different magnetic line that Q3 and Q4.

After the second quadrupole doublet, there is a Y direction steerer, high power remote slits, and a Faraday cup. Once again, the slits and cup provide tuning information to optimize beam intensity. Additionally, the high power remote slits can be brought in to reduce the beam current before tuning to the target of choice. These components are the last stop before the target beamline is selected.
Figure 2.5. Diagram of the 5U-4 accelerator and main beamline to the dipole switching magnet which allows the beam to be directed to one of four beamlines in the target room. Figure courtesy of Chris Seymour.
by adjusting the switching magnet to the correct line. The switching magnet, denoted SWM in Figure 2.5, is a dipole magnet that can deflect the beam both left and right. The target beamlines that can be selected are the St. George Recoil Mass Separator at -13°, the multi-purpose beamline at 0°, the Solid Target line at 15°, and the Rhinoceros Windowless Gas Target line at 30°.

2.8 Commissioning Experimentation

As with all new experimental equipment, it is important to test the capabilities and quantify the expected performance. For the 5U accelerator this meant testing the energy resolution and reproducibility of the beam. Additionally, the accelerator’s added stabilizing components had to be tested to understand the impact that each of them have on the beam quality and performance. Using a well known reaction, \(^{27}\text{Al}(p,\gamma)^{28}\text{Si}\), with well known resonances, \(E_p = 992\text{ keV} \& 1797\text{ keV}\) ([34], [3], [18]), several tests were performed to investigate the energy resolution, stabilizer system functionality, and long term stability of the machine.

2.8.1 Experimental set-up

The commissioning experiments of the 5U were performed on the Solid Target beamline, which is shown in Figure 2.6. An evaporated 40 \(\mu\text{g/cm}^2\) Al target was attached to a water-cooled target holder at the end of the beamline, where a HPGe detector was placed. Additionally a cold trap was placed in front of the target to reduce secondary electron emission and reduce the carbon build-up on the target. In order to determine the energy resolution of the accelerator, the front edge of the 992 keV resonance was measured. This resonance in \(^{27}\text{Al}(p,\gamma)^{28}\text{Si}\) was selected not only because it is well known in literature, but also because it is a
Figure 2.6. Current layout of the NSL with the 5U installed. It supplies the beam for four different beamlines, including St. George. The solid target beamline, used for these tests, as well as the Rhinoceros beamline have been labelled.
narrow resonance, which enabled the sharp rise of the resonance in the thick target yield to be easily measured. Using this reaction is advantageous because it is very strong, and easily seen above background, so no additional shielding was required for the set-up.

For each test, a design component of the accelerator was changed. This would allow the system to be tested in complete running mode, with all of the new components on, and then turn each of the components off so that we could measure the affect they had on the energy resolution, as well as on the overall performance of operation.

2.8.2 Thick target yields

For the analysis of the 5U calibration work, the targets used represent an infinite target since the thickness of the target is much greater than the width of the measured resonance. This is part of the reason for using the 992 and 1797 keV resonances in $^{27}$Al($p,\gamma$)$^{28}$Si. Because the widths of the resonances are much smaller than the thickness of the target, the analysis of the yields obtained becomes simplified, as shown in Equation 2.3. Additionally, the thick target provides a yield curve with a very distinct plateau. This makes determining the maximum of the yield for the resonance very easy. From there the low energy rise of yield gives all of the pertinent information required for these tests. Figure 2.7 shows the typical yield curve from a thick target.

$$Y(E_0) = \frac{\lambda_R^2 \omega \gamma}{2\pi \epsilon_R} \left[ \arctan \left( \frac{E_0 - E_R}{\Gamma/2} \right) - \arctan \left( \frac{E_0 - E_R - \Delta E}{\Gamma/2} \right) \right]$$

$$Y_{\Delta E \to \infty}(E_0) = \frac{\lambda_R^2 \omega \gamma}{2\pi \epsilon_R} \left[ \arctan \left( \frac{E_0 - E_R}{\Gamma/2} \right) + \frac{\pi}{2} \right]$$

(2.3)
2.8.3 Calibration of the analyzing magnet

Through multiple tests on the 5U-4 since it was built, the analyzing magnet was calibrated several times using the 992 keV resonance in $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$. To understand the energy of the beam being delivered, the magnetic field reading from the analyzing magnet is used. The relation between the energy of the beam and the magnet field comes from the following expression:

$$E = k^2 B^2$$  \hspace{1cm} (2.4)

$$k = \frac{\sqrt{E}}{B}$$

In the above expression, $E$ is the energy of the beam, $B$ is the magnet field, and $k$ represents the calibration constant. To find $k$, the 992 keV resonance was
TABLE 2.1

CALIBRATION CONSTANTS FOR THE 5U

<table>
<thead>
<tr>
<th>Resonance Energy</th>
<th>Magnetic Field Reading (Gauss)</th>
<th>Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>992 keV</td>
<td>1438.53</td>
<td>45.674 ± 0.012</td>
</tr>
<tr>
<td>1797 keV</td>
<td>1935.68</td>
<td>45.662 ± 0.011</td>
</tr>
</tbody>
</table>

measured and using the 50% rise point on the yield curve to define our resonance energy point and the magnet field strength, k can be calculated as shown in Equation 2.4. Each of the test calibrations were recorded and compiled as shown in Table 2.1. The calibration used for the 5U-4 is \( k = 45.673 \pm 0.012 \), which is the average of several resonance scans in \(^{27}\text{Al(p, }\gamma)^{28}\text{Si} \).

2.8.4 Resolution results

The various components of the accelerator that were tested to understand their effects on the resolution were: low vs. high beam intensity, with vs. without shorting rods, and liner on vs. off. From the resonance scans of the 992 keV resonance the resolution was determined from the difference in energy between the 75% and 25% rise points of the thick target yield. To calculate this, the yields were first fit with a thick target yield function. Then, maximum value of the yield was determined by averaging the points that were on the plateau of the thick target yield. From this value, the 75 and 25% yield was calculated and then the thick target yield equation was solved from the energy for those points. The resultant energy values were then subtracted from one another, thereby revealing
TABLE 2.2

ENERGY RESOLUTION FOR THE 5U-4

<table>
<thead>
<tr>
<th>Intensity</th>
<th>Liner</th>
<th>Shorting Rods</th>
<th>Resolution [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>ON IN</td>
<td></td>
<td>272 ± 14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OUT</td>
<td>294 ± 15</td>
</tr>
<tr>
<td></td>
<td>OFF IN</td>
<td></td>
<td>382 ± 19</td>
</tr>
<tr>
<td>High</td>
<td>ON IN</td>
<td></td>
<td>303 ± 15</td>
</tr>
</tbody>
</table>

the resolution for each of the scans. Table 2.2 shows the results from the various tests.

It was found that with a low intensity beam (≤ 10µA), that with the shorting rods in for improved optics, the liner improved the resolution by 40%. Also under low intensity with the liner on, the shorting rods were found to have a negligible effect on the energy resolution with the values being within error of each other. A high intensity beam (≥ 50µA) was also tested with the liner on and shorting rods in. The beam intensity was found to impact the energy resolution by more than 25%.

From these results it becomes clear that the liner contributes significantly to the energy resolution of the machine. In terms of operational performance, the liner visibly contributes to the stabilization of the accelerator and helps to maintain a steady voltage. However, at times, it has been known to cause a feedback loop within the stabilizing of the machine causing erratic behavior. This then requires for the liner to be shut off and turned back on after a few seconds.
to allow the electrical discharges to dissipate, restoring the system to normal operating conditions.

As the shorting rods should only affect the maximum voltage attainable on the machine and change the optics slightly, they do not appear to cause a significant change in the energy resolution of the machine. The intensity of the beam seems to affect the energy resolution, which is to be expected since the slit gain wasn’t adjusted for high intensity beams.

### 2.8.5 Long-term stability testing and results

In addition to testing the various new components for their effect on the accelerator’s performance, stability tests were also performed. For the stability tests, the energy was set to the 50% point on the yield curve and then operators were instructed not to adjust any of the settings of the machine for close to 24 hours. Spectra and charge integration were logged approximately every ten minutes to be able to track the changes in the accelerators performance. By putting the energy of the beam on the midpoint of the rise of the resonance, the yield was the most sensitive to the changes in beam energy, which can be seen in the top graphs of both Figure 2.8 and 2.9. In the low-intensity case, the yield slowly declines. This was most likely due to the settling of the analyzing magnet, which was confirmed by monitoring the settling process again during testing. The settling of the analyzing magnet should be taken into consideration for any experiment, since it takes about 5 hours to settle. This would most effect low energy cross section measurements where the count rate is low enough to require long running times.

Another aspect that the long-term stability running was testing the stability of the beam intensity. This was measured by recording the total accumulated charge
on target for each run and dividing it by the length of the run. The average initial intensity was used as the standard by which the rest of the values were compared. Presented in Figure 2.8 and 2.9 are the percentage change in the beam intensity over the length of the stability tests. The low intensity tests show that the beam stability lasted approximately 10 hours before it started to decline significantly. This was due to source gas pressure declining, which is typically adjusted by the operator to maintain a stable gas pressure.

The high intensity beam was far less stable on target with up to 20% more or less beam on target. This effect is due to not changing the slit gain to make the stabilizer less sensitive to significant changes in the current on the slits. This was also likely due to some tuning issues. For the high intensity tests, the accelerator was outputting about 80 $\mu$A of beam, which is far too much beam for the evaporated Al targets to withstand without rapid target degradation or simply melting or drilling a hole in the target. Therefore, the beam intensity was trimmed down at the water-cooled pre-switching magnet slits. From run to run the intensity of the beam could fluctuate based on the part of the beam that made it through the slits, which is dependent on the initial quality of the beam and fluctuations in the beam energy. The drop-off in yield after 1 hour of running in the long-term tests can be best explained by operator error. The slow decline in the yield that is seen in the low-intensity runs is not present, but rather a sudden drop-off. This would indicate an error, rather than a stabilization.
Figure 2.8. Stability testing with low beam intensity. The top graph shows the yield of the 992 keV resonance over time. The bottom graph shows the beam intensity stability.
Figure 2.9. Stability testing with high beam intensity. The top graph is the yield from the 992 keV resonance and the bottom graph is a measure of the intensity.
CHAPTER 3

STRENGTH MEASUREMENTS

3.1 Motivation

As previously discussed, determining the cross-section for $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ is important for understanding the NeNa cycle and the nucleosynthesis of Ne, Na, and Mg. Cross-sections to low-energies were previously measured relative to the 1169 keV resonance[37], which until recently had been thought to be an undetermined value. While correcting for reference frame certainly gives better agreement between Thomas and Tanner[45] and Keinonen et. al.[25] as demonstrated in Christian et. al.[15], large errors still exist for the strength value of this resonance. This will therefore bring about the largest amount of uncertainty in cross-section measurements made relative to this resonance. Therefore, it was determined that the resonance strength should be remeasured with the goal of reducing the error in the value. The goal of this first step in the study of $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ was to measure the resonance strength of the 1169 keV resonance relative to the 1278 keV resonance in $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ using a variety of neon implanted solid targets.

3.2 Experimental Set-Up

The strength measurements of the $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ 1169 keV resonance were some of the last measurements performed on the KN accelerator before it was
decommissioned in 2010, see Figure 3.1. The KN accelerator was a belt driven 5MV Van de Graaff accelerator capable of producing 30µA of proton beam. For the purposes of the strength measurements, a 10µA proton beam was used.

A 30% ORTEC HPGe detector was placed at 45° to the beam axis to reduce angular distribution effects. A cartoon of the set-up, not to scale, is shown in Figure 3.2. The detector was placed on a sliding table so measurements could be taken at various distances in order to understand summing effects. Maestro was used for data collection and data was processed using JTEK [20].
3.3 Working Towards the Strength Value

With knowledge of the experimental set-up, the formalism used to determine the strength of the $E_{lab}=1169$ keV will be discussed. As previously discussed in the Introduction, specifically Equation 1.21, the integral of the Breit-Wigner can be expressed by the resonance strength. The resonance strength enables the comparison of resonances across many different reactions, depending on their cross sections.

But how can the strength be determined by measurable quantities? As discussed in Section 1.2.3, the measurable quantities are reaction products, $N(E_0)$, and incoming particles from the beam, $N_{beam}$. From these quantities, the strength of the resonance can be determined. The resonance strength can be calculated via,
\[ \omega \gamma = \frac{2}{\lambda_b^2} \frac{1}{n} \frac{1}{B \eta W(\theta)} \int_0^\infty \frac{N(E_0)}{N_{\text{beam}}} dE_0 \]  

(3.1)

where \( \lambda_b^2 \) is the deBroglie wavelength, \( n \) is the number of target nuclei, \( B \) is the branching ratio of the specific transition observed, \( \eta \) is the detection efficiency of the observed transition, and \( W(\theta) \) is the angular distribution of the transition. Many of these correction factors can be found in literature, measured, or calculated. The next few sections will describe how these values were determined, and subsequently used to determine the strength of the \( E_{\text{lab}}=1169 \) keV resonance.

3.4 Targets

One of the largest uncertainties in measuring a resonance strength arises from the uncertainty in the stoichiometry of the target. Special attention was made to characterize the various targets in an effort to reduce this uncertainty.

Various implanted targets were used during the strength measurements. A variety of both isotopically enriched targets of \(^{20}\text{Ne}\) and \(^{22}\text{Ne}\), as well as a naturally enriched target were used to measure the 1169 keV resonance in \(^{20}\text{Ne}(p,\gamma)^{21}\text{Na}\) and the 1278 keV resonance in \(^{22}\text{Ne}(p,\gamma)^{23}\text{Na}\). Table 3.1 details the implantation dose and backing material used for each of the targets.

3.4.1 Analysis of tantalum targets

The targets were first analyzed using Rutherford Backscattering (RBS) in Bochum, Germany. RBS is an analytical technique used determine the composition of a material. Alpha particles are accelerated to 1-3 MeV and impinged upon
a sample. Detectors set-up at backward angles detect the backscattered particles after they have scattered off of the material. The alpha particles lose energy as they interact with the nuclei in the sample. The energy loss is dependent on the mass and atomic number of the nuclei in the sample, in accordance with the scattering cross-section shown in Equation 3.2, where $Z_p$ and $Z_t$ are the atomic numbers of the projectile and target nuclei respectively, and $E$ is the energy, and $\theta$ is the angle of detection. Therefore, for different elements contained in a sample, different peaks corresponding to their cross section will appear in the spectra. These peaks provide a means of analyzing for composition and relative abundances of the elements in a material, providing a unique capability for material analysis.

\[
\left[\frac{d\sigma(E)}{d\Omega}\right]_\theta = \left(\frac{Z_pZ_te^2}{4E}\right)^2 \frac{1}{\sin^4(\theta/2)} \tag{3.2}
\]

The spectra from the analysis of each of the targets was used to determine the number of neon atoms that were implanted into either a tantalum or beryllium
backing. In the case of the tantalum targets, the RBS measurement resulted in a large plateau with a small step at the end of the plateau, as seen in Figure 3.3. The small step at the end of the plateau is from the implanted neon, which is mainly implanted just below the surface of the backing. The plateau that carries to low energy is the “infinitely” thick Ta backing and the step is from the Ne. By subtracting a spectra taken of just the tantalum backing from the spectra of the implanted region, the neon “peak” can be extracted. The area of the resulting Gaussian gives you the number of the neon atoms in the target. While this gives a good value for the number of atoms, it also results in higher uncertainties due to the statistical scatter of the subtracted peaks.

In addition to doing background subtraction to determine the Ne quantity, simulations of the target implantations were performed using SIMNRA [32]. Simulations reproduced the Ta backing and the step from the implanted Ne for each of the targets. Performing simulations to reproduce the RBS spectra of the targets allowed greater insight and understanding into the implantation and characterization of the targets.

3.4.2 Importance of the beryllium target

Another type of target was also used and analyzed: a beryllium target implanted with $^{22}$Ne. Because beryllium is lighter than neon, the RBS analysis results in distinct energy separated peaks that allow the $^{22}$Ne to be determined more directly. A peak integration method was able to be applied to determine the quantity of $^{22}$Ne. The beryllium target spectra also show an extra peak on top of the neon peak, as shown in Figure 3.4. This peak was determined to be oxygen, the result of an oxidized layer on the front of the target. This target was
Figure 3.3. $^{20}$Ne implanted in Ta backing. The RBS spectra is overlaid with simulations from SIMNRA for both the backing and the implanted region.
TABLE 3.2

IMPLANTED TARGET CHARACTERIZATION

<table>
<thead>
<tr>
<th>Target</th>
<th>Backing</th>
<th>Yield [arb.units]</th>
<th># Active Nuclei [at/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}\text{Ne}$ I</td>
<td>Ta</td>
<td>6.62 ± 0.15 x 10^{-12}</td>
<td>5.517 ± 0.558 x 10^{17}</td>
</tr>
<tr>
<td>Natural $^{20}\text{Ne}$</td>
<td>Ta</td>
<td>6.44 ± 0.49 x 10^{-13}</td>
<td>5.365 ± 0.217 x 10^{16}</td>
</tr>
<tr>
<td>Natural $^{22}\text{Ne}$</td>
<td>Ta</td>
<td>6.58 ± 0.50 x 10^{-14}</td>
<td>5.489 ± 0.221 x 10^{15}</td>
</tr>
<tr>
<td>$^{22}\text{Ne}$ I</td>
<td>Ta</td>
<td>2.298 ± 0.094 x 10^{-12}</td>
<td>1.92 ± 0.092 x 10^{17}</td>
</tr>
<tr>
<td>$^{22}\text{Ne}$</td>
<td>Be</td>
<td>3.934 ± 0.097 x 10^{-12}</td>
<td>3.28 ± 0.091 x 10^{17}</td>
</tr>
</tbody>
</table>

able to be characterized to a greater precision, and provided a standard by which the amount of $^{22}\text{Ne}$ was able to be determined in other targets.

Using the Be target, the amount of $^{20}\text{Ne}$ implanted in the other targets was also able to be determined from a ratio of the yields. For example, comparing the yields of $^{22}\text{Ne}$ resonance with that of the $^{20}\text{Ne}$ resonance in natural target, the amount of $^{20}\text{Ne}$ was able to be determined in that target using the known natural abundances of the two isotopes. From this target, the rest of $^{20}\text{Ne}$ target were subsequently characterized. An example calculation is shown below, specifically how the $^{20}\text{Ne}$ quantity in the tantalum backed target.

The number of target atoms was verified using TRIM simulations of the neon implantation. The analysis of these targets was within 92-95% of the expected number from the TRIM calculations. These values also served as a validation of the RBS analysis. A full characterization of the targets can be seen in Table 3.2.
Figure 3.4. A selection of the RBS spectra and fits from the Be backed Implanted target. The neon has a clearly defined peak and easily subtracted oxygen contamination.
3.5 Efficiency

Another required correction factor is the efficiency of the detector. The efficiency is a measure of the percentage of gamma rays are seen by the detector vs. how many are emitted. The efficiency of the set-up is determined from source measurements, as well as measurements of well known reactions. First the total efficiency was determined. The total efficiency is the likelihood that the detector sees any amount of the gamma emitted. The total efficiency is necessary in order to determine summing corrections from multiple or partial gamma rays entering the detector at the same time as the gamma of interest. To determine the total efficiency and it’s dependence on distance, a $^{137}$Cs source was used. This source is ideal for total efficiency measurements because it only emits a single gamma at 662 keV.

The absolute peak efficiency was also determined. This is the likelihood that the entirety of the gamma of interest is seen at the correct energy. The absolute peak efficiency was determined using a $^{56}$Co and $^{60}$Co sources, as well as three different known resonances in $^{27}$Al(p,$\gamma$)$^{28}$Si: 992, 1317, and 1780 keV. The resonances provided efficiency information from 1.5-12 MeV. This was necessary because the 1278 keV resonance in $^{22}$Ne(p,$\gamma$)$^{23}$Na emits a high energy (12 MeV) gamma from the $R \to 0$ transition, requiring the detector to be characterized out to this energy. From these measurements, the absolute peak efficiency as a function of gamma energy was able to be determined. The data were then fit with Equation 3.3 [26].

$$\ln(\varepsilon_{fe}) = a + b \ln(E\gamma) + c[\ln(E\gamma)]^2$$

(3.3)
Additionally, to further validate our measured efficiency, GEANT simulations of the experimental set-up were performed [16]. The result was in very good agreement with the data as shown in Figure 3.5.

3.6 Determining $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ Branching Ratios

In working to determine the resonance strength for the 1278 keV resonance in $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$, an independent determination of the branching ratios from this
resonance were calculated. From the resonance scans taken of three different targets containing $^{22}$Ne, the branching ratios were determined by normalizing the measured intensities with the efficiency and angular distributions, as shown in Equation 3.4.

$$B_{ij} = \frac{N_{ij} / (\eta_{ij}^p W_{ij})}{\sum_j N_{ij} / (\eta_{ij}^p W_{ij})}$$ (3.4)

As previously shown, the efficiencies within the required energy range are well known. The angular distributions were determined by taking a weighted average of the $W(\theta)$ determined from the constants presented in Arnell et. al. [48], Viitasalo et. al. [46], and Bakkum et. al. [5]. A table of the calculated $W(\theta)$ and the weighted averages that were determined are shown in Table 3.3.

In addition to the efficiency and angular distributions, summing corrections were applied to the close distance resonance scans. The branching ratios calculated using the close distance measurements with summing correction were then compared to branching ratios calculated using the far distance measurements where summing is negligible. The primary transitions differed by less than 10%.

Using the angular distributions along with the determined efficiency and sum corrected yields from measurements, the branching ratios were calculated (Table 3.4). Comparing these values to literature, many of the branching ratios were found to be different than those presented, and for some a reduction in error was made. Of particular note, the $R \rightarrow G.S.$ was found to be almost double the previous value from Bakkum et. al.[5]. Additionally, the $R \rightarrow 6618keV$ is double the expected NNDC value and Bakkum et. al.[5] value, but closer to the Smit et.
### Table 3.3

**CALCULATED W(θ) VALUES**

<table>
<thead>
<tr>
<th>Transition</th>
<th>$E_\gamma$ (keV)</th>
<th>Viitasalo et. al.[46]</th>
<th>Bakkum et. al. [5]</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>R → 0</td>
<td>10016</td>
<td>0.946 ± 0.066</td>
<td>0.934 ± 0.067</td>
<td>0.940 ± 0.067</td>
</tr>
<tr>
<td>R → 440</td>
<td>9575</td>
<td>1.024 ± 0.020</td>
<td>1.022 ± 0.020</td>
<td>1.023 ± 0.020</td>
</tr>
<tr>
<td>R → 2076</td>
<td>7940</td>
<td>1.028 ± 0.022</td>
<td>1.023 ± 0.022</td>
<td>1.026 ± 0.022</td>
</tr>
<tr>
<td>R → 2983</td>
<td>7033</td>
<td>0.954 ± 0.049</td>
<td>0.952 ± 0.049</td>
<td>0.953 ± 0.049</td>
</tr>
<tr>
<td>R → 3678</td>
<td>6338</td>
<td>0.958 ± 0.045</td>
<td>0.955 ± 0.047</td>
<td>0.956 ± 0.046</td>
</tr>
<tr>
<td>R → 3848</td>
<td>6170</td>
<td>1.039 ± 0.029</td>
<td>1.047 ± 0.045</td>
<td>1.041 ± 0.037</td>
</tr>
<tr>
<td>R → 3914</td>
<td>6102</td>
<td>1.054 ± 0.049</td>
<td>1.053 ± 0.051</td>
<td>1.053 ± 0.050</td>
</tr>
<tr>
<td>R → 6618</td>
<td>3399</td>
<td>1.032 ± 0.013</td>
<td>0.987 ± 0.015</td>
<td>1.014 ± 0.014</td>
</tr>
</tbody>
</table>
al. value[43]. Some differences in the branching ratios also stem from the number of transitions that were seen in each experiment. Bakkum et. al. [5] saw more transitions than what is presented in Table 3.4, whereas Viitasalo et. al.[46] and Smit et. al. [43] only saw the transitions presented.
TABLE 3.4

BRANCHING RATIOS FOR $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R → 0</td>
<td>10016</td>
<td>2 ± 0.1</td>
<td>1.5 ± 0.1</td>
<td>1.6 ± 0.067</td>
<td>2.572 ± 0.033</td>
</tr>
<tr>
<td>R → 440</td>
<td>9575</td>
<td>15 ± 0.75</td>
<td>16 ± 0.8</td>
<td>15 ± 0.020</td>
<td>14.501 ± 0.155</td>
</tr>
<tr>
<td>R → 2076</td>
<td>7940</td>
<td>5 ± 0.25</td>
<td>4.8 ± 0.2</td>
<td>5 ± 0.022</td>
<td>4.551 ± 0.093</td>
</tr>
<tr>
<td>R → 2983</td>
<td>7033</td>
<td>33 ± 1.65</td>
<td>33 ± 1.7</td>
<td>34 ± 0.049</td>
<td>29.424 ± 0.065</td>
</tr>
<tr>
<td>R → 3678</td>
<td>6338</td>
<td>12 ± 0.6</td>
<td>12 ± 0.6</td>
<td>12 ± 0.046</td>
<td>12.622 ± 0.106</td>
</tr>
<tr>
<td>R → 3848</td>
<td>6170</td>
<td>8 ± 0.4</td>
<td>5.5 ± 0.3</td>
<td>5 ± 0.037</td>
<td>6.747 ± 0.114</td>
</tr>
<tr>
<td>R → 3914</td>
<td>6102</td>
<td>23 ± 1.15</td>
<td>20 ± 1.0</td>
<td>19 ± 0.050</td>
<td>18.949 ± 0.062</td>
</tr>
<tr>
<td>R → 6618</td>
<td>3399</td>
<td>2 ± 0.1</td>
<td>7.2 ± 0.4</td>
<td>3.7 ± 0.014</td>
<td>8.773 ± 0.065</td>
</tr>
</tbody>
</table>
3.7 Resonance Strengths

3.7.1 $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ 1278 keV resonance

Using the information described in the previous sections for the efficiency, target characterization, and improved branching ratios, the strength for the 1278 keV resonance in $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ was able to be determined via Equation 3.1 which can be written in:

$$\omega\gamma = \frac{A_Y}{n\lambda_r^2} = \frac{2}{n\lambda_r^2} \int_0^\infty Y(E_0)dE_0$$

(3.5)

where $A_Y$ is the area of the yield of the resonance (which can also be represented with an integral of the yield), $n$ is the number of nuclei in the target, and $\lambda_r^2$ is deBroglie wavelength for the energy of the resonance. The strongest transitions from the data were used to determine the resonance strength in an effort to minimize the contributing statistical error, the values for the areas can be found in Table 3.5. From the corrected yields of these transitions, an average area of the yield was determined and used to calculate the strength value.

The strength of the resonance was determined to be $12.089 \pm 0.218$ eV by taking a weighted average of the strengths in Table 3.5. This was compared with previous values, specifically the value presented in Keinonen et al. [25], and was in agreement, but with an error reduction of 70%.
TABLE 3.5

RESULTS FOR TRANSITIONS IN $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

<table>
<thead>
<tr>
<th>Transition</th>
<th>$E_{\gamma}$ (keV)</th>
<th>Area of the Yield</th>
<th>Calculated Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>R $\rightarrow$ 440</td>
<td>9575</td>
<td>8.00 ± 0.49 x 10^{-6}</td>
<td>11.99 ± 0.77</td>
</tr>
<tr>
<td>R $\rightarrow$ 2985</td>
<td>7033</td>
<td>8.51 ± 0.41 x 10^{-6}</td>
<td>12.75 ± 0.66</td>
</tr>
<tr>
<td>R $\rightarrow$ 3678</td>
<td>6338</td>
<td>8.43 ± 0.64 x 10^{-6}</td>
<td>12.63 ± 0.99</td>
</tr>
<tr>
<td>R $\rightarrow$ 3914</td>
<td>6102</td>
<td>8.09 ± 0.16 x 10^{-6}</td>
<td>12.12 ± 0.34</td>
</tr>
<tr>
<td>3914 $\rightarrow$ 0</td>
<td>3914</td>
<td>7.77 ± 0.35 x 10^{-6}</td>
<td>11.64 ± 0.58</td>
</tr>
<tr>
<td>2985 $\rightarrow$ 0</td>
<td>2985</td>
<td>8.07 ± 0.42 x 10^{-6}</td>
<td>12.08 ± 0.67</td>
</tr>
<tr>
<td>2985 $\rightarrow$ 440</td>
<td>2545</td>
<td>7.80 ± 0.46 x 10^{-6}</td>
<td>11.68 ± 0.72</td>
</tr>
</tbody>
</table>

3.7.2 $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ 1169 keV resonance

As was previously discussed in the motivation for this work, the resonance strength was thought to be unknown due to seemingly conflicting results from two separate experiments in the 1970’s [37][25]. However, recent work from the DRAGON group [15] has determined the discrepancy as a misinterpretation of reference frame from Thomas and Tanner [45]. Solving this problem still has an impact on the determination of the cross-section for this reaction, therefore the resonance strength was still determined using our fully characterized implanted targets. Using the isotopically enriched $^{20}\text{Ne}$ targets, all transitions were observed in the resonance, which provided several yield curves with which to calculate the resonance strength. Summing corrections were necessary in determining the resonance strength. Results compared with previous values can be seen in Figure...
3.6. The present value of $0.962 \pm 0.102\text{eV}$ was determined using the dominant $R \rightarrow 0$ transition.

As can be seen from the results presented, the adopted resonance strength is within agreement with the previous values, including the Thomas and Tanner [45] result. This previous result still has the smallest error of all the values, though the adopted value presented is a close comparison. This implies that the previous cross-section measurement [37], which was made relative to the 1169 keV resonance will not change much. However, there are still improvements that can be made to understanding the direct capture cross section and the subsequent effects on the S-factor and reaction rate.
CHAPTER 4

THE RHINOCEROS EXTENDED GAS TARGET

Now that the resonance strength of the 1169 keV resonance has been determined, the cross section for $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ can be found. Unfortunately, because the expected cross sections at low energy are so low, the amount of beam and length of time the beam will need to be on target would degrade and possibly melt through the implanted targets used for the resonance strength measurements. So a more robust target is required. For this a gas target was deemed appropriate and Rhinoceros was decided to be used. However, before the gas target could be used, it first needed a beamline and it needed to be refurbished and updated to be able to work in the NSL. This chapter will cover the basics of gas targets, specifics of the Rhinoceros system, the beamline that was developed for the gas target, and some initial tests.

4.1 A Historical Perspective

The Rhinoceros windowless gas target was developed at the University of Stuttgart in Stuttgart, Germany in the 1980’s by Wolfgang Hammer and his collaborators [21]. The gas target was originally built with the 2 different design set-ups: a differentially pumped extended gas target and a supersonic jet gas target. Rhino’s original usage was for atomic, molecular, plasma, and nuclear
physics. Eventually, Rhino was brought to the Nuclear Science Laboratory at the University of Notre Dame. While at the NSL, Rhino has been used for a variety of nuclear astrophysics experiments with the KN accelerator. Once the KN was decommissioned and 5U was brought in, a permanent beamline was allocated for Rhino. The beamline optics study, final layout, and the refurbishment of the gas target will be discussed in later sections, with details on the pumps used and update to the electronics. An operation guide can be found in the Appendices.

4.2 Gas Target Basics

4.2.1 Review of various types of gas targets

While the rest of this chapter will focus on Rhino in the extended gas target mode, it is important to have a general understanding of the various types of gas targets. In this section, three types of gas targets will be discussed: a gas cell, a differentially pumped extended gas target, and a jet gas target. A gas cell, as the name suggests, is just that- a cell with a set pressure of gas inside. Gas cells typically have an entrance and exit window, which is made of thin foil that the beam should be able to penetrate, but will also be able to withstand the pressure inside the cell as well. While a gas cell alleviates the problem of needing a specialized target system, there are special considerations which must be taken into account for gas cell targets. First of all, as the beam passes through the entrance foil, it will not only lose energy due to the stopping power of the material and thickness of the foil, but will also broaden in resolution due to scattering within the foil. This would therefore contribute to errors in understanding the exact energy at which a measurement was being made. A similar problem occurs at the exit foil, making subsequent beam analysis more difficult. Also from a design
consideration, keeping the entrance and exit foils intact while the cell is being filled, as well as being placed in an environment under vacuum is a very tedious task. This also brings to light that the cell can only be filled to a certain pressure, as set by the strength of the entrance and exit foils. Another consideration is that there may be background reactions from the beam particles interacting with the foil.

The second type of gas target to be discussed is a differentially pumped extended gas target, which is what Rhino is currently set-up as. Rhino is a windowless gas target, which as the name would suggest is essentially a gas cell target without the foil windows. While this eliminates the energy loss and spread from the entrance and exit foils, it does require a much more complex set-up. Without the foil windows in place, the gas in the target is free to disperse itself along the beamline, which would ruin beamline vacuum and cause the target to dissipate. To keep the gas contained, the target chamber is required to have entrance and exit collimators, which will let the beam through, but inhibit the gas from dispersing. A staged pumping scheme, called differential pumping, is required to reduce the pressure from working chamber to beamline vacuum, requiring pressure reduction of between $10^7 - 10^8$. An additional feature in this type of gas target is that the exhaust from the differential pumping can possibly be recirculated back into the target system after the gas has been cleaned. This eliminates the need for massive quantities of gas, as the gas is recirculated to maintain a constant pressure in the target region. This makes measurements using rare and expensive gases possible.

The third type of gas target that was mentioned is a jet gas target. Similar to the windowless gas target, the jet gas target requires a similar differential pumping scheme to help maintain beamline vacuum and contain the target material to the
Figure 4.1. JENSA jet gas target. The upper part is the Lavar nozzle which produces the jet and two receivers at the bottom (inner and outer) to catch the gas [14]. A cartoon jet has been drawn on over the photo to facilitate understanding.

target region. Unlike the windowless gas target, the gas is not contained to a specific volume, but is pressurized and forced out of a small nozzle at the top of the target region. Below the nozzle, are high-powered pumps that essentially “catch” the gas after its been forced out of the nozzle. Around this region the differential pumping can be applied. This scheme for the target allows a small, curved target to form out of the gas a shown in Figure 4.1. As can be seen, a jet target system requires quite a bit design work and is not as portable as a gas cell. However, the jet allows for a high density, point like gas target, which is geometrically advantageous.
4.2.2 Advantages of using a gas target

A general understanding of the various types of gas targets has been established in the previous section. However, with the exception of a gas cell, the other types of gas targets require more infrastructure to build in the laboratory for the system to be usable. But while the initial “cost” of putting in a gas target system is quite high, there are many advantages to using a gas target.

One advantage of using a gas target is that the target is indestructible in a sense. A gas target can withstand high beam current intensities without needing to be worried about target degradation. Additionally, no carbon build-up, deposits, or reactions with the target backing will cause problematic background or contamination reactions in a gas target because there is no target backing.

Recirculation of the gas within the target region is another advantage of gas targets. This feature reduced the amount of gas necessary, and therefore reduces the cost if expensive rare-isotope gases are being used. Performing relative measurements also becomes easier, since both targets can be measured at the same time by mixing the target gases of interest. While in a solid target experiment, the target thickness is determined by the composition of the solid target, the thickness of a gas target can be “tuned” by adjusting the pressure in the target region. Also by recirculating the gas, the operator has the opportunity to clean the gas to maintain gas purity throughout use.

4.3 A Closer Look at Differential Pumping

Now that types and advantages of a gas target have been discussed, a closer look at the requirements of a differential pumping scheme will be reviewed. One aspect of the design is to limit the energy loss of the beam in the stages prior
to the working chamber, otherwise the beam can be broadened by straggling. To minimize the energy loss, the distances between the pumping stages should also be minimized. While minimizing the energy loss before the target, there should also be sufficient acceptance of the beam, which means that there will be a balance between accommodating for beam transmission and attaining the necessary pressure reduction.

The pressure in the target chamber will be up to 10 Torr for nuclear astrophysics experiments performed at the NSL, while beamline vacuum is typically kept around $10^{-6}$–$10^{-7}$ Torr range. This amounts to a pressure reduction of $1 : 10^{7}$–$10^{8}$ for Rhino. This reduction can be achieved by efficient pumping and good gas flow. The gas flow through the collimators is dependent on the dimensions of the collimator, the pressure on both sides, as well as the gas used and pumping speed.

Gas flow through a tube at low to medium vacuum range, $225 - 7.5 \times 10^{-4}$ Torr, can be treated as viscous flow. For calculations later in the section, the formalism for laminar, or smooth, viscous flow is given by Equation 4.1, and the formalism for turbulent, or chaotic flow is given in Equation 4.2.

$$q = 67.5 \frac{d^4}{l} (p_1^2 - p_2^2) \quad (4.1)$$

$$q = 134d \left( \frac{d^3}{l} \frac{p_1^2 - p_2^2}{2} \right)^{4/7} \quad (4.2)$$

For both formalisms, $q$ is gas flow in mbar l/s, $d$ and $l$ are the diameter and length of the tube in cm, $p_1$ and $p_2$ are the pressure before and after the tube in
mbar [49].

Gas flow through a high vacuum range, $7.5 \times 10^{-4} - 7.5 \times 10^{-8}$ Torr, is treated as molecular gas flow. In this regime, the mean free path of the gas is comparable or larger than the tube diameter, meaning that the gas is only colliding with the walls of the duct. The formalism for molecular gas flow uses the Knudsen-Dushman formula for the flow resistance, or conductance, of the tube.

$$L = \frac{\bar{c}}{4} F \left( 1 + \frac{3l}{8r} \right)^{-1}$$  \hspace{1cm} (4.3)

where $L$ is the conductance in liters/sec, $\bar{c}$ is the average velocity of the molecules, $F$ is the narrowest cross section of the tube, $r$ and $l$ are the radius and length of the tube in cm. Using the conductance and the pumping speed($S(p)$), the pressure ratio can be found,

$$\frac{p_1}{p_2} = \frac{S(p)}{L}$$  \hspace{1cm} (4.4)

The formalisms presented will be used later in the chapter to evaluate the current configuration of Rhino and compare the theoretical pressure reduction calculated to that observed.

4.4 The New Rhino "Exhibit" at the NSL

As mentioned Rhinoceros is a windowless, extended gas target that uses differential pumping, which is achieved through staged pumping regions, shown in
Figure 4.2. Schematic of the Rhinoceros pumping system. Traditional pump symbols are used.

These regions are defined by a series of water-cooled collimators summarized in Table 4.1. The collimators are long tantalum cylinders that decrease in radius the closer they are positioned to the working chamber. The collimators were designed to help to eliminate the back flow of gas through collimators. Rhino uses eleven different vacuum pumps; three turbo pumps, denoted TP in Figure 4.2, three rotary vane pumps, denoted D, and five rootsblowers, denoted WK.

The pumps are configured to drop the pressure by orders of magnitude for each region after the working chamber. The pumping capabilities of Rhino were made for high working chamber pressure, which requires more pressure reduction over many stages, but for the nuclear astrophysics experiments of interest to
TABLE 4.1

COLLIMATOR CONFIGURATION IN RHINO

(DIAMETER x LENGTH) [mm]

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Original</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>15 x 50</td>
<td>15 x 50</td>
</tr>
<tr>
<td>A2</td>
<td>8 x 120</td>
<td>not used</td>
</tr>
<tr>
<td>A3</td>
<td>7 x 120</td>
<td>not used</td>
</tr>
<tr>
<td>A4</td>
<td>5 x 80</td>
<td>7 x 120</td>
</tr>
<tr>
<td>A5</td>
<td>5 x 60</td>
<td>3 x 60</td>
</tr>
<tr>
<td>A6</td>
<td>4 x 5</td>
<td>5 x 10</td>
</tr>
</tbody>
</table>

The NSL, only pressures up to 10-12 Torr are required in the target. This eliminates several orders of magnitude of reduction required, and enables us to use less stages to achieve adequate pumping. The original and current configuration of the collimators used to separate the pumping sections is shown in Table 4.1.

The first stage after the working chamber, which is separated by collimator A6, is pumped by a series of rootsblowers that are backed by a rotary vane pump. This section drops the pressure from the working chamber, 0-15 Torr, to $10^{-1} - 10^{-2}$ Torr. The gas flow across A6 can be treated with turbulent flow due to the chaotic nature of the gas in the working chamber from Equation 4.2.
\[
q = 134(0.5) \left( \frac{0.5^{3} 5.33^{2} - (1.33 \times 10^{-2})^{2}}{2} \right)^{4/7}
\]
\[
= 93[mbar L/s]
\]  \hspace{1cm} (4.5)

\[
\frac{P_1}{P_2} \approx 400
\]

Collimator A5 separates this section from the next, which consists of a turbo pump that is backed by the same rotary vane pump as the rootsblowers of the previous section. This section reduces the vacuum again, putting it into the \(10^{-4} - 10^{-5}\). The gas flow across A5 can be treated with laminar flow using Equation 4.1.

\[
q = 67.5^{0.34} \frac{0.34}{6} ((1.33 \times 10^{-2})^{2} - (6.66 \times 10^{-5})^{2})
\]
\[
= 1.6 \times 10^{-5}[mbar L/s]
\]  \hspace{1cm} (4.6)

\[
\frac{P_1}{P_2} \approx 200
\]

The next section, separated by collimator A4, also consists of a turbo pump, but is backed by a separate rotary vane pump. This section reduces the vacuum down to nominal beamline vacuum, making further pumping stages unnecessary. The gas flow through A4 is best described by molecular flow because it is in the high vacuum regime. The velocity of sound in Ne is used for the average velocity of the particles, and the pumping speed is approximately 500 liters/sec.
Figure 4.3. Typical vacuum achieved in the various pumping stages for the current collimator configuration.

\[
L = \frac{435 \text{m/s}}{4} (\pi \times 0.35^2)(1 + \frac{3}{8}\frac{12}{3.5})^{-1} \\
= 18.3\text{L/s}
\]  

\[
\frac{p_1}{p_2} = \frac{500}{18.3} = 27.3
\]  

There are two more pumping regions separated by A3 and A2. These regions were combined into one for the cross-section measurements by removing A3 and A2. Figure 4.3 shows that nominal beamline vacuum is established in the third pumping region past the working chamber, which made further stages of pumping past A4 unnecessary.

The pumping stages also make up the sections that are included in gas recirculation mode. This mode is used during experiment to prevent loss of expensive isotopically enriched gases. To use recirculation mode, the path to the backing pumps is closed and the output from the turbo pumps and rootsblowers is redi-
rected to be cleaned by a cold trap and then put back into the working chamber.

Rhino has the capability to have two more pumping stages, which are created by A3 and A2. As previously discussed, A3 and A2 were removed for the initial experiments. These sections are pumped by a turbo pumps, which are backed by a separate backing pump.

4.5 Rhino Beamline and Installation

The Rhinoceros windowless gas target beamline is on the 30° port on the 5U-4 switching magnet. The Rhino beamline was designed with special consideration for placement of the gas target’s structure, which is a sizable 3 X 1.5 m, while optimizing the expected optics. Simulations using COSY [7], an optics simulations program, were performed in a systematic manner to determine the number of magnetic elements necessary and their placement to achieve the focusing required to get transmission through the Rhinoceros collimators to the target.

4.5.1 Optics simulations

First, before the positioning of the magnetic elements could be determined, simulations were performed to determine the focusing capability of each configuration: one doublet, one triplet, two doublets, and one doublet with one triplet. For the simulations, the original collimator placements were used since this represents the most optically constraining case. Figure 4.4 is a compilation of the beam profile results along the Rhinoceros beamline for each of the magnetic element configurations. The beam profile was output from the COSY simulations at the entrance and exit position of each of the collimators in order to compare with the sizes of the collimators. Figure 4.4 shows that the best element configuration
is using either two quadrupole doublets or a quadrupole doublet and a triplet. Because the limited resources available for the construction of the Rhinoceros beamline, the two-doublet configuration was chosen.

The next simulations were performed to determine the best positioning of the two doublets. There were limitations on where the gas target could be placed and the amount of room between the switching magnet and wall of the 5U vault. With these constraints it was determined that the first quadrupole doublet would need to be placed before the wall between the vault and the target room because otherwise the beam would have diverged too much by the time it entered the first doublet for it to be focused to the target region. This limited the range of the first doublet to within 2.5 m from the switching magnet. It was also determined that Rhino could be placed between 3 and 5 m from the vault/target room wall to allow for access to the other beamlines with maintenance carts and liquid nitrogen dewars. Within these limits, simulations were performed at every half-meter placement of Rhino, with multiple placement options for the doublets with each distance. Figure 4.5 shows the COSY simulated beam profile results for each of the possible scenarios. From the simulations, all but one of the configuration enables the beam to be fully transmitted to the target, except one which cannot focus well enough in the X-direction. From these results, the best focusing capabilities determined the placement of the doublets along the beamline. Therefore, it was determined that the doublets for the Rhinoceros gas target line would be placed at 1 m from the switching magnet and at 2.5 m from the vault/target room vault respectively.

Since the position of the doublets has been determined, the focusing arrangement could then be determined. Similar to the focusing arrangement for the 5U doublets, it was determined that an XY-YX pattern best achieved the focusing
Figure 4.4. Beam profile results from COSY simulations for the magnetic focusing element analysis plotted along with the collimators profile. The chosen configuration, two quadrupole doublets, is plotted in green.
Figure 4.5. Beam profile results from COSY simulations for the placement of the magnetic quadrupoles. The tests are defined by their distance from the target wall, and then the placement of the first and second doublet in parenthesis, respectively.
necessary to focus the beam to the target. Figure 4.6 shows the results of the optical simulations as an assembly of possible rays of the beam for the final arrangement of the quadrupole doublets in the Rhinoceros beamline.

4.5.2 Beamline layout

Once the placement of the quadrupole doublets for the Rhinoceros beamline was determined, the other necessary beamline components could be arranged around these. A set of horizontal slits and a Faraday Cup come directly after the switching magnet, as shown in Figure 4.7. This is consistent with the design of the other target beamlines from the 5U vault and aids in determining full beam transmission through the switching magnet. Then the beam encounters the first quadrupole doublet, which as shown in Figure 4.6 prevents the beam from diverging in the X direction and minimizes its divergence in the Y-direction. The beamline continues in the target room, where there is a set of magnetic steerers for both the X and Y directions followed by a beamline gate valve. As discussed in the 5U chapter, the magnetic steerers use magnetic fields to change the angle of the beam. The beam then goes through the second quadrupole doublet, at 2.5 m from the target room wall. The second set of quadrupole doublets focus the beam to the target, as shown in Figure 4.6. Directly after the doublet is another set of XY steerers, which correct the angle of entrance into Rhino. Between the steerers and the entrance to Rhino is set of slits, which help to determine the beam’s position and size during the tuning process. Because the quantity of beam is expected to be high, especially for low cross section measurements, these slits are water-cooled. It was determined that no other beamline components were needed on the beamline to Rhino because the gas target itself has many of the
Figure 4.6. COSY output for the resultant magnetic element arrangement. The wall the separates the 5U vault and the target room along with the structural bulk of Rhino are denoted. The green lines represent the beam pathway along a certain pathway. The initial size and allowed angle of the beam coming from the analyzing slits at the beginning of the diagram was determined by NEC. The 5U quadrupole doublets, dipole switching magnet, and Rhino quadrupole doublets are labelled MQ in the figure. The size of the quadrupoles is proportional to their actual size.
components that would be implemented after the water-cooled slits.

Rhino is set at 2.5m from the vault/target room wall. After a set of four-jaw water-cooled slits, the beam enters Rhino through a 15mm water-cooled collimator. After the first collimator is the Rhino Faraday cup. It is the only cup before the target. After the Faraday cup are two beamline gate valves: one after the Faraday cup and another after the next set of collimators. The rest of Rhino consists of a series of water-cooled collimators, which define the beam before the target and create the differential pumping regions as previously discussed. Typical sizes for the collimators are listed in Table 4.1, though the size of the collimators can be changed based on the requirements of the experiment, as previously discussed. The beam is typically defined down to 2-3mm before entering the target region to contain the target gas in the working chamber as much as possible. There are various options for gas target chambers that can be attached to the end of Rhino, which allow for optimization based on the experiment. After the working chamber, the beam stop is attached. The beam stop is electrically isolated from the target region with a special ceramic connector and is also water-cooled.
4.5.3 Installation

Now that the beamline and placement of Rhino has been determined, it is important to review some of the installation considerations. Rhino stands on four legs, which are adjustable in order to level the entirety of the system to the beamline. Unfortunately, the legs were not quite long enough to be able to safely level Rhino at beam height. To safely add height to Rhino, some blocks were placed under the leveling feet. However, at the time of installation, the only blocks available were some concrete cinder blocks. In an effort to make the cinder block supports work for as long as possible, the leveling feet were placed on the central support line of the cinder block. To place Rhino, the entrance and exit of Rhino was aligned to the beamline line of sight using the laboratory standard scope.

After the main body of Rhino was level and aligned, each of the collimators had to be individually aligned. The alignment was performed with same scope as previously used. First, all of the collimators were removed and each place in the beamline where they were positioned was checked for alignment with wire cross-hairs being placed on the center using Rhino beamline stand adjusters. This ensured that the entirety of the beamline contained within Rhino was aligned, since only the entrance and exit were previously confirmed. Then working from the entrance of Rhino, each collimator structure was placed back into it’s position, and aligned. Each collimator is made up of a tantalum tube that is press-fit into a copper holder, which is then put in the collimator holder, which has four precision stand-offs for aligning the whole structure. This procedure had to be done again when the arrangement of the collimators was changed for optimization of the upcoming experimentation.
4.5.4 Refurbishment

In order to get the Rhinoceros gas target working, getting the various pumps in a working order was the first priority. The rootsblowers received full oil changes. Then the system was closed up and the pumps were turned on one at a time in order to establish a base line working status. All pumps were good working order, except the turbo pumps which experienced problems throughout the rest of the refurbishment process. The older turbo pumps didn’t work due to the bearings getting stuck and age. These pumps are likely possible to salvage, but will require a full rebuild with new bearings. The turbo that operates in the second stage after the working chamber was replaced several times due to various failures of the other turbo pumps that were available. The turbo in the next pumping stage also had to be replaced after a month of operation, once again most likely due to bearings getting stuck. This one was replaced with one of the laboratory’s new electromagnetic levitation turbo pumps. In addition to having problems with the pumps, there were also some problems with their power supplies and several have been replaced over the course of the refurbishment. Luckily the laboratory had several of the corresponding power supplies in storage so these were easily replaced.

Other than the pumps, some of the electronic controls had to be updated to work with the new LabView control systems. The upgrade of the controls to a computerized system began several years ago when the original control panel, shown in Figure 4.8 failed. The upgrade began with pump controls and status read-backs, but was stopped shortly after the National Instrument (NI) infrastructure was installed. The control refurbishment was completed using NI devices and boards that interface with LabView. To complete the update, valve controls and
status read-backs were installed. The valve status read-backs and controls had to be transferred through a voltage reducer circuit to be useable with the NI board. Once the infrastructure for the updated control system was complete, a final operation program was created and implemented. Figure 4.8 shows the operational view of the control system.

4.6 Current Configuration for Cross-Section Measurements

The installation and refurbishment of Rhino was motivated by many experiments that can be done on the system with beam supplied by the 5U. The first of these experiments is the cross-section measurements of $^{20}Ne(p, \gamma)^{21}Na$, which has allowed us to make sure that the target system is fully operational while improving upon previous measurements [37]. Due to the lack of working turbo pumps, a couple of the pumping sections were combined by removing collimators A2 and A3, as previously mentioned. The current collimator configuration is described in Table 4.1. Combining the pumping section did not negatively impact the performance of the gas target since the pressures that would be required for the
upcoming experiments did not require the high pressure reduction from previous atomic physics experiments that require high working chamber pressures.

For the cross section measurements, the so called “Octopus” target chamber was used. The Octopus chamber is a flat disk chamber with several ports at various angles. The flat sides of the chamber allow detectors to be placed in close geometry for increased statistics, and the ports around the edges are used for various diagnostic tools, gas inlet, and particle detectors for elastic scattering measurements. Additionally, an entrance collimator for the Octopus chamber was constructed in the NSL shop. A 5 mm diameter collimator was placed in a 1 inch stainless steel plug that was placed in the entrance arm of the chamber. This had to be done to replace the A6 aperture which was removed along with a beamline extension piece. These pieces were removed from the end of Rhino to help keep the experimental area within the previously discussed placement constraints. This new “A6” collimator contributes to containing the target gas to the chamber.

As previously mentioned, one advantage of a gas target is the ability to put high beam intensities on the target. This aids in the measurement of the low-energy cross sections, which tend to be extremely low. As shown in Equation 4.8, there are two way to achieve a high number of incoming particles, by increasing the number of beam particles, \( Q \), or the time required for each measurement, \( t \). Being able to increase the incident beam particles reduces the time needed.

\[
\sigma \propto Yield = \frac{N_{\text{detected}}}{N_{\text{incomingparticles}}} \\
N_{\text{incomingparticles}} = \frac{Q_{\text{beam}[A] \times t[s]}}{q_{\text{beamparticle}[C/particle]}}
\]

(4.8)
<table>
<thead>
<tr>
<th>Cup</th>
<th>Tune 1 (µA)</th>
<th>Tune 2 (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Analyzed</td>
<td>35</td>
<td>24</td>
</tr>
<tr>
<td>Analyzed</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>Pre-SWM</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Rhino Cup</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Target</td>
<td>5</td>
<td>17</td>
</tr>
</tbody>
</table>

However, the collimator design of Rhino makes getting full transmission from the accelerator to target nearly impossible. While the 5U can produce 100’s of microamps of beam, on average only 30-50% of the beam on the analyzed cup makes it to the target. Table 4.2 gives a full description of typical beam transmission from the pre-analyzed cup to target for two different tunes, resulting in both the minimum and maximum beam transmission, depending on the tuning ability and time allotted.

To fully understand our gas target, experiments to measure the energy loss and straggling as a function of gas pressure were performed. Utilizing the 90° port on the Octopus chamber, the well known 992 keV resonance in $^{27}$Al($p, \gamma$)$^{28}$Si was measured in the gas target several times with varying pressures of Ne gas in the chamber. An evaporated 40 µg/cm² Al target was cut to less than the width of the target chamber and a special isolated target holder with BNC output was created to mount the target at the center of the chamber. By adding gas to the chamber...
Figure 4.9. 992 keV resonance scans taken with different gas pressures to study the energy loss and straggling versus target gas pressure.

with each subsequent resonance scan, the energy loss could be measured. The Ne gas would causes the beam to lose energy as it moves through the chamber to the Al target. Therefore it requires more beam energy to reach the target center at the resonance resonance energy as the pressure is increased. To find the energy loss experimentally, the following equation was used:

\[ E_{\text{loss}} = E_{\text{beam}}(Y_{50\%}) - E_{\text{res}} \] (4.9)

In the above equation, \( E_{\text{res}} \) is also equal to \( E_{\text{beam}} \) with no gas in the chamber. The summation of target scans is shown in Figure 4.9. The resultant energy loss due to the beams interactions with the Ne gas matched the predicted losses calculated from stopping power tables in SRIM[50] as shown in Figure 4.10.

In addition to the beam’s energy loss, the amount of straggling the beam
experienced as a function of gas pressure was also able to measured. As can be seen in Figure 4.9, the higher the gas pressure, the more the resolution of the beam degraded, due to the beam energy being spread-out by colliding with the Ne gas. The resolution can be determined by calculating the energy difference between the 75 – 25% rise on the front edge of the resonance. By comparing the resolution measured to that obtained with no gas in the target chamber, the amount of energy spread was determined. The results from these calculations are presented in Figure 4.10 where as the gas pressure increased, the amount of straggling did too, as expected. The information gained from these simple experiments will help determine the systematic error for the cross section measurements, which will be discussed in the next chapter.

Figure 4.10. Left: Energy loss vs. target gas pressure. Right: Energy straggling vs. target gas pressure.
5.1 Purpose of the Measurement

The previous chapters have described the work done to establish the experimental infrastructure and preliminary measurements necessary to measure the $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ cross section. In addition to providing a test for the new experimental equipment and refurbished gas target, the aim of this experiment is to better understand the direct capture to ground state component of the cross section. Previous measurements by Rolfs et al.\[37\] show that the low energy reaction rate is dominated by the high energy tail of a subthreshold resonance. However, for proton energy 1.3-1.9 MeV, Rolfs et al.measurements only provide an upper limit on the cross section. In this region the sub-threshold resonance may have less of an effect, therefore providing a region where the direct capture to ground state may be measured. To better understand the direct capture component of this reaction, measurements from 0.5-2.0 MeV were made.

5.2 Experimental Set-up

The cross section measurements were made using the Rhinoceros gas target with beam from the 5U accelerator. Using the Octopus chamber, 4 Torr of $^{20}\text{Ne}$ enriched gas was recirculated through the working chamber. A Canberra HPGe
Figure 5.1. Level diagram of $^{21}$Na. The 3545 keV state corresponds to the 1169 keV resonance that will be used for the relative measurements. The 4175 and 4295 keV state corresponds to the 1830 and 1955 keV resonance, respectively. The R/DC cross sections to the 2425 keV, 332 keV, and ground were observed along with their subsequent decays. As seen in the diagram, the 2425 keV state is only 7 keV below the proton threshold, providing a subthreshold resonance that contributes to the cross section at low energy.
detector was placed at 90° with respect to the beam to face the target. The detector was also placed on a sliding table to easily make measurements at varying distances to determine summing corrections. A 6.5 mm thick lead absorber was placed in front of the detector for part of the experimentation in order to reduce the dead time in the detector from the low energy gamma rays as well as reduce summing. The lead shielding, shown in Figure 5.2, was placed around the face of the detector in order to block out beam induced background from the upstream collimators. The collimators are made of tantalum, which contain fluorine from manufacturing. The fluorine contaminate produces gamma-ray background signatures, which did not interfere with the detection of the gamma rays of interest. In addition to shielding around the detector, extra shielding was placed around the beam stop, which is about 50cm from target exit port.
The working chamber was set-up with the gas inlet on the 75° port. A baratron, used to measure the pressure to within 0.01 Torr, was placed on the 90° port, in accordance with the recommended orientation. Two ruggedized Si detectors were placed at backwards angles 135° and 160° for Rutherford scattering detection, as shown in Figure 5.2. Rutherford scattering was used to normalize the data because standard charge integration of the beam cannot be used. Standard charge integration would be affected by the charge exchange between the target gas and the beam making them unreliable, therefore Rutherford scattering was used for normalization purposes. The Si detectors used to detect the Rutherford scattering were exposed to 4 Torr of Ne gas during operation, requiring the usage of ruggedized Si detectors. Ruggedized Si detectors are different from normal Si detectors because they have a thicker, light-tight aluminum layer on the front, which enables them to operate within pressures greater than vacuum, such as in a gas target. The Si detectors were also collimated using a slit and hole combination collimator. The slit width was 0.5mm and the hole diameter was 1.524mm. The distance between the two collimators was 40.25mm. From this information the effective target length seen by each of the detectors can be determined by,

\[ l_y = \frac{1}{\sin(\theta_{lab})} \frac{sd}{f} \]  

(5.1)

where \( s \) is the slit width, \( d \) is the distance from the hole collimator to the center of the target, and \( f \) is the distance between the slit and hole collimators. Using Equation 5.1 the effective target length seen by the Si detectors can be calculated.
5.3 Relative Measurement Formalism

While an absolute determination of the cross section is preferable, it is also difficult. Making an absolute measurement can result in values with large errors carried by stopping power, efficiency, target stoichiometry, etc. It is easier and more reliable to obtain the cross section relative to an absolute, carefully measured cross section or resonance. Since a detailed, absolute measurement of the 1169 keV resonance in $^{20}\text{Ne}(p,\gamma)^{21}\text{Na}$ was measured in the previous experiment, the cross section for this reaction was measured relative to that resonance.

From the non-resonant reaction theory in the introduction, the cross section can be determined by:

$$
\sigma(E) = \frac{\epsilon}{\Delta E N_b B \eta W(\theta)} \frac{N}{N_b \Delta \theta}
$$

(5.2)

where $\epsilon$ is the stopping power, $\Delta E$ is the target thickness, $N$ represents the number of detected particles, $N_b$ is the number of beam particles, $B$ is the absolute branching ratio, $\eta$ is the detector efficiency, and $W(\theta)$ is the angular distribution. Similarly, the resonance strength can be determined by:
\[ \omega \gamma (E) = \frac{2}{\lambda^2} \epsilon \frac{1}{\Delta E B \eta W(\theta)} \int_{0}^{\infty} \frac{N(E)}{N_b(E)} dE \] (5.3)

To make a relative measurement of the cross section relative to a known resonance, Equation 5.2 can be simply be divided by Equation 5.3 to obtain:

\[ \frac{\sigma_1}{\omega \gamma (E)} = \frac{\lambda^2_1 \epsilon_1 \Delta E_2 B_2 \eta_2 W(\theta)_2}{2 \epsilon_2 \Delta E_1 B_1 \eta_1 W(\theta)_1} \frac{N_1}{N_b \int_{0}^{\infty} \frac{N(E)}{N_0(E)} dE} \] (5.4)

Rolfs et al. reduced this equation for use in determining the cross section relative to the 1169 keV resonance,

\[ \sigma_{DC} = \frac{\lambda^2_0 m + M \omega \gamma Y_{DC}}{2 m \Delta E Y_R} \] (5.5)

where,

\[ \frac{Y_{DC}}{Y_R} = \frac{N_{DC}}{N_R} \frac{\epsilon_R \Omega_R}{\epsilon_{DC} \Omega_{DC}} \frac{W(\theta)_R}{W(\theta)_{DC}} \] (5.6)

Following this formalism, \( N_{DC/R} = \frac{N_{DC}}{N_{beam/\beta}} \). For this experiment, the measurements are being normalized to Rutherford scattering, as opposed to the measured charge on target. If the Rutherford scattering cross section is constant over the target thickness, then
Since the Rutherford scattering is being measured simultaneously with the reaction products, \( N_{\text{beam}}(\gamma) = N_{\text{beam}}(\text{Ruth}) \) this can be substituted into Equation 5.6. The theoretical Rutherford scattering cross section can be calculated by:

\[
[\frac{d\sigma(E)}{d\Omega}]_{\text{Ruth}}(\theta) = \left( \frac{Z_p Z_t e^2}{4E} \right)^2 \frac{1}{\sin(\theta/2)^4} \tag{5.8}
\]

However, when the ratio of this formula is taken at two different energies, \( E_{DC} \) and \( E_R \), for the same detector \( (\theta_R = \theta_{DC}) \), the result is merely the ratio of the two energies squared.

\[
[\frac{d\sigma(E_{DC})}{d\Omega}]_{\text{Ruth}}(\theta) = \left( \frac{Z_p Z_t e^2}{4E} \right)^2 \frac{1}{\sin(\theta/2)^4} \tag{5.9}
\]

Putting this into Equation 5.6, the yield ratio becomes,

\[
\frac{Y_{DC}}{Y_R} = \frac{N_{\gamma,\text{DC}}}{N_{\gamma,\text{R}}} \frac{N_{135,\text{R}}}{N_{135,\text{DC}}} \frac{E_R}{E_{DC}} \frac{B\eta_R}{\eta_{\text{DC}}} \frac{\epsilon_R}{\epsilon_{\text{DC}}} \frac{\Omega_R}{\Omega_{\text{DC}}} \frac{W(\theta)_R}{W(\theta)_{\text{DC}}} \tag{5.10}
\]
5.4 Efficiency

5.4.1 Peak efficiency

As with the strength measurements, the detection efficiency of the experimental set-up needs to be well characterized. For the cross section measurements, two types of efficiency were necessary: the peak efficiency and the geometric efficiency. To determine the peak efficiency of the detector, several known sources were placed at the center of the target chamber. The known sources used were $^{137}$Cs, $^{60}$Co, $^{56}$Co. A $^{66}$Ga source was created in house via activation in order to expand the efficiency to higher gamma energy. Peak efficiency curves were found for the set-up with and without the Pb absorber. Figure 5.3 shows the peak efficiency curves as a function of gamma energy determined for both cases. Geant4 simulations of the experimental set-up were performed, and are in excellent agreement with the data [16].

5.4.2 Geometric efficiency

Because the target chamber acts as an extended source for the direct-capture reactions, the geometric efficiency along the beam axis of the target chamber needed to be well characterized. To measure these effects, a known source was measured every 10 mm along the beam axis. Both the close distance (mm’s from target face) and far distance (4 inches back) cases were measured. Figure 5.4 shows the efficiency as a function of position along the beam axis in the target chamber. Once again Geant4 simulations were performed and are in agreement with the data for both the close and far distance geometries. The shapes of the efficiencies as a function of position within the target chamber are different for each of the distances. At close distance, the shape is Gaussian, while at far distance
Figure 5.3. Efficiency for both set-ups: top, without, and bottom, with the Pb absorber. The effects of the Pb absorber is noticeable not only in the scale of the y-axis, but also in the shape of the efficiency curve at low-energy. This effect helped to reduce deadtime in the detector as well as reduced summing by 30%.
the shape is arctangent in nature. The difference can be best explained by the difference in scanning a flashlight across the front of your face at a distance of a few inches versus several feet away. At a few inches away, when the light is the brightest at the midpoint of your face, but it quickly dissipates in intensity as it travels past your eyes. Whereas at several feet away, the maximum brightness can be seen for a long period because your eyes can resolve most of the light. The same principle occurs here, except the light source is the reaction and your eyes are the Ge detector.

5.4.3 Distance effects

In addition to understanding the geometric efficiency at the various distances, the efficiency is also affected by the distance to the target. Measurements at close distance are useful to improve upon the statistical uncertainty, while measurements at 4 inches away from the target provide important information for summing corrections, which will be discussed in a later section. The measurements to understand the distance effects were made using the $^{137}$Cs source placed at the center of the target chamber. Figure 5.5 shows the relationship between the distance from the target chamber and the peak efficiency. Quite noticeable is the sharp drop in efficiency as the detector is moved farther away from the target.

5.5 Rutherford Scattering

Rutherford scattering was used to normalize the data for the cross section measurements. From Rolfs et.al.[37], it was known that at higher energies, the scattering deviates from Rutherford. In order to be able to correct for this effect, a measurement of the Rutherford scattering from 1.5-2.0 MeV was performed with
Figure 5.4. Efficiency as a function of position within the target. Target center is at 0mm. Top: Close distance geometric efficiency measurements with Geant4 simulation validation. Bottom: Far distance geometric efficiency measurements with Geant4 simulation validation.
Figure 5.5. Distance effects on the detector efficiency. The efficiency is reduced significantly, 87%, at 4 inches back from the target. Another 50% reduction at 8 inches back.
Figure 5.6. Rutherford scattering measurements for both neon and xenon. Measurements were taken at 135 and 160° and then a ratio between the two detectors was used. The scattering deviated from Rutherford at $E_p \geq 1.5$ MeV in neon. Using the xenon scattering, corrections to the experimental normalization was able to be deduced.

$^{20}$Ne and natural Xe gas in a ratio of 8:1. Because of it’s higher Z, the scattering on the Xe is expected to be Rutherford for the energies of interest and can be used to determine what the Rutherford scattering would be for Ne.

5.6 Angular Distributions

From Equation 5.10, the ratio of the angular distributions for resonance and the direct capture are also necessary for determining the cross section. The angular distributions can be calculated by:
\[ W(\theta) = \sum_{0}^{n} a_n Q_n P_n(\cos(\theta)) \]  

(5.11)

where the \( a_n \) terms depend on angular momentum and nuclear matrix elements involved in the specific reaction process, the \( Q_n \) terms are attenuation coefficients due to the size of the detector, and \( P_n(\cos(\theta)) \) are Legendre polynomials. The theoretical expression for \( a_n \) is given in Equation 5.12 for a two-step, pure transition process [22]. In the expression, \( J \) is the intermediate spin state that is formed from the initial spin \( j_i \) and the angular momentum, \( L_i \), of the radiation. The \( F_n \) terms are coefficients defined by [9], which are the nuclear matrix elements, factored into separate components using Clebsch-Gordon and Racah coefficients. \( F_n \) values are tabulated in [10].

\[ a_n(i) = \frac{2L_i(L_i + 1)}{2L_i(L_i + 1) - n(n + 1)} F_n(L_i j_i J) \]  

(5.12)

The attenuation coefficients, \( Q_n \), defined by the detector size and geometry of the experiment, are defined by [39] shown in Equation 5.13. In this expression \( \beta \) is the angle between where the radiation hits the detector and the detector symmetry axis, with \( \beta_{max} \) equal to the maximum angle subtended by the detector, and \( \eta(\beta, E) \) is the detector efficiency for the radiation of energy \( E \) at angle \( \beta \).

\[ Q_n = \frac{\int_{0}^{\beta_{max}} P_n(\cos(\beta))\eta(\beta, E) \sin \beta d\beta}{\int_{0}^{\beta_{max}} \eta(\beta, E) \sin \beta d\beta} \]  

(5.13)
TABLE 5.1

ANGULAR DISTRIBUTION COEFFICIENTS

<table>
<thead>
<tr>
<th>Transition</th>
<th>( a_2 )</th>
<th>( a_4 )</th>
<th>( W(\theta) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>R ( \rightarrow ) 0</td>
<td>-0.402</td>
<td>8.16 ( \times 10^{-9} )</td>
<td>1.138</td>
</tr>
<tr>
<td>DC ( \rightarrow ) 0</td>
<td>0.010</td>
<td>1.75 ( \times 10^{-4} )</td>
<td>0.996</td>
</tr>
<tr>
<td>DC ( \rightarrow ) 332</td>
<td>0.092</td>
<td>1.43 ( \times 10^{-3} )</td>
<td>0.968</td>
</tr>
<tr>
<td>DC ( \rightarrow ) 2425</td>
<td>-0.997</td>
<td>-3.09 ( \times 10^{-3} )</td>
<td>1.346</td>
</tr>
</tbody>
</table>

For the cross section measurements, the \( a_n \) terms were calculated using AZURE [4] and the \( Q_n \) terms were determined using a Geant4 simulation [8, 16]. At 90°, only the \( n=0, 2, \) and 4 contribute to the angular distributions. Table 5.1 gives the values for the \( a_n \) parameters and the determined angular distribution for each, using \( Q_2 = 0.695 \) and \( Q_4 = 0.262 \). The angular distributions were determined for both the resonance transition used as well as the direct capture transitions.

5.7 Summing Corrections

During the cross section measurements, considerations for summing corrections must be taken into account. Summing occurs when one or more gamma rays from within a particular \( \gamma \)-cascade enter the detector at the same time, therefore being seen as a single gamma with an energy equal to the sum of the individual gamma rays. This has the effect of taking away counts from the actual gamma energy peak, or conversely falsely inflating the yield of a gamma peak. This affects the true yield from the various transitions, but can be accounted for in various ways.
If the total efficiency of the detector is known, then a detailed balancing of the possible transitions that can add and subtract from the true yield can be determined. Experimentally, measurements can be made to determine the summing corrections. The likelihood of summing decreases as the detector is moved farther away from the target by reducing the probability that multiple gammas rays will enter the detector simultaneously. Therefore by taking a few measurements at a distance far enough to eliminate summing, but close enough to detect the reaction products effectively, the summing that occurs at close distance can be deduced using a series of yield ratios. This is beneficial because many unknown factors simply cancel out, reducing the possibility for error in the correction factors.

Summing corrections were determined for both the resonance and the low energy cross section data. To determine the summing corrections experimentally, measurements made at close distance, a few millimeters from the target chamber face, were compared to a measurement at the same energy, with the detector pulled back 4 inches from the close distance position. It was determined that a distance of 4 inches was a sufficient distance to eliminate summing contributions.

5.7.1 1169 keV resonance corrections

It was important to determine the summing corrections required for 1169 keV resonance because this resonance is what the direct capture was measured relative to. This means that any error in the yield of the resonance would then affect the final cross sections. To determine the summing corrections, all visible transitions from the resonance were normalized to Rutherford scattering measured at 135°, their respective branching ratios, and peak efficiencies. These yields were then compared to the $R \rightarrow 0 \ (E_\gamma = 3545\text{keV})$ yield, which is the strongest transition,
with 91.9% branching ratio, and highest energy gamma ray. These ratios were then compared with ratios derived from the far distance measurement, where there is no summing. The resultant value gives the summing corrections for the close distance resonance scan. Table 5.2 gives the yield values for the close and far distance measurements, the respective ratios to the ground state transition, as well as the resultant scaling factor.

### 5.7.2 Direct capture summing corrections

The direct capture summing effects were calculated in a similar manner. Using the highest energy direct capture point, measurements at close and far distance were performed. This data point was chosen because it has the highest cross section of all of the low energy points and therefore will not take a tremendous amount of experimental time to gain enough statistics. The various direct capture transitions were compared to the $^{2425}_{0t}$ transition, in a similar method as was used for the resonance summing corrections. The results of this method are shown
TABLE 5.3

DIRECT CAPTURE SUMMING CORRECTIONS

<table>
<thead>
<tr>
<th>Transition</th>
<th>( \frac{Y_{\text{Trans}}}{Y_{\text{DC} \rightarrow 332}} ) _close</th>
<th>( \frac{Y_{\text{Trans}}}{Y_{\text{DC} \rightarrow 332}} ) _far</th>
<th>CF</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC ( \rightarrow ) 0</td>
<td>0.18</td>
<td>0.12</td>
<td>0.66</td>
</tr>
<tr>
<td>DC ( \rightarrow ) 2425</td>
<td>4.53</td>
<td>6.21</td>
<td>1.37</td>
</tr>
<tr>
<td>2425 ( \rightarrow ) 0</td>
<td>2.43</td>
<td>2.64</td>
<td>1.09</td>
</tr>
<tr>
<td>332 ( \rightarrow ) 0</td>
<td>298.26</td>
<td>375.42</td>
<td>1.26</td>
</tr>
</tbody>
</table>

in Table 5.3. Because the high energy tail of the 2423 keV sub-threshold state dominates the ground state direct capture at low energies, the DC \( \rightarrow \) 0 transition is most affected by summing-in, the yield requires a 34% reduction.

5.8 Stopping Powers

One advantage of relative measurements is that the information regarding target stoichiometry cancels out of the calculation. However, the ratio of the stopping power remains due to its energy dependence. As previously discussed, the stopping power is the amount of energy loss as the beam travels through a material due to electronic interactions between the ions and electrons in medium. Using SRIM [50], the stopping power for protons in 4 Torr of Neon gas was determined across the energy range used in the experiment. The stopping power can be seen in Figure 5.7. The stopping power for the 1169 resonance is 170.9 keV/(mg/cm²).
Figure 5.7. Results from SRIM. Tabulated stopping power for hydrogen in 4 Torr of Neon gas.
5.9 Determining the Cross Sections

Now that the various correction factors have been discussed, the cross sections can be calculated. Figure 5.8 shows some of the raw data from the low energy measurements where the various R/DC transitions can be seen. The various DC transitions and their subsequent decays were analyzed in ROOT [11]. Once the runs were analyzed, they were used to calculate the cross section using the formalism described earlier in the chapter.

5.9.1 Sample calculation

Recall that the determination of the cross section will be relative to the 1169 keV resonance. Using Equation 5.8 with Equation 5.6, the direct capture cross section were determined. For reference, Equ. 5.6 is shown.

\[
\frac{Y_{DC}}{Y_R} = \frac{N_{DC}}{N_R} \frac{\epsilon_R}{\epsilon_{DC}} \frac{\Omega_R}{\Omega_{DC}} \frac{W(\theta)_R}{W(\theta)_{DC}}
\]

(5.14)

Many of the values have been described in previous sections. The ratio of the stopping powers can be determined from Figure 5.7, and the angular distributions were determined in a previous sections. But the ratio of the solid angle and normalized counts still need to be determined. The ratio of the solid angles is necessary because of the difference between measuring the resonance in an extended gas target versus measuring the direct capture. The resonance acts as a point source within the gas, moving along the beam axis, similar to the geometric efficiency measurements. While the direct capture reactions act as an extended source over the length of the gas target. Because of these differences, the solid
Figure 5.8. Spectra from $E_{\text{beam}}=1130, 1030, \text{ and } 875 \text{ keV} \text{ DC measurement in counts versus channel number. The peaks from the various transitions of importance are labelled.}$
angle is different. The solid angle can be calculated from measurements of the experimental set-up using,

\[
\Omega = 2\pi \left( 1 - \cos(\theta_1 + \theta_2) \right)
\]  \hspace{1cm} (5.15)

where

\[
\theta_1 = \arctan \left( \frac{x}{d} \right) + \arctan \left( \frac{R - x}{d} \right)
\]
\[
\theta_2 = 90 - \arctan \left( \frac{d}{R + x} \right) + \arctan \left( \frac{x}{d} \right)
\]

For these equations \( R \) is the radius of the detector crystal, \( d \) is the distance to the target, and \( x \) is the position of along the target. For the solid angle of the resonance, we assume \( x = 0 \), assuming it would be at the center of the target. From there it’s a simple matter of using measurements of the set-up in Equation 5.15.

\[
\Omega = 2\pi \left( 1 - \cos \left( \arctan \left( \frac{0mm}{4.76mm} \right) + \arctan \left( \frac{50.8mm}{4.76mm} \right) \right) \\
+ 90 - \arctan \left( \frac{4.76mm}{50.8mm} \right) + \arctan \left( \frac{0mm}{4.76mm} \right) \right) = 12.456 \text{sr}
\]

For the solid angle of the direct capture, the solid angle is that of an extended source. This requires Equation 5.15 to be integrated over the position in the target.
\[
\Omega = \int 2\pi \left( 1 - \cos \left( \arctan \left( \frac{x}{4.76} \right) + \arctan \left( \frac{50.8 - x}{4.76} \right) \right) \\
+ 90 - \arctan \left( \frac{4.76}{50.8 + x} \right) + \arctan \left( \frac{x}{4.76} \right) \right) dx = 1245.486 \text{sr}
\]

Due to the symmetry of the target, from the middle to one side may be integrated and then doubled. Now a simple ratio of the two calculated solid angles can be used to determine the yield ratios for the cross sections.

\[
\frac{\Omega_R}{\Omega_{DC}} = \frac{12.456 \text{sr}}{1245.486 \text{sr}} = 0.01 \quad (5.16)
\]

So far most of the parameters for the yield ratio have been determined. The final piece is the ratio of the normalized counts. These come from directly from the experimental data. First, the normalized counts for the resonance will be discussed, then it will be apparent how the direct capture counts are normalized. From \(N_R/N_{DC}\),

\[
N_R = \frac{N_{\gamma}}{N^*_{135} B \eta_{\text{geo}} \eta_{\text{peak}}} \quad (5.17)
\]

where \(N_{\gamma}\) is the number of counts from in the peak of interest, \(N^*_{135}\) is the number of counts in the Si detector at 135° corrected for deadtime, \(B\) is the branching ratio of the resonance transition used, and \(\eta_{\text{geo,peak}}\) are the geometric and peak efficiency. Too measure the large energy range covered in this experiment, two separate experimental runs were performed. For each of the experimental
runs, a resonance scan of the 1169 keV resonance was performed in order to keep the relative measurements self-consistent. So two different $N_R$ values were calculated.

$$N^L_R = 481.3 \pm 12.1_{\text{stat}}^{19.2_{\text{syst}}}$$

$$N^H_R = 622.7 \pm 24.9_{\text{stat}}^{26.9_{\text{syst}}}$$

For each cross section data point, the $N_{DC}$ will be different. To determine $N_{DC}$ the following expression was used,

$$N_{DC} = \frac{N_\gamma}{N^*_135 \eta_{\text{geo,p}}}$$

(5.18)

where the variables used are the same as for Equation 5.17. Using the above values along with those determined for each of the energies measured, the yield ratio can be calculated.

The previous sections covered all of the necessary parameters and calculations to determine $Y_{DC}/Y_R$. This parameter can now be used in Equation 5.8:

$$\sigma_{DC} = \frac{\lambda_{\gamma}^2 m + M \gamma Y_{DC}}{m \Delta E Y_R}$$

(5.19)

Using the masses of a proton and $^{20}Ne$, the resonance strength that was determined in Chapter 3, and the measure target thickness of 10 keV the cross
section was determined for each energy point measured. The following sections will show the resultant cross sections from the various transitions and compare them with digitized data from Rolfs et al.[37], which is the only previous cross section measurement for this reaction.

5.9.2 Resonance/Direct capture to ground state

The resonance/direct capture to ground state cross section was the most improved from this experiment. Figure 5.9 shows most of the cross sections to be within the values from Rolfs et al. [37], but with greatly reduced error bars. This can be attributed to the technological improvements in detectors and experimental insights since the 1970’s, when Rolfs performed his experiment, as well as more time available to perform the measurements. This region of the cross section is also dominated by the sub-threshold resonance at 2425 keV. This state is only bound by 7 keV and the high-energy tail of the resonance dominates the low energy cross section. This will have an impact as the cross sections are used to determine the S-factor and reaction rate of this transition in the next chapter.

The most significant improvements to this cross section are in the 1.3-2.0 MeV region, where Rolfs only claimed upper limits for a few energy points. The present measurements are within these proposed upper limits. There is some scatter between the data at 1.3-1.5 MeV, which stems from this region being measured in two separate passes. There may simply be a systematic reason for the discrepancy between the two, such as the analyzing magnet not being fully recycled, which would alter the energy of the beam from the known calibration.
Figure 5.9. R/DC to ground state cross section measurements compared to Rolfs et al. [37].
Figure 5.10. R/DC to the first excited state and subsequent ground state transition measurements compared to Rolfs et al. [37].
5.9.3 Resonance/Direct capture to first excited state (332 keV)

The resonance/direct capture to first excited state at 332 keV cross section is in agreement with Rolfs et al. in the low energy region, as shown in Figure 5.10. However, from 1.3-1.9 MeV, the present cross section is stronger than that from Rolfs. The present cross section shows a stronger interference of the 1830 keV resonance with the non-resonant component. It was deduced that previous data may not have been properly corrected for the elastic scattering on $^{20}\text{Ne}$ being non-Rutherford in this region, which will be discussed in the next section, which would contribute to data being different than that presented in Rolfs. The measurements in this region were measured at far distance, so summing corrections are negligible. Additionally, it should be noted that AZURE fits to the Rolfs data were attempted, but were unable to match the data in this region. The subsequent first excited state transition to the ground state maintains agreement with that presented in Rolfs, except through the mid-energy range. From 0.8-1.6 MeV, the Rolfs data is consistently lower than the present measurement.

5.9.4 Resonance/Direct capture to 2425 keV

The resonance/direct capture to 2425 keV state cross section, shown in Figure 5.11, is in agreement with the Rolfs et al. cross sections. There is a slight discrepancy in the higher energy region, from 1.5-2.0. This discrepancy was found to be eliminated if the elastic scattering in the 135° detector was not corrected for it’s deviation from Rutherford, which was shown to occur in this region. The 1830 keV resonance once again provides a significant interference with the non-resonant contribution in the cross section. The present cross section from the 2425 keV to ground state follows a similar trend.
Figure 5.11. R/DC to 2425 keV level and subsequent ground state transition measurements compared to Rolfs et al. [37].
CHAPTER 6

RESULTS AND CONCLUSIONS

The previous chapter presented the cross sections determined for the various transitions in $^{20}$Ne(p,$\gamma$)$^{21}$Na. From these cross sections, an R-matrix analysis was performed to extract the astrophysical S-factor from the data. Additionally, the new cross section’s impact on the reaction rate compared to that currently available in reaction rate libraries will be determined and discussed.

6.1 R-matrix Analysis

6.1.1 Brief overview

Before going into the results of the fits, a brief overview of R-matrix will contribute to the understanding of the results. R-matrix theory is a formal theory of resonance reactions, which allows for a reliable interpolation of observed experimental data. Cross sections in astrophysically important areas are extremely low and in many cases cannot be measured directly. Therefore, extrapolation down to these energies is important to our understanding of stellar environments. To this end, the concept of the S-factor $S(E)$ is used to correct for the effects of Coulomb repulsion, making the extrapolation to low energies more straightforward. R-matrix theory is a powerful tool to help perform this extrapolation from experimental data[4].
R-matrix theory, originally, was only used to describe resonances. But procedures were developed to include non-resonant and radiative capture reactions [1, 6]. AZURE utilizes these procedures in order to produce fits to cross section data, extract S-factors, and calculate reaction rates. R-matrix theory relates the internal nuclear forces, which are not well understood, to the external interaction possibilities, or channels, which has an analytical solution [29]. The total wave function of the nucleus can be expanded to a complete set of eigenstates that are determined by complicated many-body nuclear physics[4]. The external interactions between the possible combinations of coupled particle pairs depend upon known quantities such as energy and angular momenta. R-matrix then works from the quantum mechanical assertion, that the wavefunctions and their derivative must match at the boundary[4]. For direct capture, non-resonant components of the cross section, the external component has a given energy dependence, and its magnitude is given by the asymptotic normalization coefficient (ANC) of the bound state [27]. ANC’s can be fit, or derived from spectroscopic factors of the bound states taken from literature. The internal part of the non-resonant/direct-capture components are treated with high-energy background poles [27].

6.1.2 Determined S-factors

An R-matrix analysis was used to analyze the cross sections from $^{20}$Ne(p,γ)$^{21}$Na because the reaction is a system of light nuclei with a discrete level structure at low energy, making it ideal for R-matrix analysis. The cross section data has been used to determine the S-factor. Recall, from the introduction, that the S-factor is merely the cross section with the large energy dependence removed, making it better to use for extrapolation down to low energies. Equation 6.1 gives the ex-
pression that defines the S-factor, where $\eta$ is the Sommerfeld parameter and $\mu$ is the reduced mass. All of the cross sections were fit and converted to S-factor using AZURE [4]. The parameters used in the AZURE fits compared to literature are presented in Table 6.1. Most notable is the difference in the ANC for the 2425 keV sub-threshold resonance. The ANC for this state, presented by Mukhamedzhanov et. al.(2006) is $8 \times 10^{16}$, compared to the value determined from the cross section fitting in this work, $6 \times 10^{15}$.

$$S(E) = E\sigma(E)e^{2\pi\eta} \text{ where } 2\pi\eta = 31.29Z_1Z_2\left(\frac{\mu}{E}\right)^{1/2}$$  \hspace{1cm} (6.1)

From Figure 6.1, one can see that the fits to the data agree extremely well for the $R/DC \rightarrow 332$ and $R/DC \rightarrow 2425$ transitions. The $R/DC \rightarrow 0$ fit we well in the high energy region, however, the S-factor deviates in the low energy region. Summing corrections were applied to the low energy data, as was discussed in Chapter 5, but the poor fit in this region would suggest that an energy dependent corrections may be required.

To compare with the present S-factors, Figure 6.2 shows the S-factor results from AZURE using the literature values for the subthreshold ANC. Using the ANC from Mukhamedzhanov (2006), AZURE gives a warning during the fitting process indicating that the input parameters are unphysical, specifically that the internal function is too large for the boundary of the radius. Using the literature ANC yields fits that do not agree with $R/DC \rightarrow 2425$ or the $R/DC \rightarrow 0$. In working to more accurately fit the data, the present subthreshold ANC value was determined.

Looking closer at the ground state transition, Figure 6.3 shows the present
### TABLE 6.1

**AZURE FIT PARAMETERS**

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>Levels [keV]</th>
<th>ANC/ $\Gamma_p$</th>
<th>$\Gamma_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>Literature$^b$</td>
<td>Present</td>
</tr>
<tr>
<td>$\frac{3}{2}^+$</td>
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<td>0</td>
<td>0.435</td>
</tr>
<tr>
<td>$\frac{5}{2}^+$</td>
<td>331.9</td>
<td>331.9</td>
<td>1.67</td>
</tr>
<tr>
<td>$\frac{1}{2}^+$</td>
<td>2423.8</td>
<td>2423.8</td>
<td>$6 \times 10^{15}$</td>
</tr>
<tr>
<td>$\frac{3}{2}^-$</td>
<td>4110</td>
<td>4169.6</td>
<td>180 keV</td>
</tr>
</tbody>
</table>

Note: The branching ratio for the 2425 keV state is 100% to the ground state. The partial widths used for the 4110 keV state are 0.012, 1.0, and 0.35 eV to the g.s., 332, and 2425 keV states, respectively.

(b) Rolfs et.al., Nucl. Phys. A 241(1975) [37].
(c) Lambert et. al., Jour. de Phys. 33 (1972) [28].
Figure 6.1. S-factor results from AZURE fits for all of the direct capture transitions. Interference from the 1.83 MeV is present in all three transitions that were observed. The fits are in agreement with the R/DC→332, R/DC→2425, and high energy R/DC→0 transition. The fit in the low energy region of the R/DC→0 is poor, indicating that energy dependent corrections to the data may be required.
Figure 6.2. S-factor results from AZURE fits using the prescribed literature values for the subthreshold resonance ANC, as shown in Table 6.1. With the prescribed ANC, the S-factor for the R/DC→2425 transition is too large to fit the data. Additionally, the R/DC→0 transition becomes too low. AZURE also gives a warning for the subthreshold state, due to unphysical input parameters. The value was therefore lowered to the present value.
data in comparison with that from Rolfs et al. [37] as well as an extrapolation calculated by AZURE. The present data is within excellent agreement with the extrapolation at high energy, though at low energy the agreement is still poor. The present data was found to be lower than that presented in Rolfs [37]. The effects of the sub-threshold state, which was included in the AZURE calculations, can be seen in the changing S-factor value as it approached $E_{cm} = 0$. The sub-threshold state at 2425 keV is only bound by 7 keV, so the high energy tail of this rather broad resonance effects the low energy S-factor, making the corrections to this region more complex than the initial constant summing corrections used during this analysis.

6.2 Implications on the $^{20}$Ne(p,$\gamma$)$^{21}$Na Reaction Rate

To further understand the impact of the cross section measurements, the reaction rates for the various components of the reaction were determined. As a reminder from the introductory chapter, the formula for the reaction rate is given by:

$$<\sigma\nu> = \sqrt{\frac{8}{\pi\mu}}(kT)^{-3/2} \int_{0}^{\infty} S(E)e\left(-\frac{E}{kT} - \frac{E}{v_{c}}\right) dE \quad (6.2)$$

For each non-resonant and resonant component, the reaction rates were determined. AZURE was used to calculate the contributions of each component individually for the non-resonant reaction rates, the subthreshold resonance, and the 4.175 MeV resonance [4]. Additionally, the STARLIB reaction rate calculator was used to determine the resonance reaction rates for each resonance individually [41],

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Figure 6.3. Ground state S-Factor from the present data compared with the data from Rolfs [37] and the extrapolation calculated by AZURE. The thick target yields for the resonances at $E_{cm}= 1.113, 1.3, \text{ and } 1.9$ MeV from Rolfs et.al. were included in the extrapolation. Present S-factors and the extrapolation are below that presented in Rolfs.
with changes made to the inputs based on the current work where necessary. The components were then summed together to determine the total reaction rate. Figure 6.4 shows the ratio of each of the components of the reaction rate to the total. As shown in Figure 6.4, the 2425 keV subthreshold state dominates the reaction rate at low temperatures, with the R/DC→2425 contributing equally at around 0.07GK. Around $T_9 = 2$, the 1169 keV resonance is the dominant component of the reaction rate. The new resonance strength for this resonance causes a 14.5% reduction in the rate for this specific resonance, as is shown in Figure 6.5. The present reaction rate reduction affects the total reaction, reducing it by up to 11% in the temperature region around $T_9 = 2$.

To understand the effects of the present work, the determined reaction rates and those from STARLIB were compared to NACRE, as shown in Figure 6.6 [2, 41]. For the comparison, the rates were normalized to the NACRE adopted rate. The reaction rates presented are also tabulated in Appendix B. The present total rate is lower by roughly 25-30% in the low temperature region compared to STARLIB and NACRE. This is, once again, due to a reduction in the subthreshold resonance ANC. STARLIB uses the ANC presented in Mukhamedzhanov et.al. (2006) [35], while the current reaction rate uses the value determined from this work. As previously discussed, the present ANC is a full order of magnitude below what is currently available in the literature. This has a dramatic affect on the low temperature reaction rate because the sub-threshold resonance dominates in this regime, as shown in Figure 6.4. The overall effect of the present cross section measurements is a reduced reaction rate at low temperatures, as shown in Figure 6.6.
Figure 6.4. Ratio of the various reaction components rates to the total rate determined as a function of the temperature in GK. The subthreshold state is shown to dominate in the low temperature region. At higher temperatures, the DC→2425 keV and 1113 keV resonance dominate the reaction rate.
Figure 6.5. Ratio of the present resonance reaction rate for the 1169 keV resonance, using the present $\omega\gamma$, to NACRE [2]. For comparison the ratio of the STARLIB resonance reaction rate to NACRE is also plotted [41]. STARLIB uses the resonance strength from Rolfs et.al. [37]. The rate determined with the new resonance strength is reduced by 14.5%. This therefore reduces the total reaction rate in the temperature region around $T_9 = 2$, where this resonance is the dominate component to the reaction rate. The error bands correspond to the ratio of the lower and upper limits for the resonance reaction rates to NACRE.
Figure 6.6. Ratio of the present total reaction rate and that given in STARLIB normalized to NACRE[2, 41]. The error bands for the present reaction rate include the upper and lower limits presented by NACRE as well as an assumed 10% systematic error from the present work. The STARLIB rate uncertainties and the NACRE uncertainties are included in the error band for the STARLIB ratio. The new value for the subthreshold resonance ANC contributes to the reduction of the present total reaction rate at low temperatures compared to NACRE and STARLIB.
APPENDIX A

RHINOCEROS OPERATING INSTRUCTIONS

This Appendix will cover the basic operations of Rhinoceros from start-up to shut down, including directions for establishing recirculation mode. Figures are labelled for guidance through the instructions, however it should be noted that the set-up pictured is current as of May 2016, and changes past this date may make this information obsolete. Information about how the Rhino beamline was created and specifics on current set-up, please refer to Chapter 4. For design information, please refer to Wolfgang Hammer’s paper [21].

A.1 Establishing Proper Vacuum

To start-up Rhino, the Rhino beamline first needs to be under good vacuum. To ensure this, the various pressure gauges should be checked to ensure that the low pressure reading is working, all ion gauges should be OFF at this point. It is important before attempting to rough out the beamline, that the Rhino gate valves, V1 and V2, are closed to separate the various sections of Rhino. The pumping staging for each section will be able to pump out these sections, but the roughing out the entire line can take a long time, so working in stages is typically preferred. To turn on power to Rhino, the power switches on the wall across from Rhino need to be activated and turned on. Figure A.1 shows the power switches.
First, following any required lock-out tag-out procedures, flip the manual switch to the ON position. Then press the START button. This will send the correct type of power to Rhino, which operates on German power.

Next, the Rhino control program, MissionControl.vi, should be launched on the Rhino computer, which lives in the red Rhino cabinet. After the program begins running, click the red power button at the top of the interface page. Figure A.2 has the location of this button highlighted. When the power to Rhino is initiated, valves that were open when there is no power may suddenly close and sometimes this makes an awful lot of startling noises- it is merely Rhino’s way of making sure you are awake. Next confirm that V1 and V2 are still closed via the indicators on the interface. Now pumping out the system can begin.

To pump out the main beamline, a roughing cart needs to be attached near the
The entrance point of Rhino, where a hand valve and Hornet gauge have been installed. The backing pump behind the beamline turbo can also be used to pump through the turbo and help rough out the beamline. Once the roughing cart and backing pump are on, Rhino can provide some help using D2, the backing pump for the first turbo pump in the system, TP1. Turn on D2 by toggling the switch next to its label, highlighted in Figure A.2. Monitor PP2 with the Pirani gauge monitor, which is shown in Figure A.3, to ensure that the pump has started up properly.

Then open V6 with the toggle switch in the control program. Ensure the vacuum again begins to decline on PP2, and then open V3 to begin pumping through the turbo pump. The rough vacuum in the beamline needs to be under $5 \times 10^{-3}$ Torr before the turbo pumps can be started up. Once this level is achieved in the beamline, then the beamline turbo can be started locally with the start button on its power supply. The first turbo of Rhino, TP1, can started up as well. To turn
TP1 on, first press the STOP control button in Mission Control, to de-activate the stop, then press the START button that is next to it. This allows you to turn on TP1, which must be done using the switch on it’s power supply, shown in Figure A.3. The steps of turning on TP1 sometimes have to be repeated several times in order to get the pump turned on, which can be determined when the yellow and subsequent green light on the power supply turn on.

Next the other section of Rhino need to be roughed out. Depending on the status of the target chamber, V2 can be opened so that the back end can be pumped out together. However, if the target area is open to air, V2 MUST remain closed. To initiate the roughing out of the second section, turn on D3, monitoring PP3 to ensure it gets up to speed. Then open hand valve V9 which will begin this sections pump out through TP3. DO NOT toggle V8, there is a short of some kind in the wiring for this valve and toggling it seems to turn everything off, which causes panic. V8 is left in a permanent OPEN position, no matter what the indicator says. Once the hornet reading for this section reads under $5 \times 10^{-3}$Torr, TP3 may be turned on. This is done only from it’s power supply in the Rhino rack. TP3 is not connected to Mission Control.

To pump out the target region and last section of Rhino, there are two options. If you are able to pump it out simultaneously with the target region, V2 may be opened to facilitate pump out that way, or hand valve V10 and V12 can be opened, which allows D3 to back both TP3 and TP4. There are separate high-pressure(low vacuum) reading for each of these sections, but the ion gauge is only reading the section pumped on by TP4. The other way to pump out the target region is using D4. After turning on D4, open hand valve V30 and monitor the vacuum using PP10. Next open the hand valve that goes to D4, which is near the vent valve.
Figure A.3. Front Panel of the Rhino controls, MissionControl.vi.
for the target chamber, its location is shown in Figure ??.

Once the vacuum gets low enough, $5 \times 10^{-2}$ Torr, you can begin to turn on the rootsblowers (WK1-5) to help quicken the roughing out process. Once the system is roughed out, the turbo pump directly after the target chamber, TP4, may be turned on. TP4, shown in Figure A.2, only has computer control for stopping, so it must be turned on locally using its power supply that is in the Rhino rack. Close the hand valve that goes directly to D4 so that the roughing pumps are now only backing the turbos.

A.2 Stand-By Mode

It is recommended that Rhino and its beamline be pumped out for several days before beginning an experiment. This ensures that the pumps are working properly and that vacuum can be maintained. Stand-by mode should be engaged to ensure that the TP4 does not get turned off. Stand-by mode keeps the TP1, 3, and 4 on along with backing pumps D2 and D3. Pump D3 is used to back both TP3 and TP4 by keeping hand valves V9, V10, and V12 open. Typically in this mode, it is also wise to keep at least V1 closed to separate the target area from the main beamline if a problem does arise.

A.3 Recirculation Mode

See Figure A.4 for reference of where the various valves are located. To get Rhino ready for experiment and recirculation mode from stand-by mode, the rest of the pumps will be turned on and the TP4 will be backed by a series of rootsblowers instead. To begin, start up D4 in a similar manner as listed in the start-up section. Then open V40 and V41, monitoring the vacuum on PP8. Then begin turning on the rootsblowers in sequential order from WK5-3 with the toggles on.
the control interface. Open V14 and monitor the vacuum on PP4 while turning on WK1 and 2. Then V13 can be opened. V13 is a very noisy valve. If after about 30 seconds of compressed air blowing, it hasn’t stopped, then close and reopen the valve. This valve could use refurbishing or replacement. Now that all the rootsblowers are on and backing TP4, hand valve V9 can be closed so that the rootsblowers are also backing TP3. This will ensure that any gas that makes it into this region will also get recirculated back into the gas target. At this point V19 should also be opened, this valve has a significant delay to it’s operation, but it will open and close remotely.

Now Rhino is almost ready for recirculation mode. But first the gas manifold should be evacuated to ensure that contaminates are kept at a minimum. Open V42 and V44, monitoring the hornet gauge that is attached to the TP4 pumping section. If using a cold trap, evacuate these lines as well by opening V43 and V45 to the trap. Next open V46, this is the injection valve for gas on the system and will be used to set the gas pressure to the desired setting. It is also a good idea to evacuate the gas manifold along V50, V51, and V52. Make sure that the target gas bottle is CLOSED to ensure you do not pump away all of the target material. To do this open V53, which is directly connected to D4. This is also the "panic valve" that can be opened to evacuate the gas manifold to the roughing pump if things go badly. Re-close V46, V50, V51, V52, and V53. Now that all of the lines have been evacuated, the system can be put into Recirculation mode by closing V40 and V41.
Figure A.4. Gas Manifold area of Rhino.
A.4 Inserting Gas

Before beginning to put gas into the system, make sure V46 is closed and the remote valve behind it is open. This valve is controlled at the 5U console to allow gas to be removed from the target region for tuning purposes without needing to readjust V46. The rest of this process is a sequence of opening and closing many different valves one after another to pass the gas from the source bottle to the target input in small amounts so that the system is not over pressured.

For example purposes, let’s say the target gas source bottle is attached to V51. First open/close the source bottle and adjust the moderator to a pressure under 10-20 Torr. Then to pass the gas along open/close V51, then V48. You will be able to notice some increase in the vacuum readings at this point as the gas back fills into the system only slightly. Slowly open V46 to the desired pressure. To put more than about 2 Torr into the target, the process of moved gas from the source bottle to V46 will need to be repeated several times. Before injecting more gas each time, close V46 and open it slowly once the gas is ready to be input to the target again.

A.5 Shutting Down

As would be expected the shutting down process is much easier than the start-up. To remove the target gas from the system, simply open V41 and V40 to open the line to the D4 backing pump which will simply pump the gas to air. In some cases, this is not allowed or the target material needs to be reclaimed. In these cases, a procedure to do that should be developed by the experimenter. Rhino has features to assist with the reclamation of gas.

After the gas is taken care of, close all gas manifold valves, preferably in the
reverse order they were opened to make sure they are evacuated before shutdown. Then hand valve V9 can be reopened to use D3 as the backing pump for TP3. Next close V19, V13 and V14, turn off the rootsblowers, and close V22 and V23. Then D4 can be turned off and V30 can be closed. At this point close V1 and V2. If Rhino is to be left in Stand-by mode, then this completes the shut-down.

For a complete shutdown, TP4, TP3, and TP1 can be turned off so they can spin down while being backed by roughing pumps. Additionally, the beamline gate valves and hand valve should be closed and then the beamline turbo can be turned off, this includes V3 and V6 in the front section of Rhino. Remember to turn off the ion gauges before turning off the turbos. Then after the turbos have spun down, the backing pumps can be turned off. Finally, the Main Power button can be turned off. Then the wall mount power switch is next to be turned off, press STOP and then return the switch to the off position and perform any required lock-out tag-out procedures necessary.
APPENDIX B

TABULATED RESULTS

This Appendix gives the tabulation of the cross section measurements and reaction rates.

B.1 Cross Sections
<table>
<thead>
<tr>
<th>$E_{lab}$ [keV]</th>
<th>$\sigma (R/DC\rightarrow 0)$ barns</th>
<th>$d\sigma$</th>
<th>$\sigma (R/DC\rightarrow 332)$ barns</th>
<th>$d\sigma$</th>
<th>$\sigma (R/DC\rightarrow 2425)$ barns</th>
<th>$d\sigma$</th>
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<td>500.46</td>
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## B.2 Reaction Rates

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BIBLIOGRAPHY


8. A. Best. private communication, 2016.


