

Constraining the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction using $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ with GODDESS

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For my family

Acknowledgments

It's fall! The maple leaves swirling in the autumn wind reminds me of the fall of 2017 when I joined the graduate school at the University of Tennessee from the land of the Himalayas. It's been 5 years. Unbelievable! Looking back at it, this journey seems akin to climbing a mountain.

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Abstract

The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction acts as a bottleneck for classical nova nucleosynthesis beyond $A=30$ in ONe novae, due in part to the long lifetime of ^{30}P (~ 2.5 minutes) with respect to the timescale of a nova outburst. Also, the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate directly affects the isotopic ratio of $^{30}\text{Si}/^{28}\text{Si}$, which is an important nova identifier in the analysis of pre-solar grains. O/S, S/Al, O/P and P/Al elemental abundance ratios can be used as nuclear thermometers for classical novae by constraining the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate.

However, direct measurement of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction is not feasible because proton capture reactions at astrophysical energies have very low cross sections as the proton has to tunnel through the Coulomb barrier and due to experimental challenges in producing an intense ^{30}P beam at relevant astrophysical energies. An indirect method was used which measured the $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ transfer reaction with a radioactive ^{30}P beam at 8 MeV/A at Argonne National Laboratory using the GODDESS (GRETINA-ORRUBA: Dual Detectors for Experimental Structure Studies) system, which is a coupling of position-sensitive silicon detectors array ORRUBA, with the γ -ray tracking array GRETINA.

The angular distributions and the single-neutron spectroscopic structure of ^{31}P was studied. The single-proton spectroscopic structure, resonance structure and reaction rate of the astrophysically important resonances in ^{31}S was constrained via mirror symmetry. Details of the experiment, data analysis process, and results from this work will be presented.

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Chapter 1

Introduction

Nuclear astrophysics is an intriguing interdisciplinary branch of physics that aims to understand the nuclear processes occurring in the cosmos. A deeper insight into these nuclear processes may answer some of the fundamental questions regarding nucleosynthesis and stellar evolution.

1.1 Stellar Evolution and Nova Nucleosynthesis

A star is born when large clouds of gases and dusts collapse under gravity making the core hot enough for nuclear fusion reactions to take place. These fusion reactions happening at the core of a star generate outward pressure which balances the inward forces of gravity, thus creating a hydrostatic equilibrium. They are also responsible for the synthesis of heavier nuclei from pre-existing seed nuclei (16). A star undergoes several stages of nuclear fuel burning that changes its size, mass, composition, temperature and luminosity during its lifetime. Once a star exhausts its nuclear fuel, it dies with a stellar event that depends on its mass.

1.1.1 Nuclear Fusion Reactions in a Star

Hydrogen Burning

Hydrogen burning is the first phase of nuclear fuel burning in a star, in which the protons in the hot core, at $\sim 2 \times 10^7$ K (17), convert to ^4He and trace amounts of heavier nuclei. The star remains in hydro-static equilibrium until it burns all of its protons in the core. After consuming all the protons in the core, the production of nuclear energy stops and the thermal pressure decreases. This causes the gravitational contraction to dominate and the core of the star contracts and heats up. Since the outer layer is cooler and less dense, hydrogen burning is slower. The pressure from the hot core layer causes the outer layer to expand massively. This stage is a red giant star.

Helium Burning

When the temperature of the core reaches the order of 10^8 K, helium burning is initiated releasing a new source of nuclear energy. The thermal pressure from the helium burning in the core expands the outer layer which still contains hydrogen. Since ^8Be is unstable, helium burning mainly occurs via triple- α process producing ^{12}C (18). ^4He can further fuse with ^{12}C producing ^{16}O .

Carbon Burning and Beyond

The core of a medium mass star (mass $\sim 8\text{-}10 M_\odot$) will further contract increasing its temperature, and gradually overcoming the Coulomb barrier via tunneling, to initiate carbon burning and produce even heavier nuclei like ^{20}Ne and trace amounts of ^{24}Mg and ^{28}Si . However, low mass stars (mass $\lesssim 8 M_\odot$) cannot reach the temperature to initiate carbon burning and a helium flash phase occurs. A helium flash burns large quantities of ^4He into ^{12}C through the triple- α process in the core. The inner regions of the star have higher temperatures and densities than those outside, which creates an outward radiation pressure and the star loses most of its mass from the outer layer into interstellar medium.

1.1.2 Nuclear Fuel Exhaustion in a Star

White Dwarfs

With all of the nuclear fuel exhausted, the core cannot support itself from gravitational contraction. Therefore the star contracts, packing the electrons tighter and tighter. Eventually, the contraction is halted by the pressure arising from electron degeneracy. Electron degeneracy is one of the stellar applications of Pauli's exclusion principle, which states that in the same atom, no two electrons can have identical values for all four of their quantum numbers (19). Once the lowest energy level is filled, other electrons should occupy higher energy states. Once all the levels up to the Fermi energy are filled, the electron gas is said to be degenerate (16). The electron degeneracy pressure supports the star against gravitational contraction. The highly dense core remnant of a star, composed mostly of electron-degenerate material, is called a white dwarf (WD)(20). A WD supported only by electron degeneracy pressure cannot be stable if its mass is greater than $\sim 1.44 M_{\odot}$. This limiting mass is called the Chandrasekhar limit.

The composition of WDs depend on the mass of the progenitor stars. Very small stars ($\lesssim 0.5 M_{\odot}$) never reach the temperature to initiate the helium burning process and their cores will turn into helium (He) WD. Lower mass stars ($\lesssim 8 M_{\odot}$), which can burn helium via the triple- α process and have ^{12}C and ^{16}O in their core, will spend their final stage as carbon-oxygen (CO) WDs. However, medium mass stars ($\sim 8\text{-}10 M_{\odot}$), with ^{16}O , ^{20}Ne and trace amount of ^{24}Mg and ^{28}Si , will reach their final stage as oxygen-neon (ONe) WDs. This work aims to study nucleosynthesis in classical novae involving ONe WDs.

Black Hole and Neutron Star

The highest mass stars ($\gtrsim 10 M_{\odot}$), after exhausting nuclear fuel, will continue to contract under gravity. This contraction heats up the core and heavier elements are formed until the core collapses, eventually, forming a neutron star or a black hole (21).

1.1.3 Nucleosynthesis in Classical Nova

Classical novae are astronomical events happening in a binary system with one member, a WD, and the other member enriched with hydrogen, usually a main sequence star (16). When the orbital separation between the WD and the main sequence star is small enough, the main sequence star begins to shed its envelope onto its WD companion as Roche lobe overfflows from the main sequence star. This results in the WD accreting H-rich matter from the main sequence star into an accretion disk as shown in Figure 1.1. This system is called a cataclysmic variable. The temperature of the accreted H-rich matter rapidly increases due to gravitational compression on the surface of the WD, where it mixes with heavier nuclei present in the WD. As WD is supported by the electron degeneracy pressure, it can not expand and regulate its temperature. Thus, thermonuclear runaway (TNR) fusion occurs because of a sharp increase in temperature, initiating different nuclear fusion reactions, causing an explosion called a classical nova outburst(22).

During TNR, the seed nuclei present in a classical nova go through different reactions. These include fusion reactions of the proton, the CNO cycle, in which isotopes of carbon, nitrogen, and oxygen acts as catalyst to fuse four protons to helium nucleus, and several proton captures and β -decays. This mechanism is called nova nucleosynthesis and the explosion ejects newly synthesized nuclei into the interstellar medium. While the main nuclear activity in CO nova is CNO cycle, ONe nova can synthesize nuclei up to intermediate mass region ($A \sim 40$)(23).

About 30 ± 10 classical nova explosions are expected in our Galaxy each year. The nova peak temperature ranges from $1 - 4 \times 10^8$ K, and the TNR timescales are on the order of a few hundred sec (22). Classical novae are often recurring phenomena as the companion main sequence star can feed the dense atmosphere of WD multiple times with the time scales usually ranging from 10^4 to 10^5 years. The luminosity of a classical nova increases by a large amount reaching $\gtrsim 10^4 L_{\odot}$. The amount of mass ejected

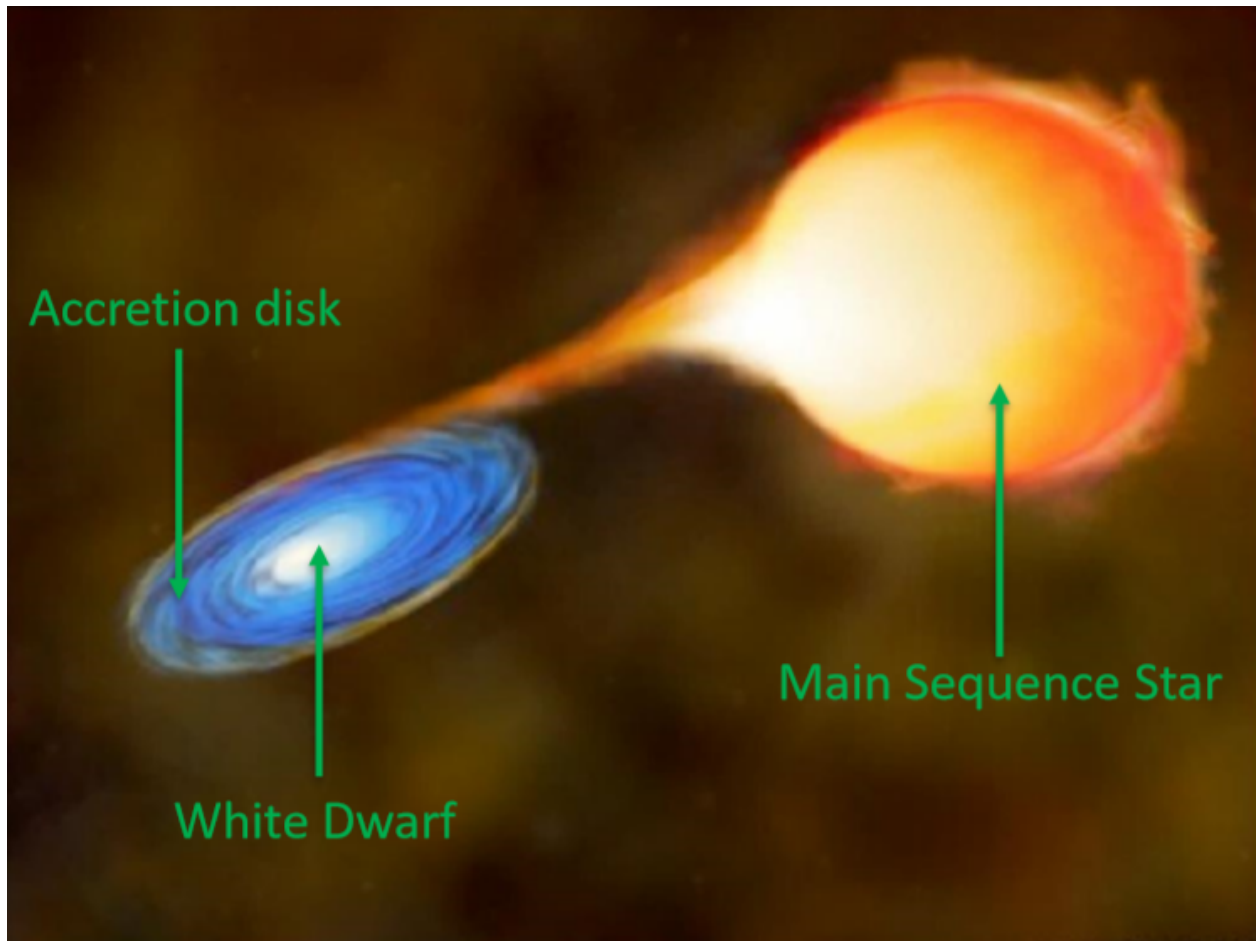


Figure 1.1: Artist's impression of a binary system where a white dwarf accretes H-rich material from the main sequence star (Image Credit : NASA/CXC/M.Weiss)

in a classical nova is 10^{-4} to $10^{-5} M_{\odot}$, and the mean ejection velocity is 10^2 to 10^3 kms^{-1} (24).

1.2 Motivation

Hydrodynamic and nucleosynthesis models suggest that classical novae involving CO WD mainly synthesize nuclei in CNO-group, and the classical novae involving ONe WDs can synthesize CNO-group nuclei and nuclei from Si to Ca. Jose *et al.*(25) studied the main nuclear paths, with proton captures and subsequent β^+ -decays, which synthesize several intermediate-mass nuclei in ONe WD as the temperature of the burning shell increases.

1.2.1 The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ Reaction as a Bottleneck for Nucleosynthesis Beyond A=30 in ONe Novae

In ONe classical novae, $^{30}\text{P}(p, \gamma)^{31}\text{S}$ is one of the dominant nuclear paths which synthesizes nuclei beyond A=30. $^{30}\text{P}(p, \gamma)^{31}\text{S}$ is of particular interest for understanding ONe classical nova nucleosynthesis(26), due in part to the long lifetime of ^{30}P (~ 2.5 minutes) with respect to the timescale of a nova outburst. Rather than β -decay, proton capture is responsible for significant destruction of ^{30}P produced during a nova outburst.

Intermediate-mass nuclei, above ^{29}Si , can be produced through several reaction pathways including $^{29}\text{P}(p, \gamma)^{30}\text{S}(p, \gamma)^{31}\text{Cl}$, $^{30}\text{Si}(p, \gamma)^{31}\text{P}(p, \gamma)^{32}\text{S}$, and $^{30}\text{P}(p, \gamma)^{31}\text{S}(p, \gamma)^{32}\text{Cl}$ as shown in Figure 1.2. The first chain, $^{29}\text{P}(p, \gamma)^{30}\text{S}(p, \gamma)^{31}\text{Cl}$, can not produce heavier nuclei because of the low proton separation energy of ^{31}Cl (283 keV), it photo-disintegrates back to ^{30}S via $^{31}\text{Cl}(\gamma, p)^{30}\text{S}$ which β -decays to ^{30}P . The second chain, $^{30}\text{Si}(p, \gamma)^{31}\text{P}(p, \gamma)^{32}\text{S}$, requires an abundant amount of ^{30}Si . However, since ^{30}Si is not produced in carbon burning, it is not adequately abundant to significantly produce more massive nuclei. Hence the synthesis of intermediate-mass nuclei must proceed via proton capture on the ^{30}P , making ^{31}S .

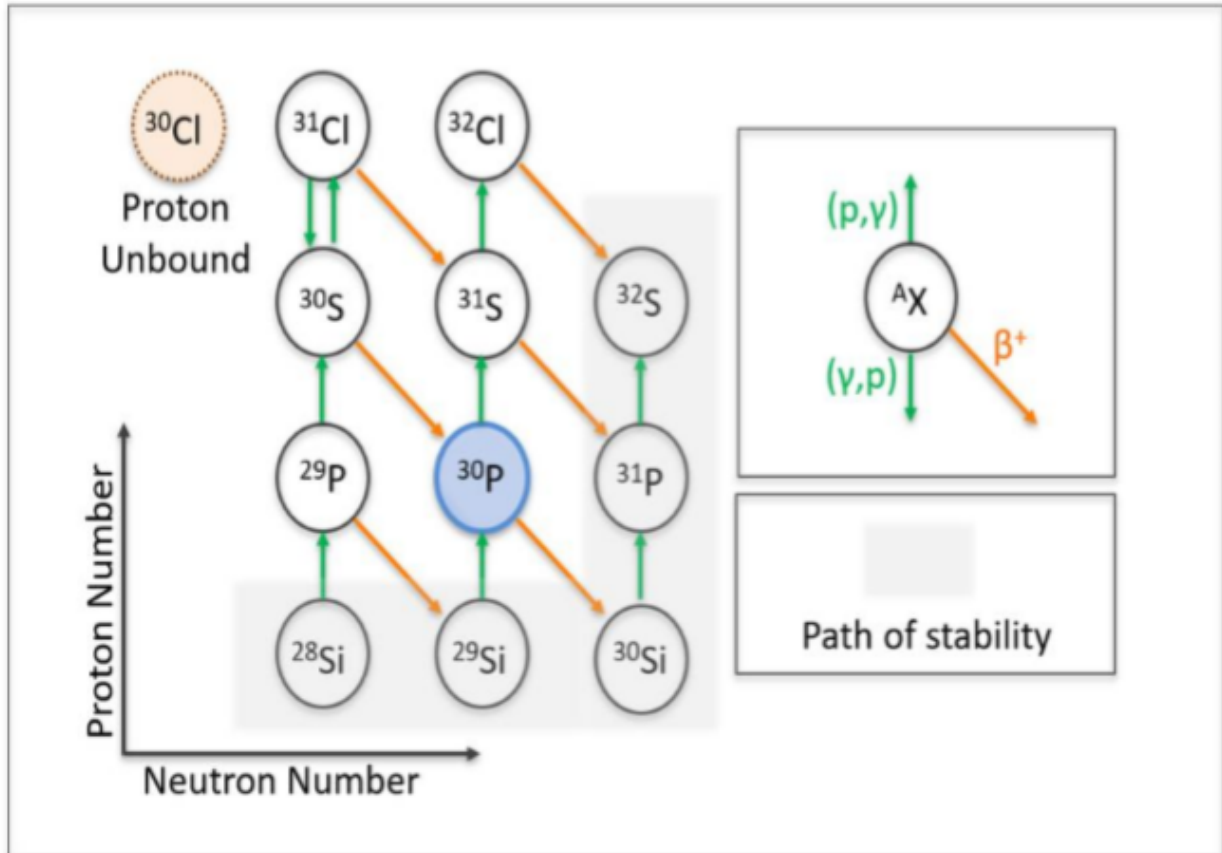


Figure 1.2: The reaction network illustrating possible nuclear reactions occurring around the ^{30}P region in a classical nova (Image Credit: Sean Burcher)

Proton capture on ^{30}P being responsible for the significant destruction of ^{30}P , and the $^{30}\text{P}(p, \gamma)^{31}\text{S}(p, \gamma)^{32}\text{Cl}$ being the nuclear reaction chain responsible for the production of intermediate mass nuclei, $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction acts as a bottleneck for nucleosynthesis beyond $A=30$ in ONe novae(25).

1.2.2 Isotopic Ratio of $^{30}\text{Si}/^{28}\text{Si}$

The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate directly affects the isotopic ratio of $^{30}\text{Si}/^{28}\text{Si}$, which is an important nova identifier in the analysis of the pre-solar grains(3). Pre-solar grains are tiny interstellar solid grains containing different materials ejected from a star before the solar system formation. The typical sizes of the presolar grains are in the range of micrometers as shown in Figure 1.3. In laboratories, the grains are isolated from meteorites by breaking up meteorites into small pieces and dissolving them in strong acids. Different analysis techniques are then used to identify their isotopic abundances. The study of the isotopic abundances in pre-solar grains can provide information about nucleosynthesis, stellar evolution, and the origin of the pre-solar grains.

The isotopic ratios $^{12}\text{C}/^{13}\text{C}$, $^{14}\text{N}/^{15}\text{N}$, $^{20}\text{Ne}/^{22}\text{Ne}$, $^{29}\text{Si}/^{28}\text{Si}$, $^{30}\text{Si}/^{28}\text{Si}$ are important to identify if the origin of pre-solar grains is a classical nova. If the pre-solar grains have very low $^{12}\text{C}/^{13}\text{C}$ compared to the solar values, they are expected to have a classical nova origin. The ratio $^{14}\text{N}/^{15}\text{N}$ can help distinguish the grains originating from classical novae involving CO, or ONe, WD as this ratio is linked to the peak nova temperature. If the $^{20}\text{Ne}/^{22}\text{Ne}$ ratio in pre-solar grains is above the solar value, they have ONe classical nova origin.

Since in ONe novae consist heavier nuclei than those in CO novae, $^{29}\text{Si}/^{28}\text{Si}$, $^{30}\text{Si}/^{28}\text{Si}$ ratios can be used to identify pre-solar grains from ONe novae. In particular, it has been shown that the $^{30}\text{Si}/^{28}\text{Si}$ ratio increases monotonically with the mass of a WD. Since, ^{30}Si is formed via $^{29}\text{Si}(p, \gamma)^{30}\text{P}(\beta^+)^{30}\text{Si}$, the precise measurement of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate is important. Thus, constraining the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate can

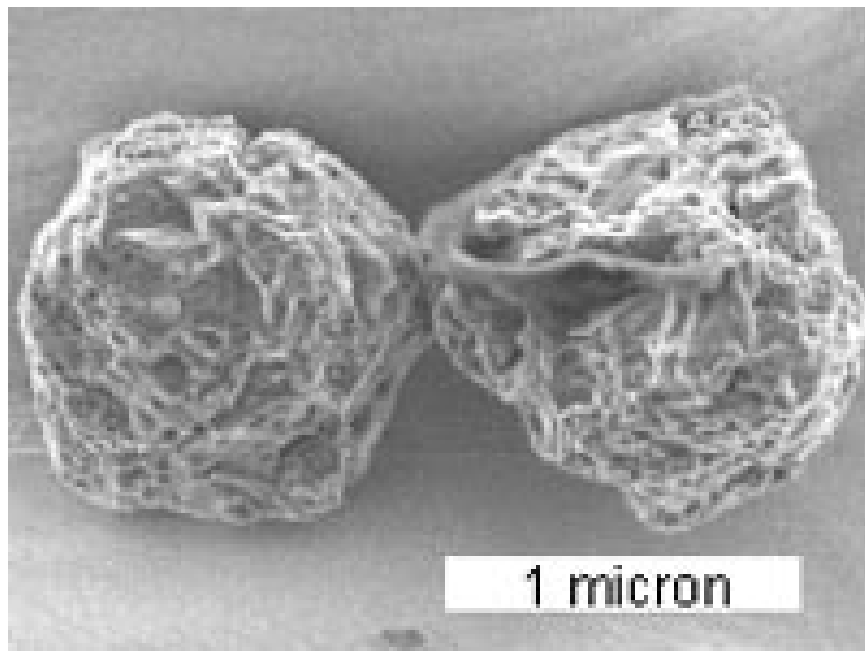


Figure 1.3: Presolar grains from the Murchison meteorite adapted from(2)

constrain the important isotopic ratio which can be used to calculate the mass of the WD involved in the ONe novae. Figure 1.4 shows Si isotopic ratios of different presolar grains, where the purple points, with $^{30}\text{Si}/^{28}\text{Si}$ ratio higher than the solar ratio, infers nova origin of the presolar grain.

1.2.3 O/S, S/Al, O/P and P/Al Elemental Ratios

Thermonuclear runaways on classical nova involving ONe WD can reach peak temperatures of order 10^8 K. The mass of the WD involved in the nova is strongly correlated with these peak nova temperatures. Downen *et al.*(4) studied the effect of peak nova temperature on the ratios of elemental abundances in classical novae ejecta. Using STARLIB (27), a library listing different reaction rates with uncertainties, they generated several hydrodynamic models using the SHIVA code(28) for different WD masses.

In their work, they found that the elemental abundance ratios of N/O, N/Al, O/S, S/Al, O/Na, Na/Al, O/P and P/Al revealed strong dependence on peak nova temperature as shown in Figure 1.5. The solid lines represent dependence for N, O, Al, and S, which are observed in the ONe nova shells and the dashed lines represent the dependence for Na, and P, which are not observed in the ONe nova shells. Using post-processing nucleosynthesis simulations, they found that the ratios N/O, N/Al, O/Na, and Na/Al are minimally affected by unknown reaction rates. On the other hand the ratios O/S, S/Al, O/P and P/Al have revealed strong dependence on peak temperature and the poorly constrained $^{30}\text{P}(p, \gamma)^{31}\text{S}$ rate(4). These ratios can be useful to constrain the nova peak temperatures. But, the uncertainty in the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ rate was highlighted as the major nuclear physics uncertainty in interpreting these ratios, currently hampering the use of these ratios to constrain the energetics of novae.

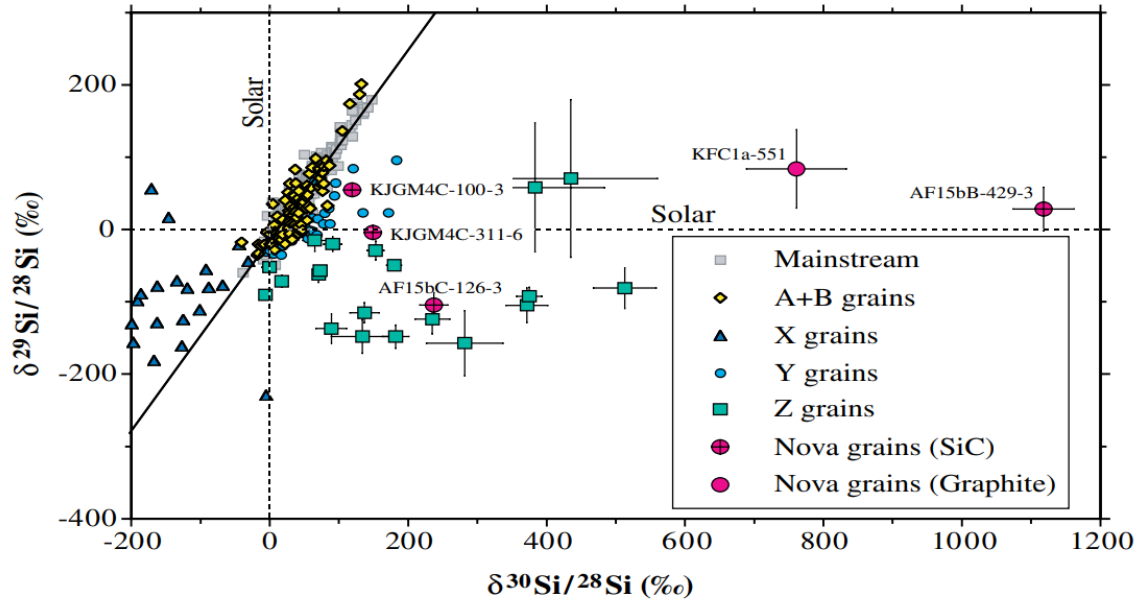


Figure 1.4: Si isotopic ratios of different presolar grains, where the five purple points infer their nova origin. Adapted from(3)

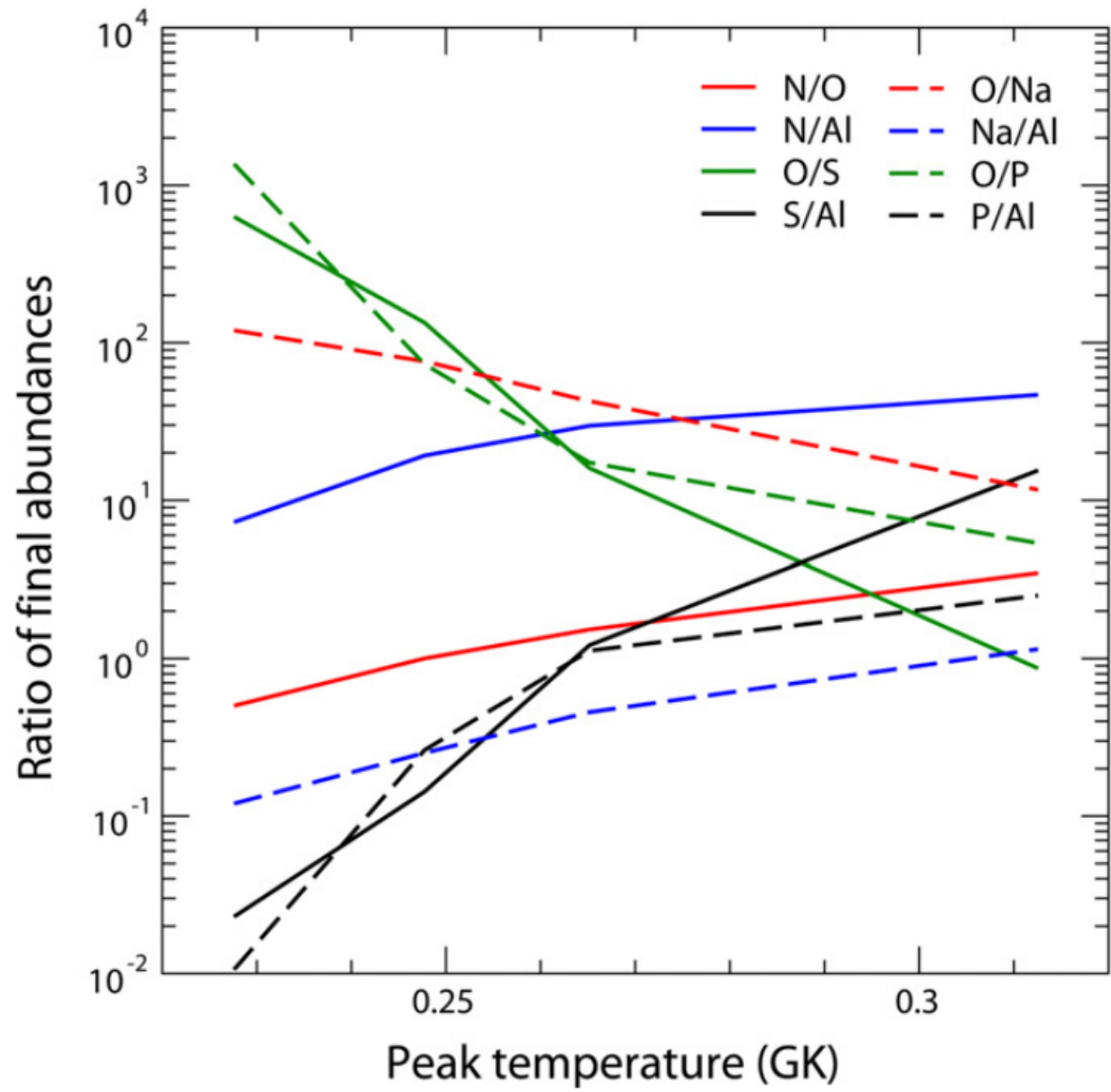


Figure 1.5: Elemental abundance ratios as a function of nova peak temperature adapted from(4)

Chapter 2

Theoretical Framework

2.1 Transfer Reactions

Transfer reactions are the reactions of the type:

$$A + a \rightarrow B + b,$$

where $A = b+x$ and $B = A+x$ (29). Here A is the projectile, nucleons x are transferred from the target a to the projectile, B is the recoil nucleus and b is the light ejectile as shown in Figure 2.1a. In this way, one or more nucleons can be transferred between the projectile and the target nuclei. Two examples of such reactions are (t,p) where two neutrons are transferred from the triton, and (d,p) where a single neutron is transferred from a deuteron.

Figure 2.1b shows the example of a (d,p) reaction in normal kinematics where a light deuteron beam is used to transfer one of its neutrons to the heavy target, and Figure 2.1c shows the (d,p) reaction in inverse kinematics where a heavy ion beam is used to transfer a neutron from a deuteron target.

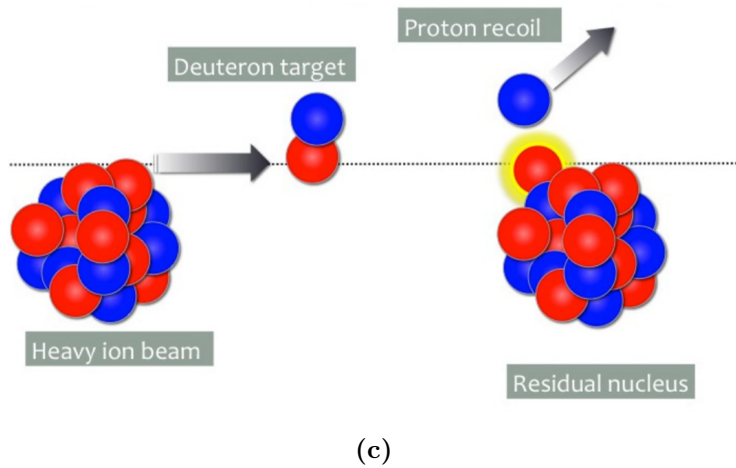
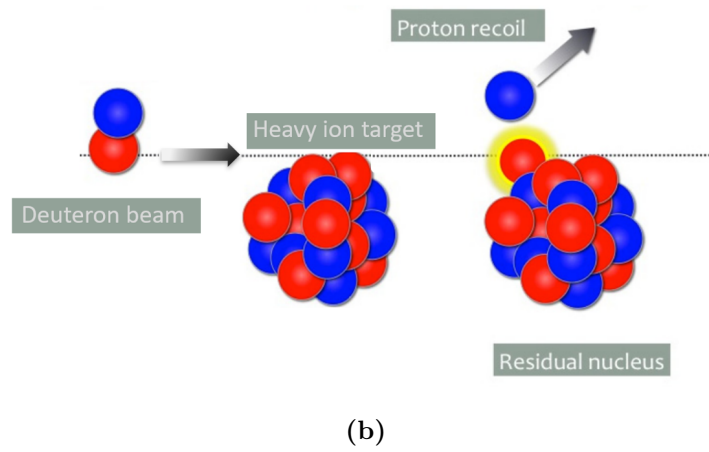
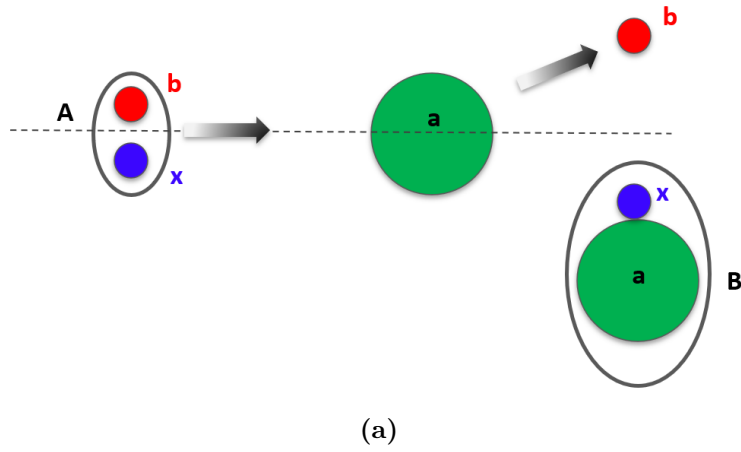


Figure 2.1: Transfer reaction in normal and inverse kinematics. (a) Illustration of a transfer reaction showing transfer of a particle x from the projectile A to the target nucleus a . Adapted from(5). (b) (d, p) reaction in normal kinematics. Adapted from(6). (c) (d, p) reaction in inverse kinematics. Adapted from(6).

Transfer reactions involving heavier radioactive nuclei must be performed in inverse kinematics because of the challenges in making targets with short-lived nuclei. Generally, detectors are used to measure the energy and angle of the ejectile. These can be used to find Q-values, which is defined in Section 4.4 as the amount of mass-energy released during a nuclear reaction, and excitation energies of the states populated in the recoil nucleus. After identifying different excitation states, the data can be divided into different angular bins to extract ejectile angular distributions. From this, transferred orbital angular momentum, l , can be obtained. The differential cross section, $d\sigma/d\Omega$, is defined as the probability of an incident particle being scattered into the solid angle $d\Omega$ (30). It can be obtained by normalizing the ejectile angular distribution. Spectroscopic factor is a measure of how much the state resembles a pure single-particle shell-model state. It can be extracted from the measured differential cross section using the calculated cross section for single-particle shell-model state as follows(30):

$$\left(\frac{d\sigma}{d\Omega}\right)_{meas} = S\left(\frac{d\sigma}{d\Omega}\right)_{calc} \quad (2.1)$$

where $(d\sigma/d\Omega)_{meas}$, $(d\sigma/d\Omega)_{calc}$, and S are the measured differential cross-section, the cross-section for the pure single-particle shell-model state, and the extracted spectroscopic factor respectively. For a pure shell-model state, the measured cross section is equal to the calculated cross section, which results in a spectroscopic factor of 1(30).

The (d, p) cross section for a single-particle shell-model state can be calculated with a variety of formalisms. The most commonly used ones are the Distorted-Wave Born Approximation (DWBA), which assumes that the nucleon transfer occurs in a single step, and Adiabatic Distorted Wave Approximation (ADWA), in which breakup of the deuteron is important. These formalisms are constructed using optical potentials that are extracted by fitting elastic scattering data. Thus, the extraction of spectroscopic factor is model dependent and the uncertainties arise from the choice of the optical potential, the bound state potential and the formalism.

2.2 Thermonuclear Reaction Rate

Consider a nuclear reaction of the type: $a + X \rightarrow C^* \rightarrow Y + b$, for which the reaction rate averaged over the velocity distribution $\phi(\nu)$ of particles in the stellar environment is given by(7):

$$r = N_a N_X \int_0^\infty \sigma(\nu) \nu \phi(\nu) d\nu = N_a N_X \langle \sigma \nu \rangle \quad (2.2)$$

where N_a and N_X are the number densities of the entrance channel nuclei, ν is the relative velocity of particles a, $\sigma(\nu)$ is the cross-section, reaction rate per-particle pair, $\sigma \nu$, is given by:

$$\langle \sigma \nu \rangle = \int_0^\infty \sigma(\nu) \nu \phi(\nu) d\nu \quad (2.3)$$

Assuming Local Thermal Equilibrium, the velocity distribution is given by the Maxwell-Boltzmann velocity distribution as (31):

$$\phi(\nu) = 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} \nu^2 e^{-\frac{\mu^2}{2kT}} \quad (2.4)$$

where μ and T are the reduced mass and temperature. The reaction rate per particle in terms of center-of-mass energy $E = \frac{1}{2}\mu\nu^2$ is given by(7):

$$\langle \sigma \nu \rangle = \left(\frac{1}{kT} \right)^{3/2} \left(\frac{8}{\pi\mu} \right)^{1/2} \int_0^\infty E \sigma(E) e^{-\frac{E}{kT}} dE \quad (2.5)$$

To account for the Coulomb repulsion between the charged reactants, the nuclear cross-section can be expressed in terms of an astrophysical S-factor, $S(E)$ as follows:

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E) \quad (2.6)$$

This is because the Coulomb barrier tunneling probability for two positively charged particles is proportional to the penetration factor P , which can be approximated for low energies as:

$$P = e^{-2\pi\eta} \quad (2.7)$$

where η , the Sommerfeld parameter is given by:

$$\eta = \frac{e^2 Z_a Z_X}{\hbar v} \quad (2.8)$$

By substituting Equation 2.6 to Equation 2.5, the rate of reaction per particle pair is given by(7):

$$\langle \sigma v \rangle = \left(\frac{1}{kT} \right)^{3/2} \left(\frac{8}{\pi \mu} \right)^{1/2} \int_0^\infty S(E) e^{-\frac{E_G^{1/2}}{E^{1/2}} - \frac{E}{kT}} dE, \quad (2.9)$$

where E_G is called Gamow energy and is given by:

$$E_G = \left(\frac{2\mu}{\hbar^2} \right) (\pi e^2 Z_a Z_X)^2 \quad (2.10)$$

The first part of the exponential term in Equation 2.9 arises from the Coulomb barrier tunneling probability and the second exponential term arises from the high energy tail of the Maxwell-Boltzmann velocity distribution of particles in a stellar environment. The convolution of these leads to a peak function around the effective energy E_0 called the Gamow peak as shown in Figure 2.2. The effective energy, E_0 at a given temperature, T , and the effective width of the Gamow window, Δ , is approximated by the following equations(32):

$$E_0 = 0.12204 (\mu Z_a^2 Z_X^2 T_9^2)^{1/3} \text{ MeV} \quad (2.11)$$

$$\Delta = 0.23682 (\mu Z_a^2 Z_X^2 T_9^5)^{1/6} \text{ MeV} \quad (2.12)$$

Since, the nova peak temperature ranges from $1 - 4 \times 10^8$ K, Equation 2.11 and Equation 2.12 gives the values of E_0 to be between 158 keV and 399 keV respectively and the values of Δ to be between 85 keV 271 keV respectively. This gives the region of interest in resonance energy, called Gamow window where the reaction is likely to occur, to be $E_r = 116 - 534$ keV.

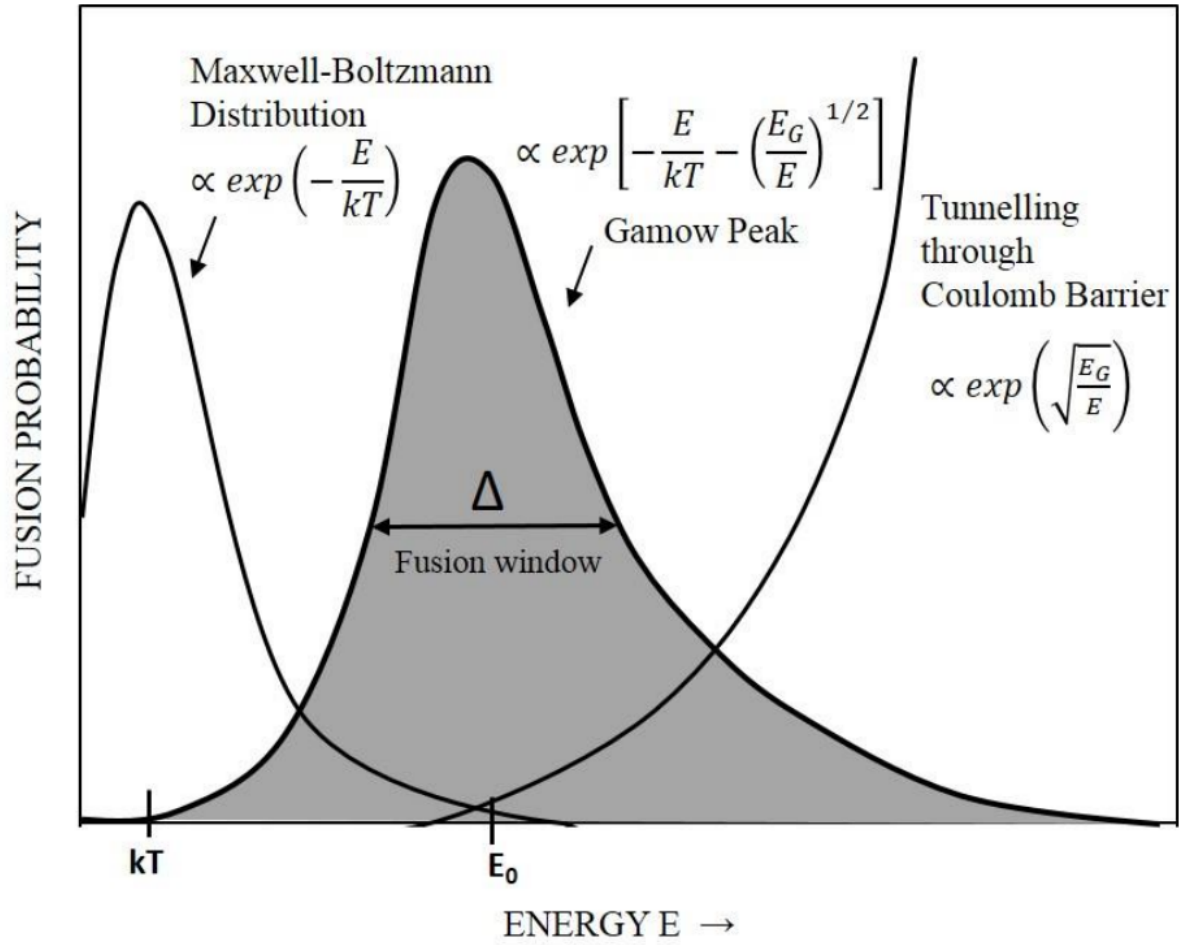


Figure 2.2: Gamow peak, magnified for illustration, from the convolution of the Maxwell-Boltzmann distribution and penetration probability through Coulomb barrier. Adapted from(7)

2.3 Thermonuclear Reaction Rate for narrow and isolated resonances

Resonant reactions occur the entrance channel energy matches the excited state energy of the compound nucleus as shown in Figure 2.3. The Breit-Wigner formula expresses the nuclear cross section for a single-level resonance as:

$$\sigma_{\text{BW}}(E) = \pi\lambda^2 \frac{2J+1}{(2J_a+1)(2J_X+1)} \frac{\Gamma_a(E)\Gamma_b(E)}{(E-E_R)^2 + (\Gamma(E)/2)^2}, \quad (2.13)$$

where E_R is the energy of the resonance, Γ_a , Γ_b , and Γ are the partial widths in the entrance and exit channels and the total width respectively and J_a , J_X , and J are the spins of the two incident nuclei and the final resonance respectively. From Equation 2.5, the reaction rate per particle pair in terms of Breit-Wigner cross-section is given by(7):

$$\langle \sigma \nu \rangle = \left(\frac{1}{kT}\right)^{3/2} \left(\frac{8}{\pi\mu}\right)^{1/2} \int_0^\infty E \sigma_{\text{BW}}(E) e^{-\frac{E}{kT}} dE \quad (2.14)$$

Narrow and isolated resonances have widths (Γ) that are much smaller than the resonance energy and the spacing between nearby levels, as shown schematically in Figure 2.4. The energy dependent term in the integrand of this equation remains same over the resonance region for these resonances. Also, the cross-section can be expressed as a sum of the contributions of all the individual resonances. In such cases, the reaction rate per particle pair for a single resonance at resonance energy E_R is given by:

$$\langle \sigma \nu \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \omega \gamma_R e^{-\frac{E_R}{kT}} \quad (2.15)$$

where $\omega \gamma_R$ is the resonance strength in MeV and is given by:

$$\omega \gamma_R = \frac{2J+1}{(2J_a+1)(2J_X+1)} \frac{\Gamma_a \Gamma_b}{\Gamma} \quad (2.16)$$

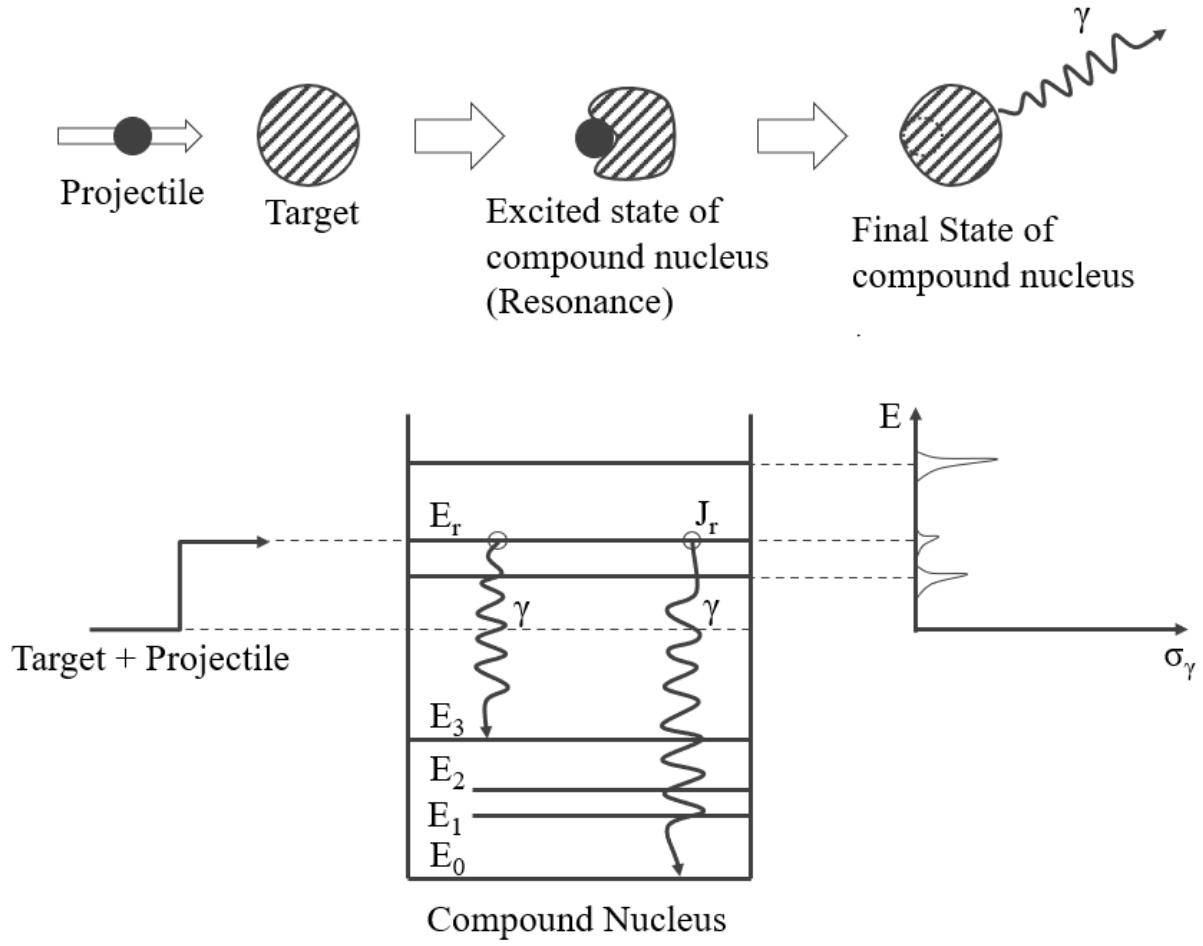


Figure 2.3: Illustration of a resonant capture reaction which can occur if the entrance channel energy matches the excited states energies. The capture cross section are peaked at these resonant energies E_r . Adapted from(7).

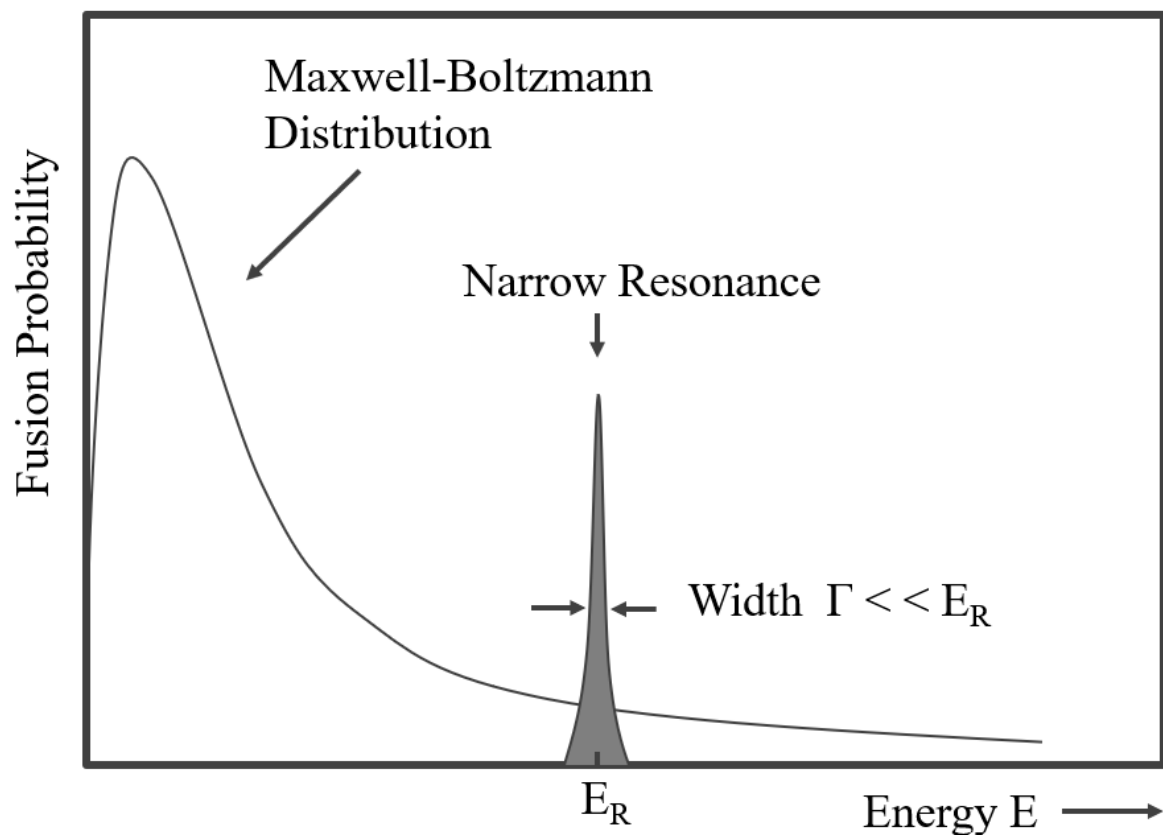


Figure 2.4: Gamow peak coinciding with the resonance energy region for narrow resonance. Adapted from(7).

2.4 Measurement of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ Reaction Rate

The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction proceed via narrow and isolated resonances. From Equations 2.15 and 2.16, it is clear that to calculate the resonant reaction rate one would need the following nuclear information:

1. The energy of the resonance (E_R),
2. The angular momenta of the ground state of the ^{30}P nuclei (J_x), and resonances (J),
3. The proton decay width (Γ_p) and γ -ray decay width (Γ_γ) of the resonance state. Due to low cross sections of the proton capture reactions, these widths are measured via indirect methods with certain approximations.

For low-lying resonances, which are expected to dominate the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate, the Coulomb and centrifugal barriers suppress Γ_p and $\Gamma_p \ll \Gamma_\gamma$. With this,

$$\omega\gamma \approx \omega\Gamma_p, \quad (2.17)$$

where Γ_p can be expressed in terms of single-particle width as follows(29):

$$\Gamma_p \approx C^2 S \Gamma_{sp}. \quad (2.18)$$

S is the single-particle spectroscopic factor, which provides a measure of how much the populated state resembles a pure shell-model state, C is the isospin Clebsch-Gordan coefficient, and Γ_{sp} is the single-particle width which is defined as the partial width of a pure single-particle resonance. The single-particle width depends on the experimentally extracted orbital angular momentum, l_p of the proton. The single-particle spectroscopic factor can be determined by alternate reaction that is easier to measure, such as a transfer reaction, by comparing the measured differential cross sections to those calculated for pure single-particle states as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \frac{(2J+1)}{(2J_a+1)(2J_X+1)} C^2 S \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}. \quad (2.19)$$

Thus, the proton-decay width can be extracted from the single-particle spectroscopic factor and the single-particle width. Spectroscopic factors, and the other two nuclear inputs listed above; resonance energy and angular momenta, need to be extracted from experiment. Direct measurement of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction is not feasible because proton capture reactions at astrophysical energies have very low cross sections as the proton has to tunnel through the Coulomb barrier and due to experimental challenges in producing an intense ^{30}P beam at relevant astrophysical energies. These nuclear data must be calculated by an indirect method, such as $^{30}\text{P}(d, n)^{31}\text{S}$ or $^{30}\text{P}(^3\text{He}, d)^{31}\text{S}$. However, it is difficult to perform the $^{30}\text{P}(d, n)^{31}\text{S}$ and $^{30}\text{P}(^3\text{He}, d)^{31}\text{S}$ reactions in the laboratory because of the difficulty in measuring neutrons and producing ^3He targets respectively. Another indirect method was used which measured the $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction to study the single-neutron spectroscopic structure of ^{31}P . The single-proton spectroscopic structure and resonance structure of the astrophysically important resonances in ^{31}S was constrained via mirror symmetry.

Mirror nuclei pairs are those where the nuclei have opposite numbers of protons and neutrons. For example, ^{31}P has 15 protons and 16 neutrons, while ^{31}S has the opposite, 15 neutrons and 16 protons. In principle, these nuclei are identical except for the charge of the proton, which has a small effect compared to the strong nuclear force. This symmetry is called isospin symmetry, and a quantum number, called isospin, can be used to denote two possible states of a nucleon as proton or neutron. Since our eventual goal is to constrain the proton spectroscopic factors for the mirror states in ^{31}S , shell model embedded in the continuum (SMEC) formalism will be used for calculations of spectroscopic factors for the states in ^{31}P and ^{31}S . The ratio of the theoretical spectroscopic factors will be used to scale the experimentally determined neutron spectroscopic factors for ^{31}P to calculate proton spectroscopic factors for the mirror states in ^{31}S . A similar indirect measurement was performed by S.D. Pain *et al.* (33) using the $^{26}\text{gAl}(d, p)^{27}\text{Al}$ reaction measurement to constrain the spectroscopic factors, and resonance strengths, of ^{27}Si using the mirror symmetry.

2.5 Previous Studies

To reduce the ambiguities in energies, spins, parities, and spectroscopic factors of astrophysically-important states, several experiments have studied the level structure of ^{31}S . The mirror to those states that can be populated by low- l proton capture on the 1^+ ground state of ^{30}P ($1/2^+$, $3/2^+$, $1/2^-$, $3/2^-$, $5/2^+$, $5/2^-$, $7/2^+$ states) are of the particular importance.

2.5.1 Fusion-Evaporation Measurement using Gammasphere

The $^{28}\text{Si}(^4\text{He},n)$ fusion-evaporation reaction measurement(8; 34) was performed with a beam of $^4\text{He}^{1+}$ ion and a ^{28}Si target at Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory. The compound nucleus, ^{32}S , decayed to ^{31}S , ^{31}P , and ^{28}Si via the single-neutron, -proton and $-\alpha$ particle-evaporation channels respectively. The gammasphere detector array was used to detect the prompt γ rays, and the level scheme was built by sorting the data into $\gamma-\gamma$ matrices and $\gamma-\gamma-\gamma$ cubes. This measurement provided extensive $^{31}\text{P}/^{31}\text{S}$ mirror assignments in the excitation energy range of astrophysical interest, identifying resonances that are likely to dominate the reaction rate at nova temperatures, and their mirrors in ^{31}P , which lie between 6.2 and 6.9 MeV as shown in Figure 2.5.

2.5.2 Shell Model Calculation by Brown *et al.*

Brown *et al.*(35) performed a shell-model calculation that includes the states from the fp -shell. Using the WBP Hamiltonian, a complete $1\hbar\omega$ basis was made from all possible excitations of one nucleon from the $0p$ to $1s-0d$ orbitals, or the excitation of one nucleon from the $1s-0d$ to $1p-0f$ orbitals. This study suggests that $l_p = 1$ states in the 6.1 to 6.7 MeV excitation region may dominate the astrophysical reaction rate. Due to experimentally-unconstrained spectroscopic information, previous studies have assumed $C^2S = 0.1$ for even-parity, and 0.02 for odd-parity states to calculate the reaction rates(34; 36; 37; 38). However, this study predicts a state at 116 keV resonance energy with $l_p = 1$ and large $C^2S = 0.23$.

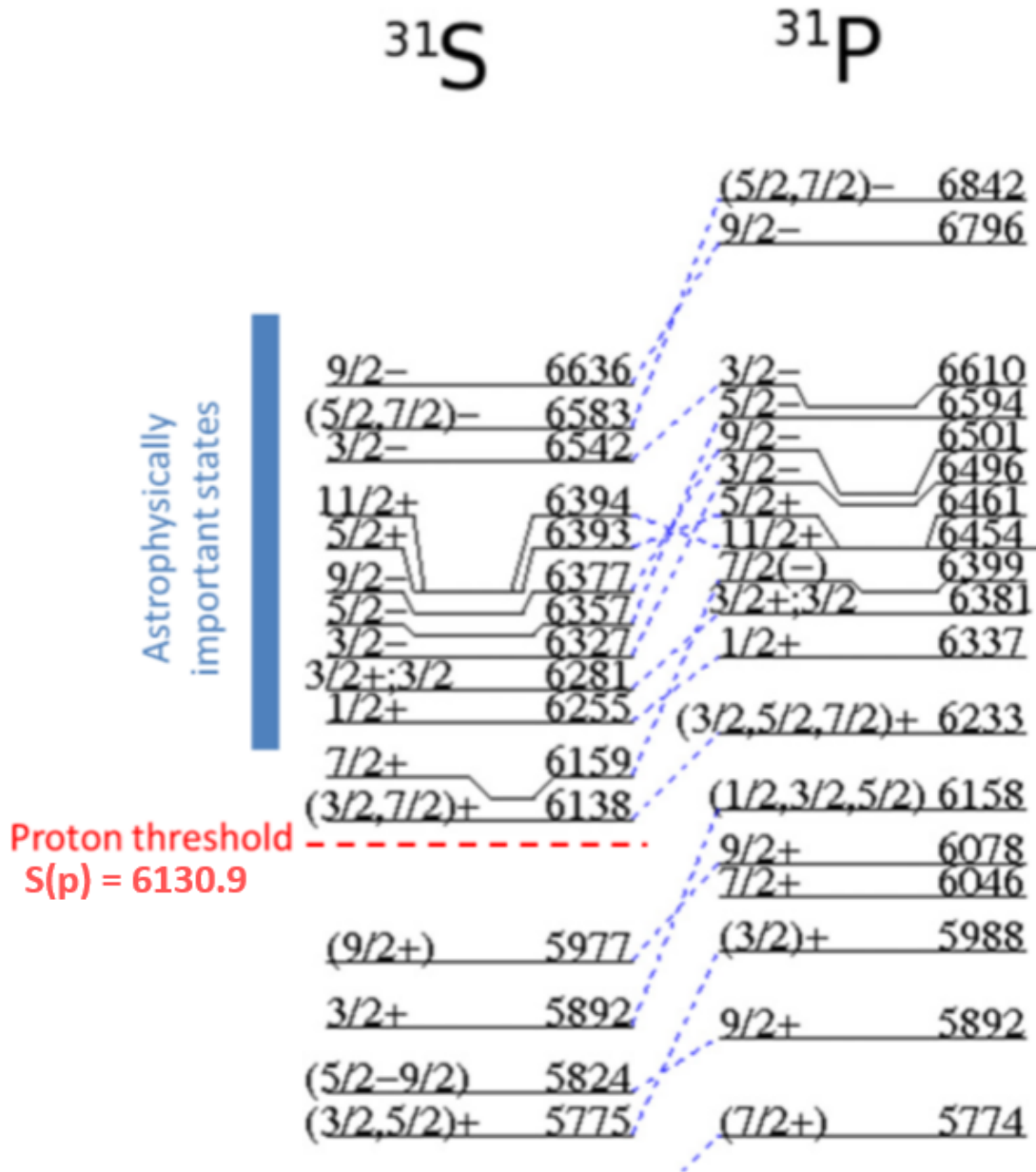


Figure 2.5: Figure adapted from(8), showing $^{31}\text{P}/^{31}\text{S}$ mirror assignments in the excitation energy range (in keV) of astrophysical interest

2.5.3 $^{30}\text{P}(d, n\gamma)^{31}\text{S}$ Reaction Measurement

The measurement using the $^{30}\text{P}(d, n\gamma)^{31}\text{S}$ reaction was performed at the NSCL using GRETINA and the S800 spectrograph with 30-MeV/A ^{30}P beam to measure the important resonance states for the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate(9). This measurement provided the first constraints on the spectroscopic factors of a number of resonances. They reported order of magnitude lower spectroscopic factors than the shell model prediction for the strongly produced negative-parity states. This study predicted that a 196-keV resonance dominates the reaction rate in the lower temperature region ($T \sim 0.10 - 0.17$ GK), and a 260-keV resonance, found recently in ^{31}Cl β -decay experiment (39), dominates the reaction rate in the higher temperature region ($T \gtrsim 0.17$ GK), as shown in Figure 2.6. But the 260-keV resonance was not observed in this measurement, so the strength of this resonance depends upon theoretical calculations. Also, the strong $l_p = 1$ single-particle states predicted by the shell model were not observed in this region. The reaction neutrons were not measured in this experiment. So there was no angular distributions to constrain the l values of the transferred protons. There are several ambiguities in J^π in the ^{31}S level structure and because of non-zero spin of the ^{30}P ground state, non-unique l transfers are also possible for a given J^π , which were not deconvolved in this measurement. In addition, the non-observation of the 260-keV state maybe explained by the low l_p associated with this state, which has a low cross-section at the 30-40 MeV/A. While this measurement is an important first-step to constraining the spectroscopic strength in this region, several ambiguities remain in spectroscopic factors, and J^π . If the 250-keV state with such large spectroscopic factor exists in the ^{31}S level structure, its mirror, in ^{31}P should be strongly populated.

To study the ^{31}P spectroscopic structure, we performed the $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction using the newly commissioned GODDESS system. The measurement of protons in charged-particle detectors will be critical in determining transferred angular momentum, l , and thereby, the total angular momentum J^π . The γ -ray detector array will play a vital role to disentangle the states with very high level-density.

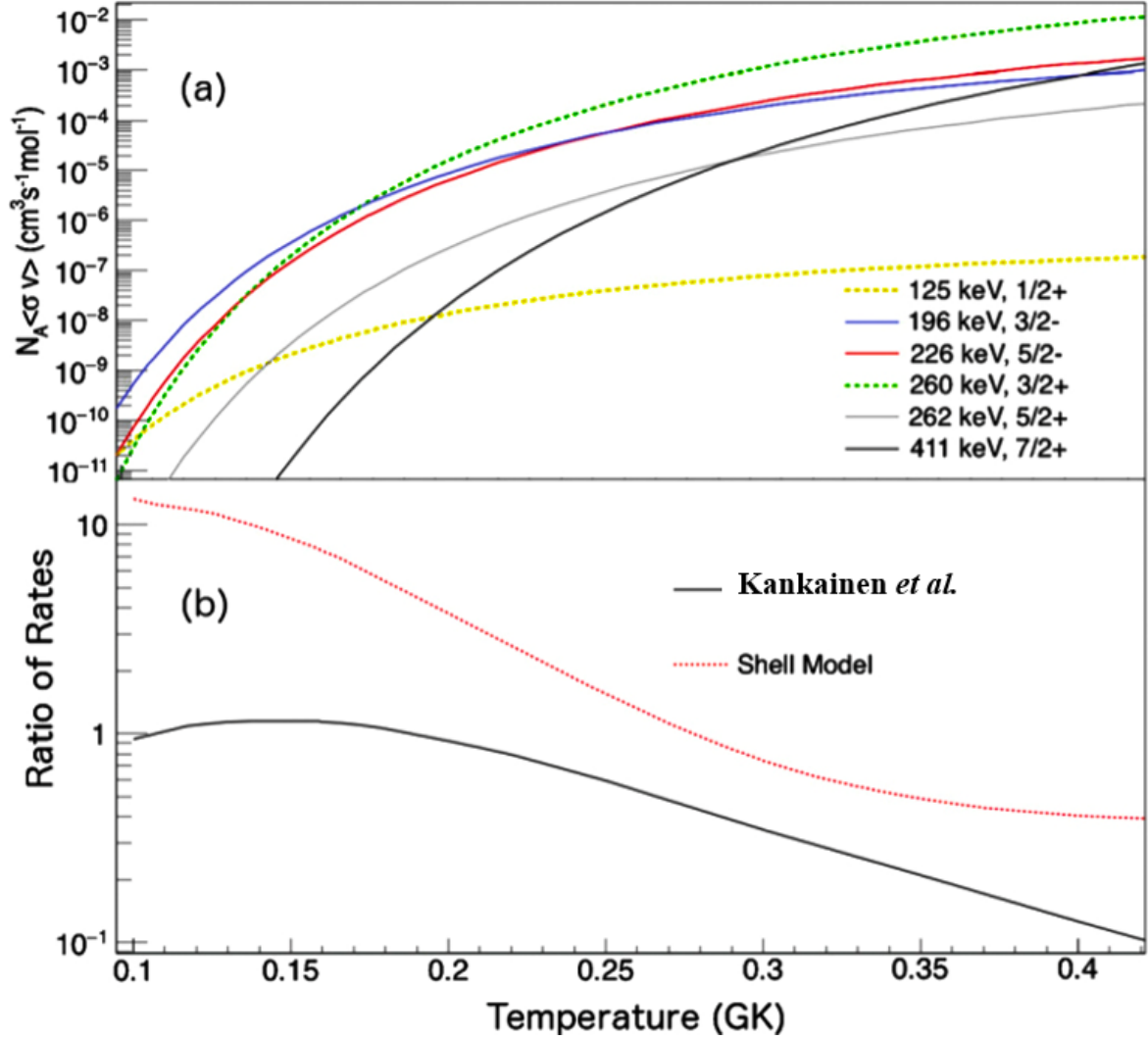


Figure 2.6: Reaction rate for $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction as a function of temperature. In (a), the dotted lines represent reaction rates based on theoretical calculation, and solid lines represent rates from this work. In (b), ratio of reaction rates based on the work by Kankainen *et al.* and shell model calculation to statistical model rates are shown. Adapted from(9).

Chapter 3

Experimental Setup

$^{30}\text{P}(d, p\gamma)^{31}\text{P}$ is a transfer reaction in which a neutron, from a deuteron, is transferred to the ^{30}P nucleus. Because of the challenges in making targets with radioactive ^{30}P nuclei, this reaction was performed in inverse kinematics with a radioactive ^{30}P beam and a deuteron target. An accelerator system at Argonne National Laboratory can create a radioactive ^{30}P -beam via in-flight method at a well suited energy to the population of the astrophysically-important low angular-momentum states. The $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction was measured using the GODDESS (GRETINA-ORRUBA: Dual Detectors for Experimental Structure Studies) system. For ejectile kinematics, the energy and angle of protons were measured using a silicon detectors array at 90° - 163° polar angles. In addition, silicon detectors were instrumented at polar angles $<90^\circ$ to measure elastically-scattered particles. The measurement of elastically-scattered deuterons was used for beam normalization to extract differential cross-sections. A fast ionization chamber was used to identify the ^{30}P beam and ^{31}P recoil from several contaminants, and to find the beam vertex. The ionization chamber measurement is also critical for beam flux determination. The resolution of the excitation energy spectrum of the ^{31}P was dominated by the broadened optics of the in-flight beam. The γ -ray tracking array, GRETINA, was used to measure the γ rays emitted from the ^{31}P recoil nucleus to disentangle the tight level spacing in the excitation levels of the ^{31}P .

3.1 ^{30}P Beam and CD_2 Target

The $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction measurement was performed at the Argonne National Laboratory using the GODDESS system. A radioactive ^{30}P beam, with an energy of 240 MeV and intensity of the order 10^5 pps, was produced via the in-flight method at the Argonne Tandem Linac Accelerator System (ATLAS) shown in Figure 3.1. A primary stable beam of ^{29}Si was accelerated onto a deuterium gas cell and the $^{29}\text{Si}(d, n)^{30}\text{P}$ reaction produced a secondary beam of ^{30}P . The Argonne In-Flight Radioactive Ion Separator (RAISOR) was used to select and purify the radioactive ^{30}P beam. The beam energy was extracted by Doppler correcting the γ rays using different speeds of recoil, and making a γ -ray energy vs recoil speed spectrum as shown in Figure 3.2. The Doppler correction converged on the dashed red line with $\beta=0.128$, which corresponds to 240 MeV beam energy at the center of the target.

As the broadened optics of the in-flight beam degrades the resolution in the excitation energy, derived from the ejectile energy, a thicker target can be employed without further resolution degradation. A deuterated polyethylene film of thickness $621 \mu\text{g}/\text{cm}^2$ was used as a main reaction target. These CD_2 foils were produced by making a mixture of CD_2 powder and xylene which was heated and evaporated. In addition, a $720 \mu\text{g}/\text{cm}^2$ CH_2 target was used for background identification and subtraction.

3.2 The GODDESS System

GODDESS (GRETINA-ORRUBA: Dual Detectors for Experimental Structure Studies), shown in Figure 3.3, is a coupling of a silicon detectors array, ORRUBA, with the γ -ray tracking array GRETINA. The implementation of the γ -ray detectors along with the silicon detectors is important to resolve the tight level spacing in the excitation spectrum of ^{31}P , to identify the states and their branching ratios and spins.

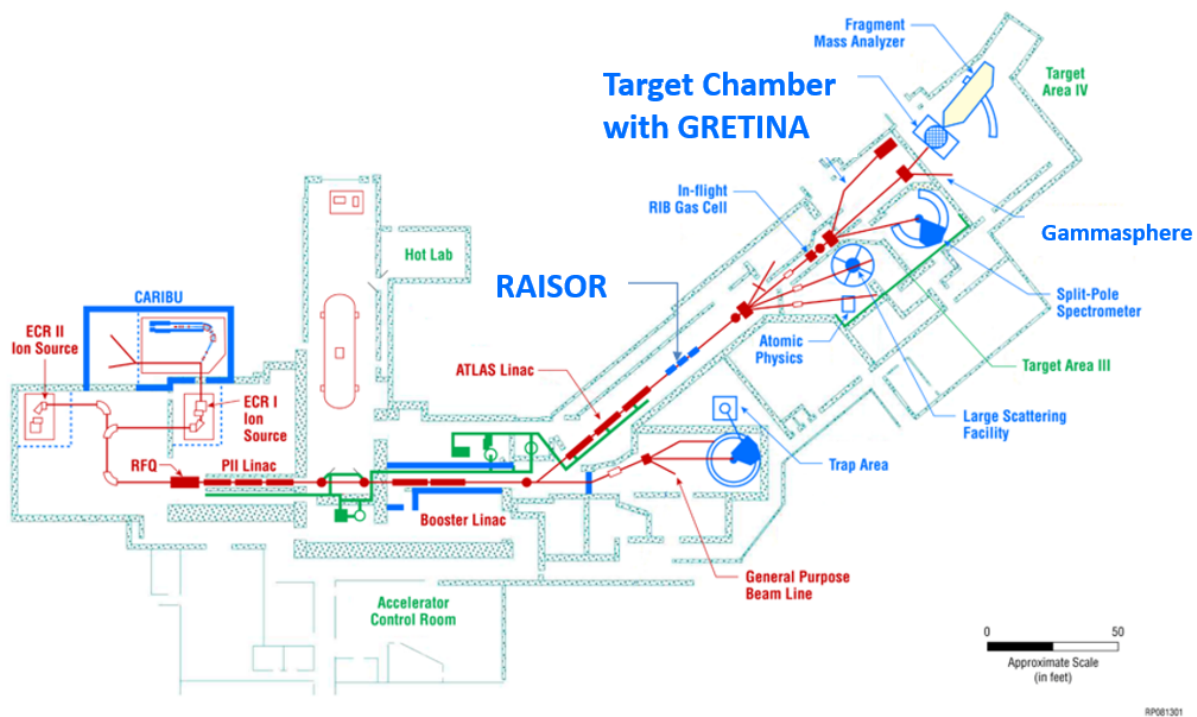


Figure 3.1: The layout of ATLAS at Argonne National Laboratory illustrating the location of RAISOR and GRETINA. Adapted from (10)

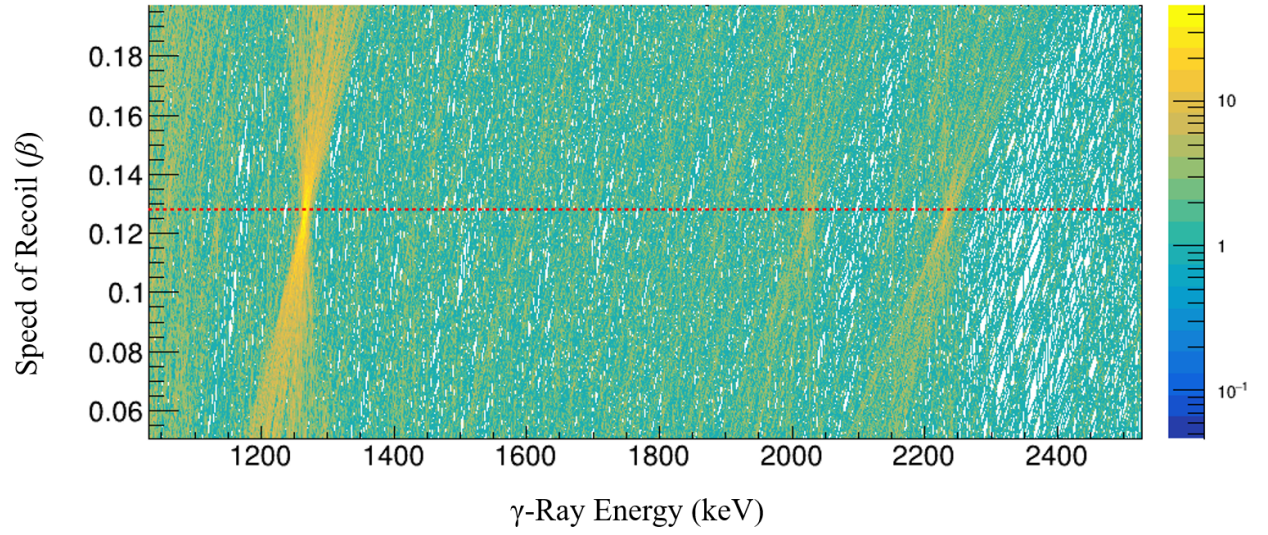


Figure 3.2: Speed of the recoiling nuclei versus the Doppler-corrected γ -ray energy spectrum. The convergence at $\beta=0.128$, represented by the horizontal line, corresponds to 240.298 MeV beam energy at the center of the target.

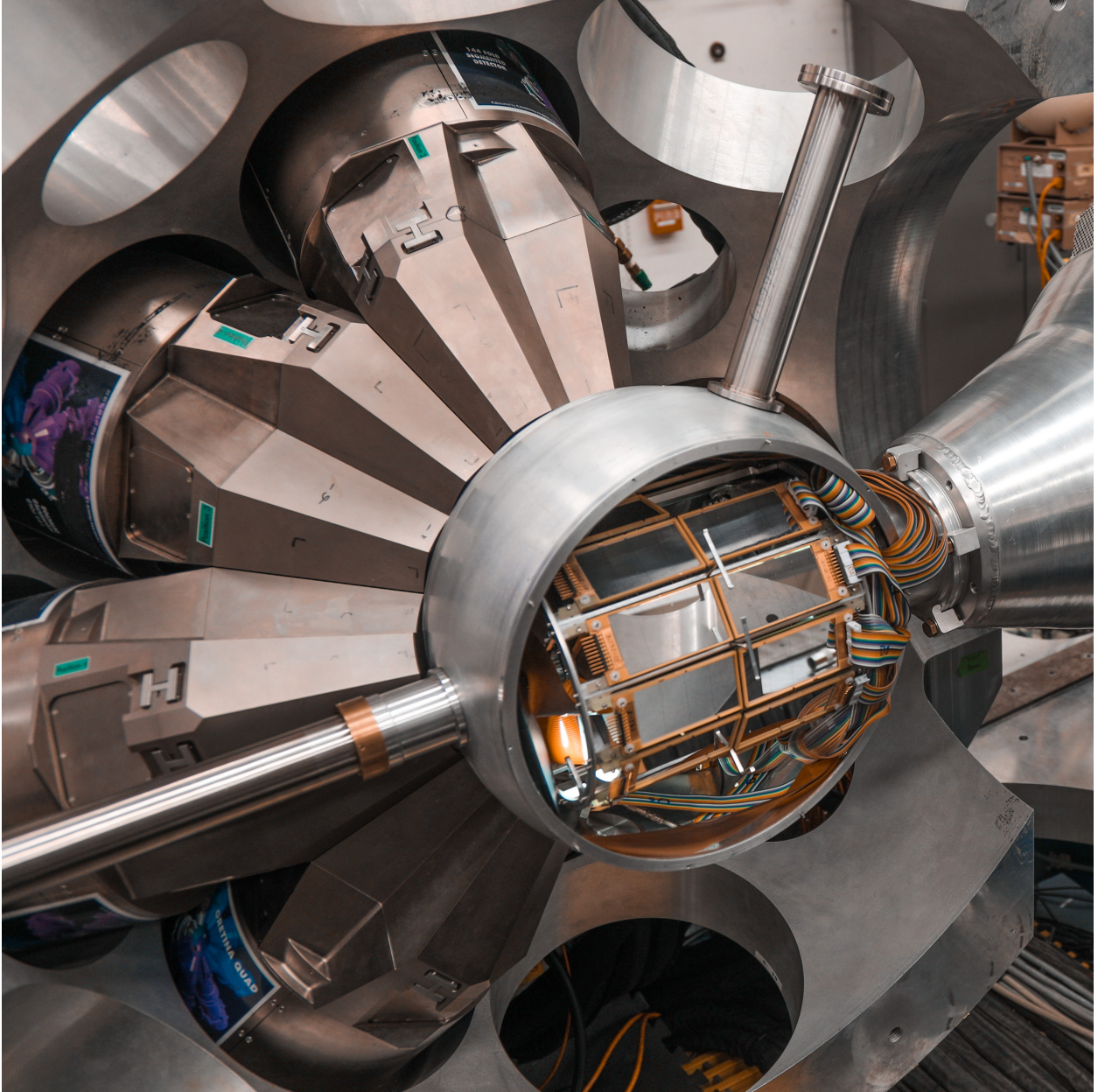


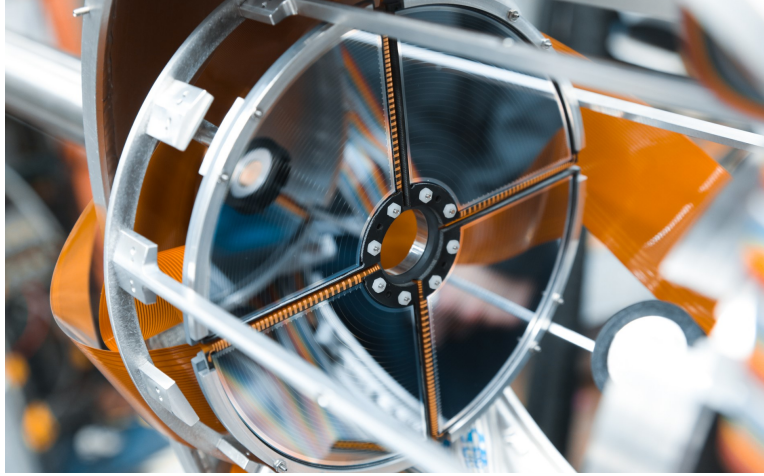
Figure 3.3: GODDESS system comprising of a coupling of the silicon detector array, ORRUBA with the γ -ray tracking array, GRETINA (Image Credit: S.D. Pain)

3.2.1 ORRUBA

ORRUBA (Oak Ridge Rutgers University Barrel Array) is an array of high-resolution charged particle detectors manufactured by Micron Semiconductor Ltd. The barrel consists of up to 24 position-sensitive (22 were used in this experiment) 1 mm-thick super X3 silicon detectors shown in Figure 3.4b. Super X3 detectors are 75 mm long and 40 mm wide and have 4-fold-segmented Ohmic contacts on the rear side in addition to the resistive strips on the junction side of the detectors. The resistive strips allow for the high-resolution measurement of the particle position, and the rear side segments allow for the high-resolution measurement of the particle energy. Downstream of the $621 \mu\text{g}/\text{cm}^2$ CD_2 target, eight $65 \mu\text{m}$ -thick BB10 detectors, shown in Figure 3.4c were placed in front of super X3 detectors for the particle identification of elastically scattered particles. BB10 detectors have the same dimensions as super X3 detectors, but unlike super X3 detectors, they have eight non-resistive strips.

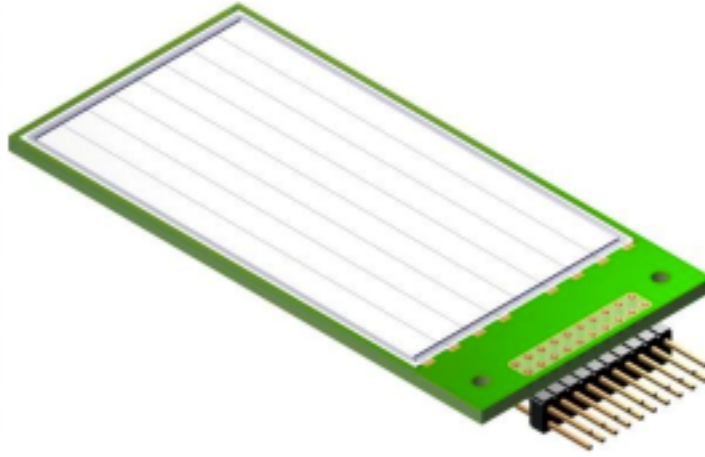
The barrel with super X3 detectors and BB10 detectors is capped upstream and downstream with highly segmented QQQ5 detectors. QQQ5 detectors, shown in Figure 3.4a, are quadrant style detectors with 32 strips on the front side and 4 sectors on the rear side. In this experiment, the upstream endcap consisted of four 1 mm-thick QQQ5 detectors, the downstream endcap consisted of a single 100-1000-1000 μm -thick stack of three QQQ5 detectors for light ion identification. As shown in Figure 3.5, the upstream QQQ5 endcap covered 135° to 163° azimuthal angles, the barrel with resistive strips covered 50° to 130° polar angles, and the downstream QQQ5 endcap covered 18° to 45° azimuthal angle.

The silicon detectors were calibrated using ^{228}Th alpha source which has five main α -lines with the energies 5423 keV, 5685 keV, 6288 keV, 6778 keV, and 8784 keV. The calibration steps for the super X3 detectors included gain matching both ends of the resistive strips, energy calibration of the resistive strips, position calibration of the resistive strips, and energy calibration of the non-resistive back pads. For gain matching of the resistive strips, a left side raw value versus right side raw value histogram was drawn for each strip.



(a)

(b)



(c)

Figure 3.4: Different silicon detectors used in the ORRBUBA barrel. (a) ORRBUBA upstream endcap consisting of four QQQ5 detectors. (b) CAD model of a super X3 detector (c) CAD model of a BB10 detector (Image Credit: (a) by S.D. Pain, (b) and (c) by Micron Semiconductor Ltd.)

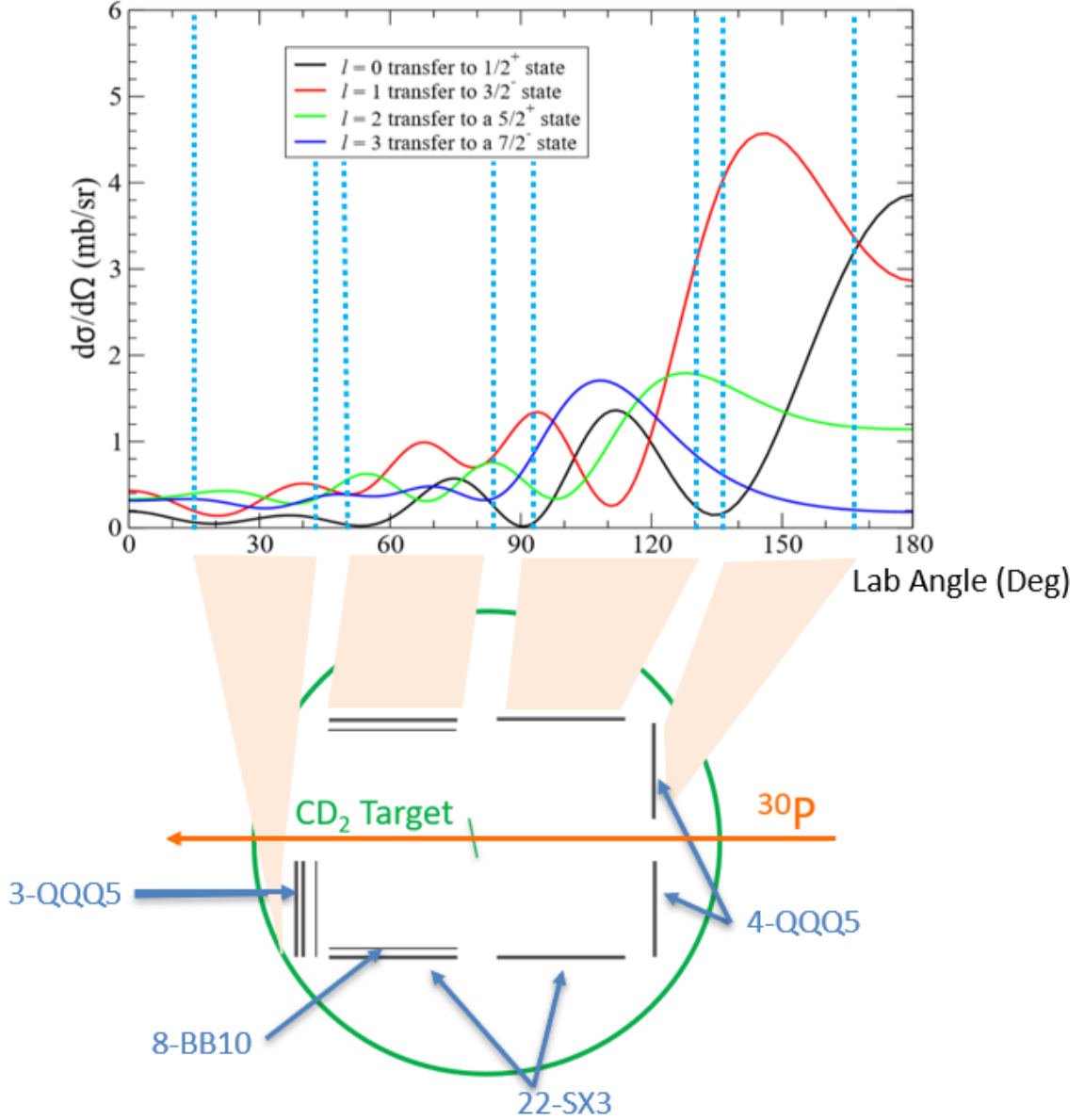


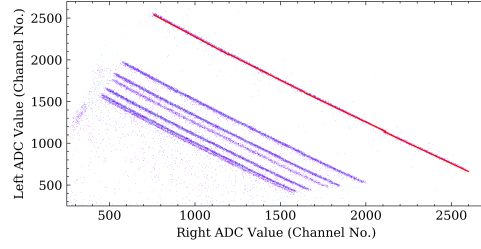
Figure 3.5: A schematic illustrating the angular coverage of ORRUBA detectors and differential cross sections in the laboratory frame calculated for the $^{30}\text{P}(d,p)^{31}\text{P}$ reaction at 8 MeV/A in inverse kinematics ($C^2S = 1.0$), to a hypothetical state at 7 MeV excitation

The slope of the highest energy α line was evaluated by fitting the histogram with a linear function as shown in Figure 3.6a. The slope of this line was used for gain matching. For energy calibration of the resistive strips, the gain matched right side raw value was added to the left side raw value. This sum, which is the uncalibrated resistive strip energy, was filled into a 1-D histogram. The histogram was fitted with a function that had the sum of five Gaussian functions as shown in Figure 3.6b. The five centroids were extracted, which were linearly calibrated to the energies of the five α lines in keV. The slope and intercept of this linear function were used as the parameters for the energy calibration of the resistive strips. For position calibration of the resistive strips, the position was calculated using the left raw value and the right raw value of each strip. The sum and difference of the left raw value and the right raw value were first calculated, and the position was calculated by dividing the difference by the sum. A position histogram was filled with this uncalibrated position and fitted with a linear function as shown in Figure 3.6c. The two x-values, corresponding to the y-values equal to half of the maximum, were calculated. These two x-values, which are equivalent to 0 mm and 75 mm of the strip, were used to extract position calibration parameters.

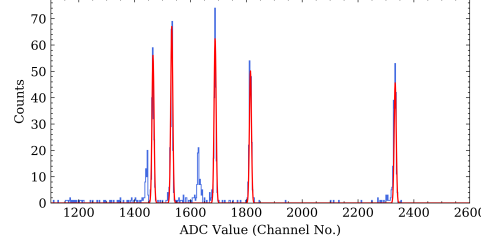
Similar to the front resistive strips, the non-resistive back pads of super X3 detectors, the non-resistive strips of the BB10 detectors, and the annular rings of the QQQ5 detectors were calibrated by fitting the raw value histogram with five Gaussian functions. The calibrated super X3 energy versus position histogram is shown in Figure 3.6d.

3.2.2 GRETINA

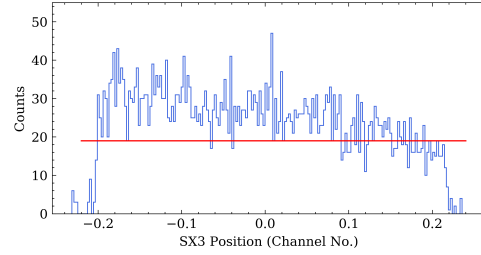
The Gamma-Ray Energy Tracking In-beam Nuclear Array (GRETINA), shown in Figure 3.7, is the state-of-the-art γ -ray detection system consisting of 28 highly-segmented Hyper-Pure Germanium (HPGe) crystals capable of tracking the interactions of γ rays within it, which allows for the reconstruction of full γ -ray energies from multiple individual Compton scatter events followed by photoelectric absorption.



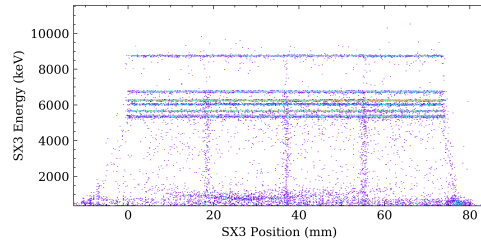
(a)



(b)



(c)



(d)

Figure 3.6: Data from different silicon detectors used in ORRUBA barrel (a) super X3 gain matching plot with left raw value versus right raw value where slope of the highest energy alpha line was used to match the gains. (b) Raw super X3 energy energy spectrum where the centroids of the Gaussian fit correspond to 5423 keV, 5685 keV, 6288 keV, 6778-keV and 8784 keV α -particles from a ^{228}Th α source. (c) Raw super X3 position spectrum where the two ends of the histogram correspond to 0 mm and 75 mm position on the strip. (d) super X3 calibrated energy versus position histogram where the horizontal lines are different alpha lines extending from 0 mm to 75 mm in position.

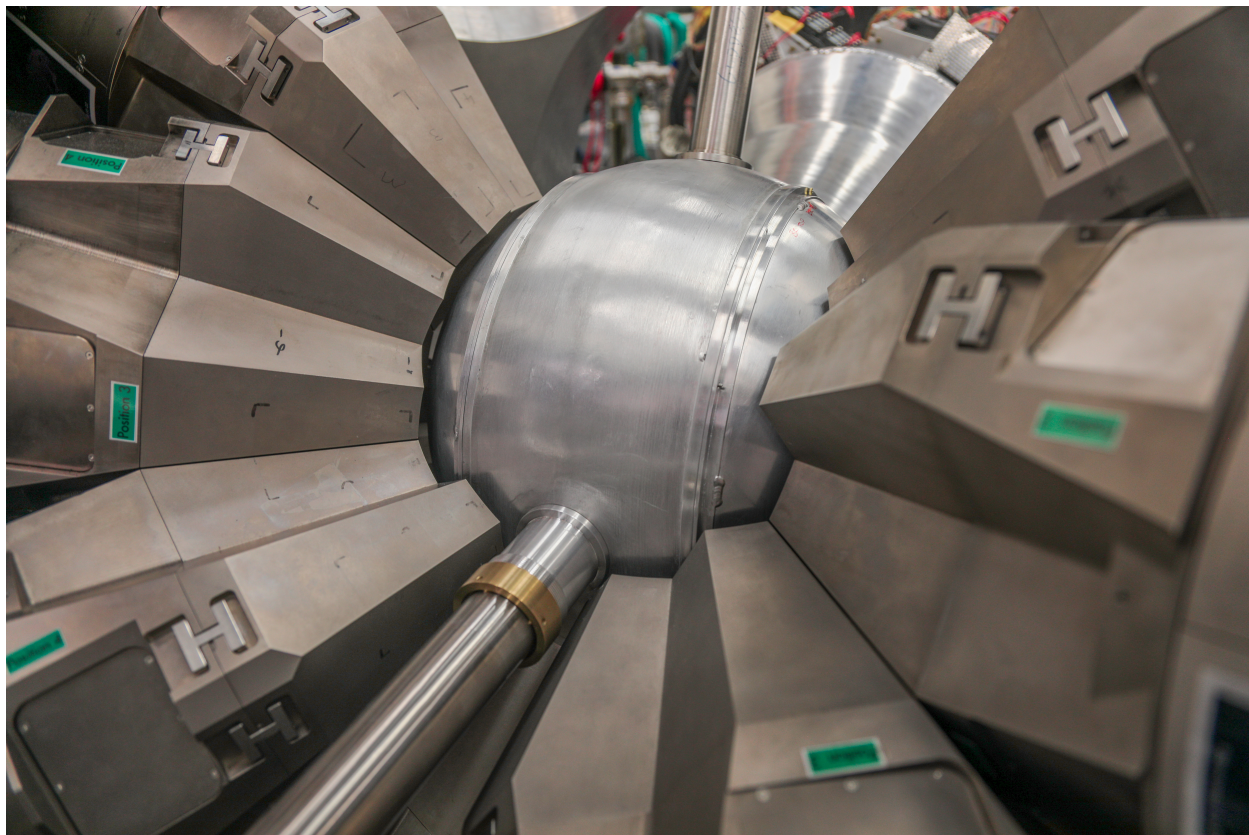
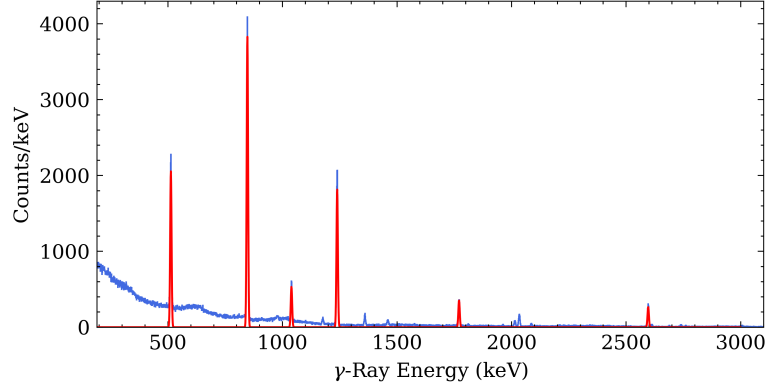


Figure 3.7: Two hemispheres of GREY-MAT enclosing the scattering chamber with the CD_2 target and ORRUBA detectors inside (Image Credit: Steve Pain)

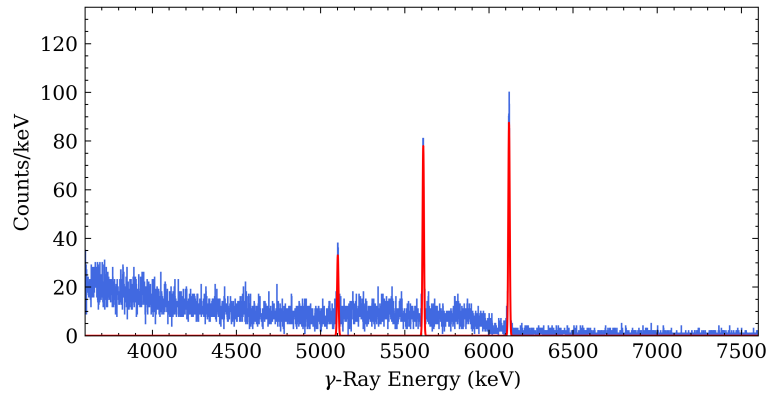
Each GRETINA crystal is segmented into 36 segments and four crystals are combined in a single cryostat to form a quad. 11 such quads were used in this experiment. A liquid nitrogen cooling system is used to maintain the germanium crystals at an operating temperature. Since the energies of γ rays recorded by GRETINA crystals are Doppler-shifted because of the moving recoil nuclei, these energies must be corrected for such shifts.

For online analysis during the experiment, GRETINA crystals were calibrated for energy measurement using imprecise calibration parameters. For precise energy calibration of these GRETINA crystals, ^{56}Co , ^{88}Yt and $^{238}\text{Pu}^{13}\text{C}$ sources, with range of gamma emission lines, were used. ^{56}Co has γ -ray lines at 511 keV, 846 keV, 1037 keV, 1238 keV, 1771 keV and 2598 keV. ^{88}Yt has γ -ray lines at 898 keV and 1836 keV. $^{238}\text{Pu}^{13}\text{C}$ has high energy γ -ray lines at 5107 keV, 5618 keV and 6129 keV. For each of the three sources, the raw γ -ray energy was filled into a histogram for each crystal, and the peaks were fitted using different Gaussian functions as shown in Figure 3.8. The centroids of these Gaussian functions were plotted with the energies of the γ -ray lines in keV, and a linear fit was used to extract the slopes and intercepts, which are the calibration parameters.

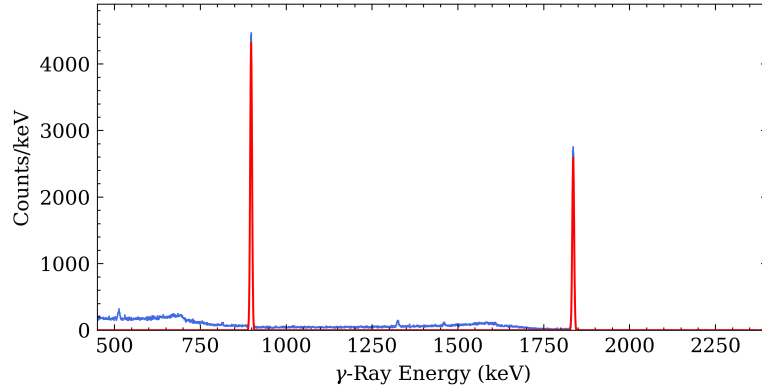
To recover the full γ -ray energy of the Compton-scattering events, where a fraction of γ -ray energy is deposited in one crystal and the remaining energy is deposited in a neighboring crystal, the energies are summed via a process called addback. In Figure 3.9a, a γ - γ matrix for ^{56}Co source is shown where horizontal and vertical lines are γ decay lines, and the diagonal lines are Compton scattered events. After addback was implemented, the full γ -ray energy was recovered and the strength of these diagonal lines decreased as shown in 3.9b. The comparison of the γ -ray lines before and after implementation of the addback is shown in Figure 3.9. We are currently investigating the precision of the addback procedure.



(a)

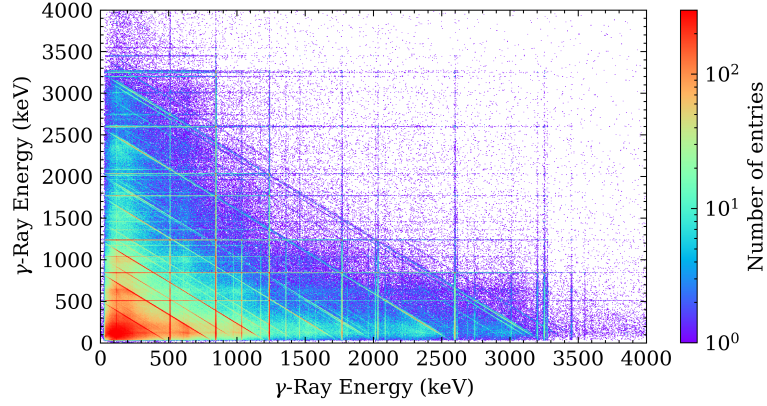


(b)

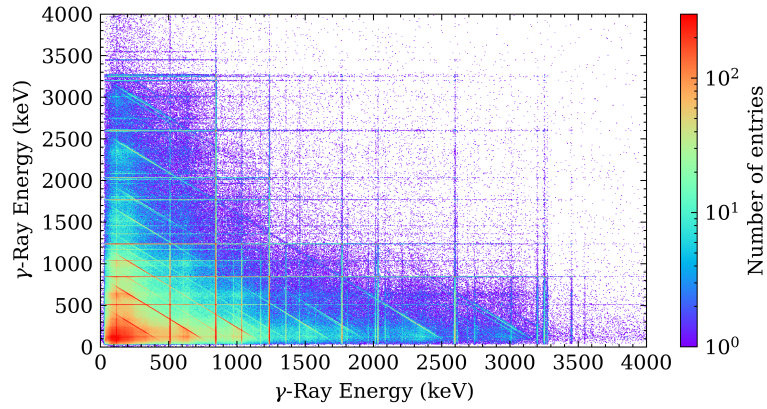


(c)

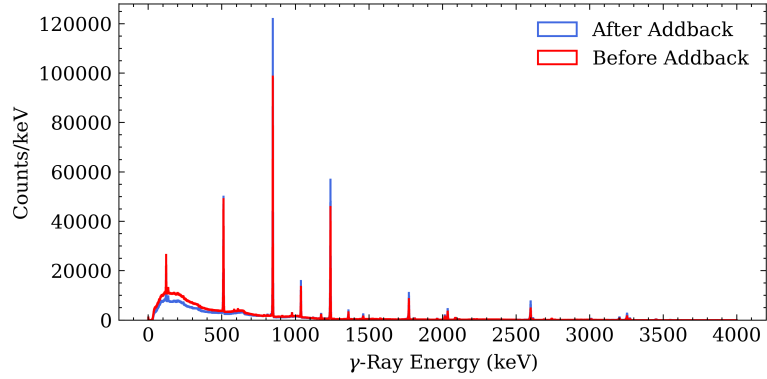
Figure 3.8: GRETINA calibration using different sources. (a) Energy calibration of a GRETINA crystal with a ^{56}Co source where the centroids of the Gaussian fit correspond to 511 keV, 846 keV, 1037 keV, 1238 keV, 1771 keV and 2598 keV. (b) Energy calibration of a GRETINA crystal with a $^{258}\text{Pu}^{13}\text{C}$ source where the centroids of the Gaussian fit correspond to 5107 keV, 5618 keV and 6129 keV. (c) Energy calibration of a GRETINA crystal with an ^{88}Yt source where the centroids of the Gaussian fit correspond to 898 keV and 1836 keV



(a)



(b)



(c)

Figure 3.9: Comparison of γ -ray energies before and after implementation of addback. (a) γ - γ matrix with ^{56}Co source before addback where the horizontal and vertical lines represent gamma lines and the diagonals represent Compton scattering, where part of the γ -ray energy is unaccounted (b) γ - γ matrix with ^{56}Co source after addback where the strength of diagonal Compton scattering is reduced (c) ^{56}Co source γ -ray energies before and after the implementation of the addback

3.3 Ionization Chamber

A perpendicular-grid, fast ionization chamber (IC), shown in Figure 3.10, was instrumented downstream of the scattering chamber for event-by-event particle identification, and for beam flux and vertex determination. The chamber utilized a 13 μm mylar window and was filled with isobutane gas at ~ 155 Torr. The IC consisted of a series of alternating anode and cathode wire grids, each comprising of fine gold-plated tungsten wires, with 2 mm spacing between wires. The biasing voltage for the IC grids was ~ 450 V. The anodes were connected to the Canberra preamplifiers, which were passed to Mesytec MSCF-16 shaping amplifiers with 0.25 μs shaping time. The wires of the front two anode grids were instrumented individually in a position-sensitive configuration and were used for beam tracking. The wires of the back anode grids were ganged into two energy signals for a ΔE and a residual energy measurements. Plotting ΔE versus a residual energy, particle identification was obtained.

3.4 GODDESS Data Acquisition

The GODDESS data acquisition system utilizes the Oak Ridge Physics Acquisition System (ORPHAS). The signals from the ORRUBA array were brought out from the vacuum chamber to the preamplifier boxes using feedthrough boards. The preamplified signals were passed to Mesytec MSCF-16 shaping amplifiers, and the shaped signals were digitized in CAEN V785 Analog to Digital Converters (ADCs). Apart from shaping the signals, the shaping amplifiers also produced trigger signals. The silicon triggers from each MSCF-16 units were commoned together via Caen N454 logic Fan-In-Fan-Out (FIFO) modules. Similarly, the IC triggers from the MSCF-16 units were also commoned together, and were prescaled in a prescaler module with scaling factor 2^{12} . The common IC triggers, before and after prescaling, were sent to Struck SIS3820 32-channel VME scaler module. The common outputs from the FIFO modules were sent to the scaler module, and the delayed signals were sent to the Caen V775 TDC modules to produce silicon stop and IC stop signals. Also, the

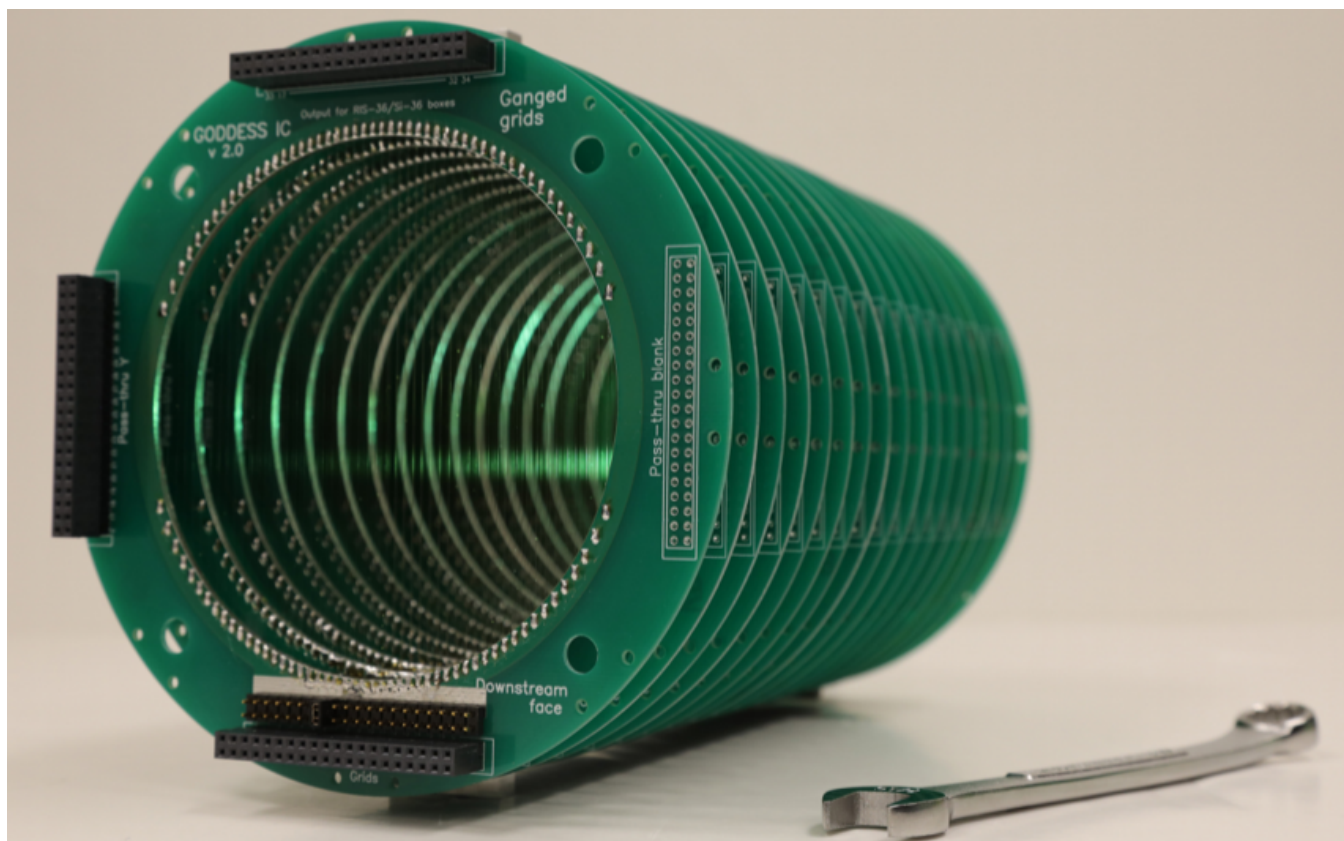


Figure 3.10: Assembled grids used in the GODDESS fast ionization chamber (Image Credit: S.D. Pain)

common silicon triggers from the FIFO modules and the common IC triggers after prescaling were sent to a Caen N405 logic module to create a master trigger vetoed by a busy signal from the trigger module in the data acquisition system.

The vetoed trigger signals were used to generate the gate of length $\sim 2\mu s$ for the ADC peak-sense-and-hold circuit to get a readout when the DAQ was triggered. The master triggers were also used to provide a start signal to the Caen V775 TDC modules. The TDC start and different stop signals were used to separate the events generated by different triggers. As silicon array is the master and the GRETINA the slave, the vetoed trigger signals were also used to pass a trigger to the GRETINA. ORPHAS DAQ can automatically start and stop of runs by the by running start and stop scripts which broadcasted the commands to Gretina data acquisition computer. The vetoed trigger signals were also used to latch the time-stamp in the Multipurpose γ -Ray Interface to Auxiliary Detectors (MyRIAD) module which received time information via SERDES from a global clock in the GRETINA DAQ. This clock signal was also recorded by GRETINA, and subsequently used in offline analysis for particle- γ event correlation. Finally, the vetoed trigger signals were used to latch the scaler module. Scalers were also recorded for a raw and a vetoed clock as a measure of average livetime.

Chapter 4

Analysis

The data collected by the GODDESS data acquisition system can be used for further analysis only after rigorous steps of calibrations and corrections. These include the event-by-event identification of the beam particles, calibration of the silicon detectors, calculation of the target interaction point, and Doppler correction of γ rays.

After calibration, the Q-values and excitation energies of ^{31}P populated in the (d,p) reaction were extracted. From this, a particle- γ matrix was generated, showing several transitioning γ rays. These transitions were used to infer what states were populated, and to build the level scheme. The particle singles and γ -gated particle angular distributions were extracted for different states, which were then normalized to extract differential cross-sections. The spectroscopic factors for different states populated in ^{31}P were obtained by comparing the measured differential cross-sections to calculated differential cross-sections. Using the mirror symmetry, the spectroscopic factors and resonance strengths for ^{31}S were extracted. Finally the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction rates for several states were extracted.

4.1 Beam Identification

A ^{30}P radioactive isotope beam was produced inflight using the $^{29}\text{Si}(d,n)^{30}\text{P}$ reaction. Following the reaction with CD_2 target, the total flux measured in the ionization chamber consisted

unreacted ^{30}P , ^{31}P from $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction, unreacted ^{29}Si , ^{30}Si from $^{29}\text{Si}(d, p\gamma)^{30}\text{Si}$ reaction and other contaminants. With an event-by-event ΔE and E_{residual} measurements, particle identification plots for each runs were obtained as shown in Figure 4.1a. In the particle identification plot shown in Figure 4.1a, red ellipse indicates the mixture of ^{30}P beam, and ^{31}P recoil particles. The black ellipse indicates the mixture of ^{29}Si contaminants in the beam, and ^{30}Si recoil from $^{29}\text{Si}(d, p\gamma)^{30}\text{Si}$ reaction. Multiple particles arriving the IC in a short span of time causes pileup indicated by the arrows in the particle identification plot. The events in the stopping-loci, indicated in the left side of the particle identification plot, correspond to the particles colliding with the wire grids. Also, an x-y beam vertex measurement were obtained from the position sensitive grids of the IC as shown in Figure 4.1b. The position measurements in the IC were scaled to the CD_2 target to extract the target interaction point as discussed in Section 4.2.

The timing gates, discussed in Section 4.3, were used to deconvolve the trigger type, to separate the events that were IC-triggered, and reaction-triggered. By gating over the events in the IC self-stop peak of timing gate, the particle identification plot, shown in Figure 4.2a, was extracted. The events inside the red ellipse correspond to the unreacted ^{30}P beam, and the events inside the black ellipse correspond to the unreacted ^{29}Si . By gating over the events in the silicon-started broadened peak of timing gate, the particle identification plot, shown in Figure 4.2b, was extracted. This plot includes recoil events from the (d, p) , (d, d) , and (p, p) reaction that triggered the silicon detectors. By gating over the events in the silicon-started broadened peak in timing gate, and the <9 MeV excitation energy (d, p) events, the particle identification plot, shown in Figure 4.3, was extracted. The red ellipse indicates ^{31}P recoil events from $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction and ^{30}Si recoil events from $^{29}\text{Si}(d, p\gamma)^{30}\text{Si}$ reaction. Run-by-run (d, p) events were selected by making ^{31}P recoil gates.

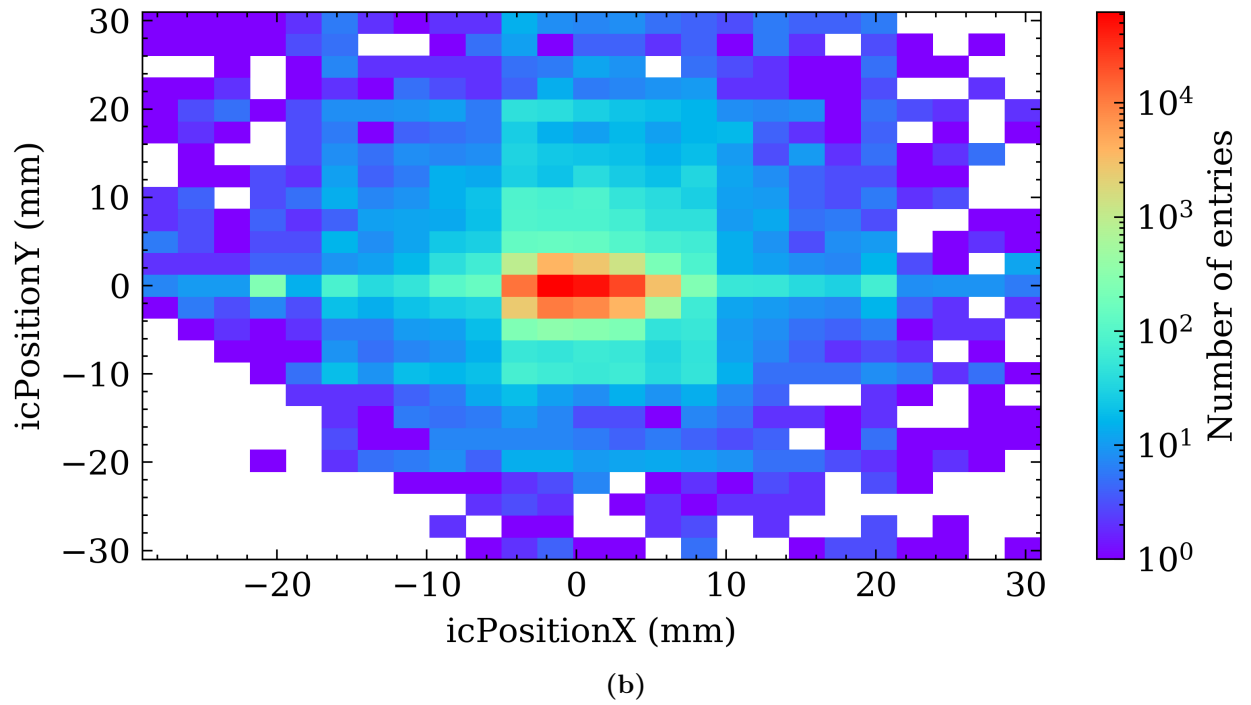
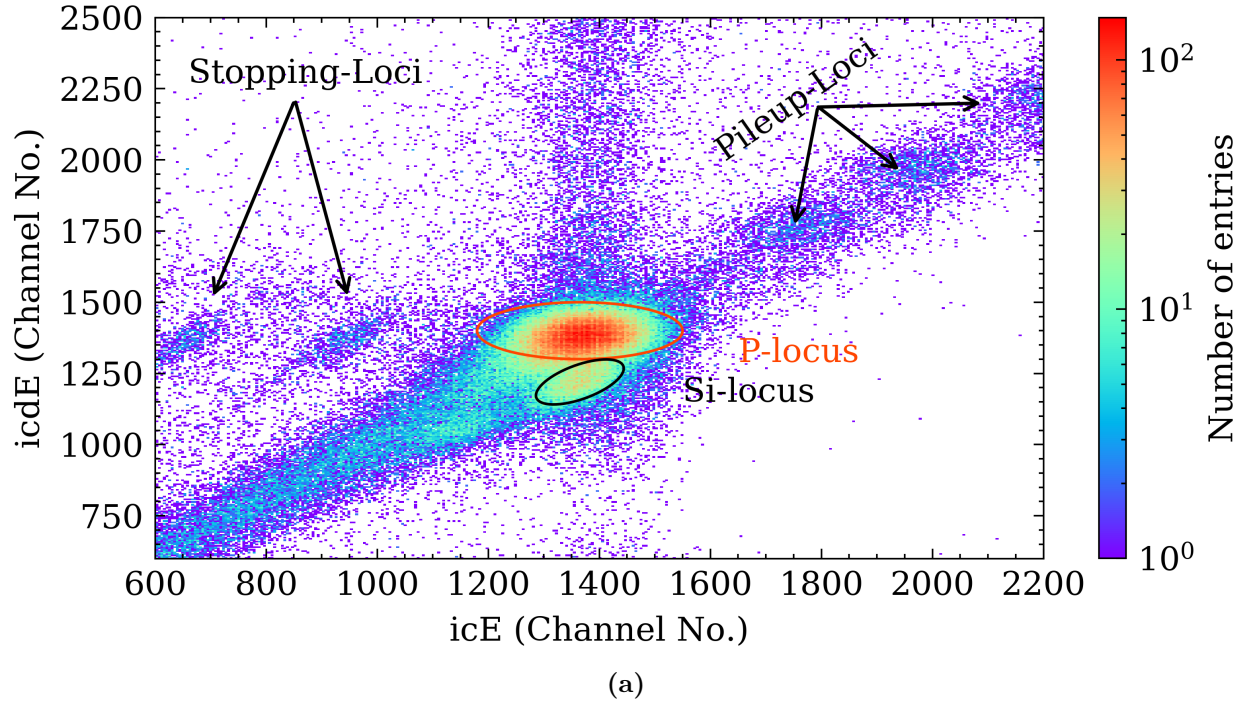


Figure 4.1: Data from the ionization chamber. (a) Particle identification spectrum with several features (b) X vs Y spectrum for beam position at the IC

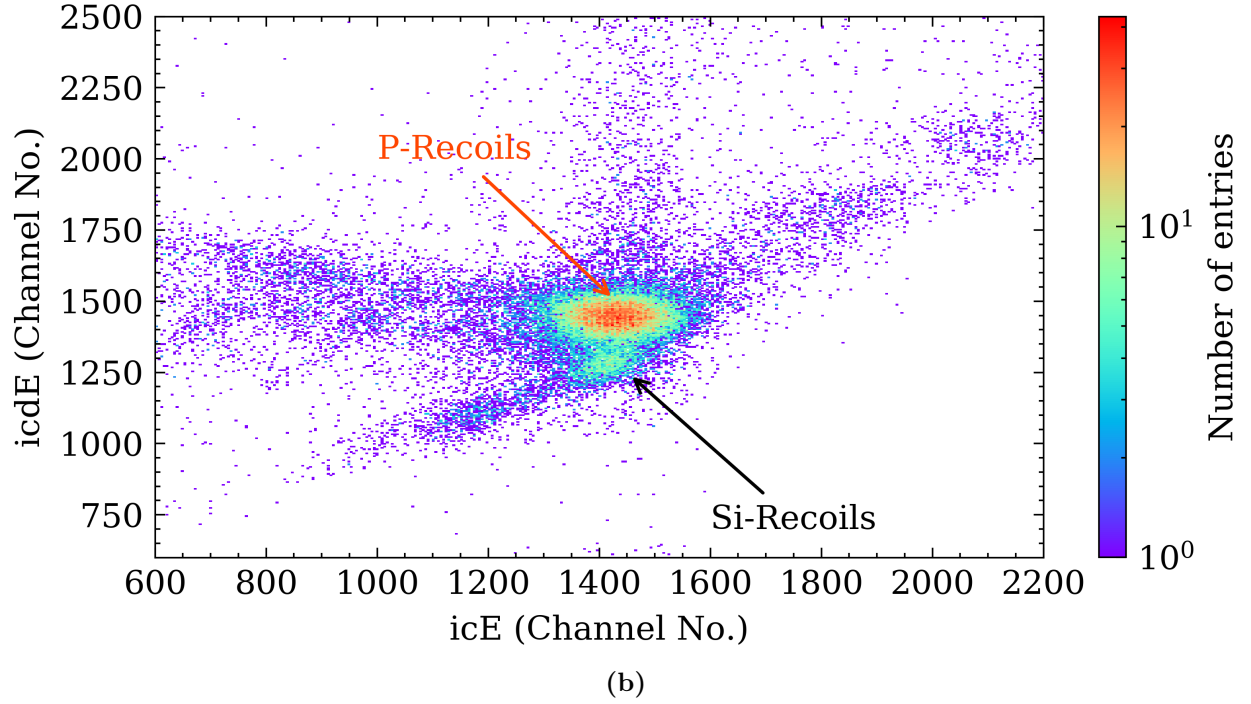
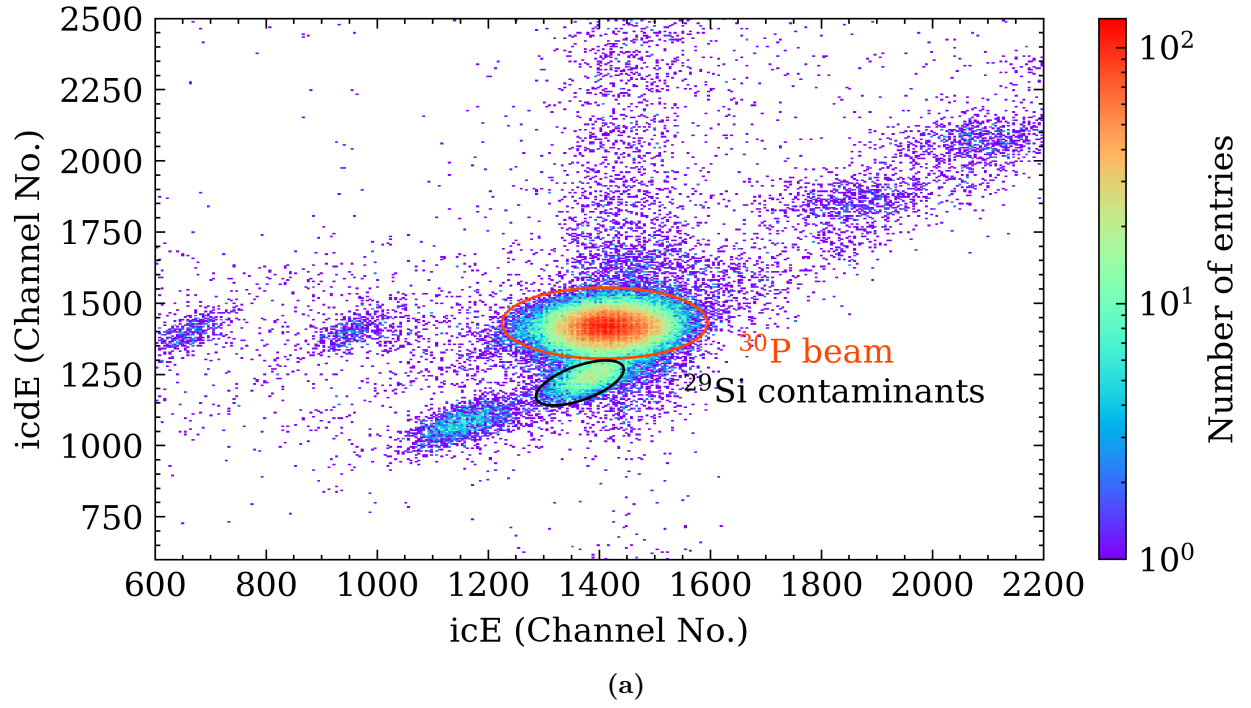


Figure 4.2: Particle identification spectra with timing gates. (a) Particle identification plot gated on IC self-stop peak in TDC showing beam loci. (b) Particle identification plot gated on silicon-started peak in TDC showing the energy spread of the recoil loci.

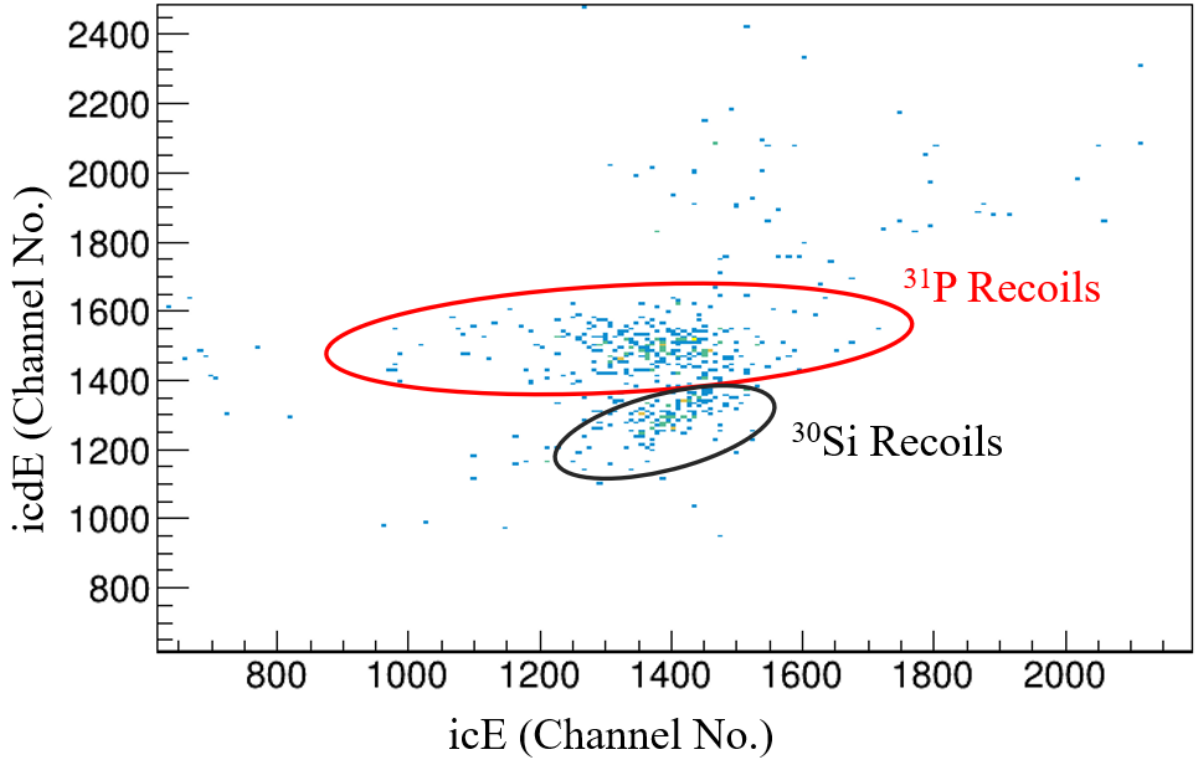


Figure 4.3: Particle identification spectrum with timing and kinematics gates showing different recoil loci from the (d, p) reactions.

4.2 Target Interaction Point

As the beam optics at ATLAS are focused at the CD_2 target and it spreads out as it moves away, the beam image at the IC entrance is, to the first order, a magnification of the image at the target. To find the target interaction point, the position measured by the position sensitive grids of the ionization chamber were scaled to the interaction point in the target with the appropriate scaling factor given by the following equation:

$$\begin{aligned} X_{\text{target}} &= X_{\text{IC}} \times F_X \\ Y_{\text{target}} &= Y_{\text{IC}} \times F_Y \end{aligned} \tag{4.1}$$

where X_{target} , Y_{target} , X_{IC} , Y_{IC} , F_X and F_Y are X target interaction point, Y target interaction point, X ionization chamber measurement point, Y ionization chamber measurement point, X scaling factor and Y scaling factor respectively. A combined scaling parameter was made with F_X and F_Y , and excitation energies were calculated for different scaling parameters. An excitation energy versus scaling parameter plot was extracted, and the parameter that generated the best resolution in the excitation energy was chosen as the appropriate scaling parameter as shown in Figure 4.4. With 5754 combined scaling parameter, the F_X and F_Y were extracted to be 0.14 and 0.08 respectively.

4.3 TDC

As discussed in Section 3.4, a Caen V775 32-channel 12-bit TDC module, set to $\sim 1\mu\text{s}$ full scale, was used to separate the events generated by different triggers. For this, a delayed copy of each type of trigger signal, including IC, silicon, and GRETINA, is sent to the stop channels of the TDC module. A TDC spectrum for events generated by IC trigger with OR of silicon and prescaled IC as TDC start and IC raw as TDC stop is shown in Figure 4.5. The sharp peak represents the events triggered by the IC itself (IC self-stop events), and the broadened peak to its right represents the events triggered by the silicon detectors. Reaction events can be selected by gating on this broadened peak.

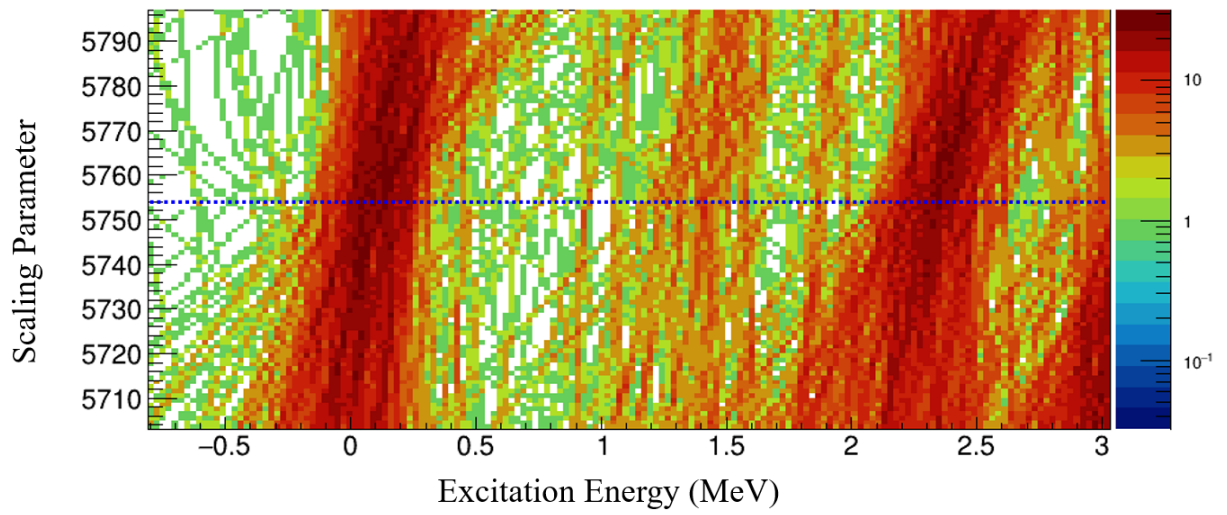


Figure 4.4: An excitation energy versus scaling parameter spectrum. The 5754 scaling parameter was chosen which produced the best excitation energy resolution. This value corresponds to $F_X=0.14$ and $F_Y=0.08$.

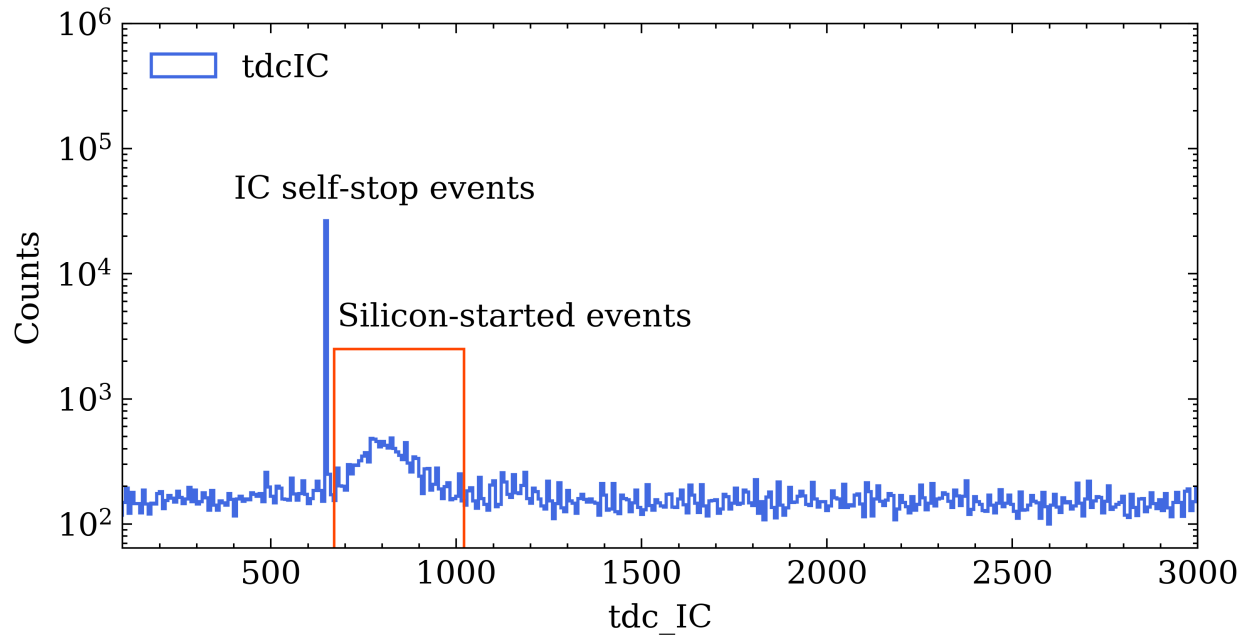


Figure 4.5: A TDC spectrum for events generated by IC trigger showing IC self-stop events and silicon detector-started events. The red box is an illustration of the gate to select the events that triggered the silicon detectors.

4.4 Nuclear Reaction Kinematics

The kinematics of the $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction is represented in Figure 4.6, where M_a and T_a are the mass and the energy of the ^{30}P beam, M_b and T_b are the mass and the energy of the proton, M_Y and T_Y are the mass and the energy of the ^{31}P recoil, θ is the angle at which protons are ejected, and α is the angle between the ^{31}P recoil and the incident beam direction. The energies and angles of proton ejectiles were measured in the silicon detectors. Figure 4.7 shows the measured kinematics of protons originating from $^{30}\text{P}(d, p)^{31}\text{P}$ reactions and of other elastically scattered particles.

The Q-value of a nuclear reaction is defined as the amount of mass-energy released during a nuclear reaction and is calculated as the difference between the initial mass-energy and the final mass-energy of nuclei involved using the following equation(30):

$$Q = (M_a + M_X - M_b - M_Y)c^2 \quad (4.2)$$

$$Q = T_b + T_Y - T_a - T_X. \quad (4.3)$$

As the energy of the ^{30}P beam (T_a), the masses of the ^{30}P beam (M_a), the ejected proton (M_b) and the ^{31}P recoil (M_Y) are known and the proton ejection angle (θ) and energy (T_b) are measured, we can determine the Q-value as(30):

$$Q = T_b \left(1 + \frac{M_b}{M_Y}\right) - T_a \left(1 - \frac{M_a}{M_Y}\right) - 2 \left(\frac{M_a}{M_Y} \frac{M_b}{M_Y} T_a T_b \right)^{1/2} \cos\theta. \quad (4.4)$$

The Q-value equation should be modified to include the mass-energy of excited states of ^{31}P in the case that the reaction reaches these excited states(30).

$$Q = (M_a + M_X - M_b - M_Y^*)c^2 \quad (4.5)$$

$$Q_{ex} = Q_0 - E_x \quad (4.6)$$

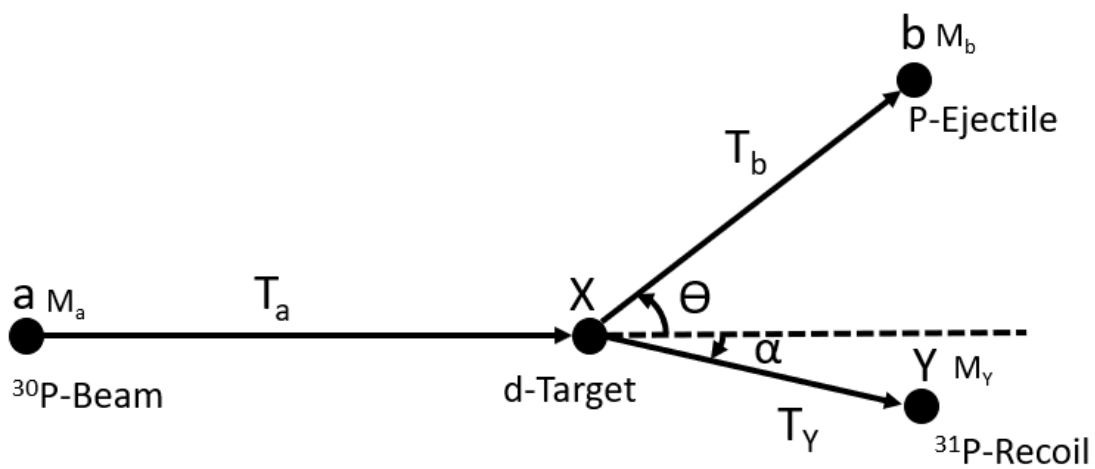


Figure 4.6: Kinematics diagram showing the $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction in the laboratory frame

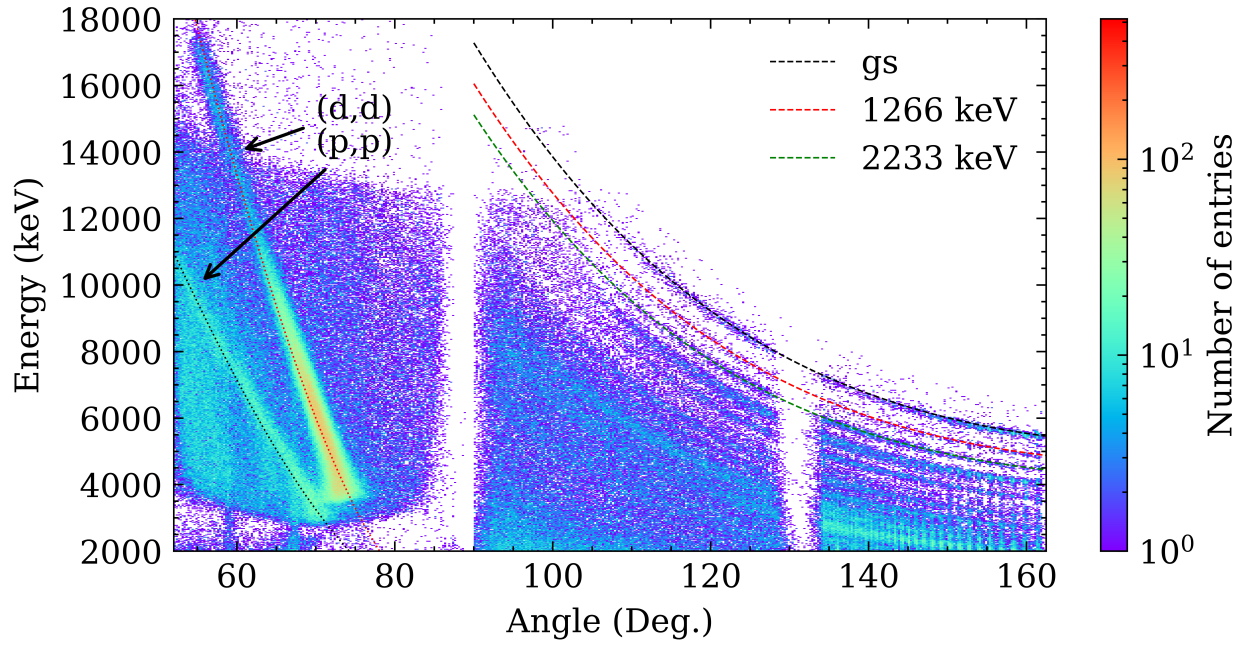


Figure 4.7: Proton energy vs angle plot (gated on IC and the IC TDC) showing kinematics of different reactions. Dashed lines represent the kinematics of (d,p) protons corresponding to different Q-values and the arrows point to the kinematics of elastically scattered particles.

$$E_x = Q_0 - Q_{ex} \quad (4.7)$$

Here Q_0 is the ground state Q-value of ^{31}P and $M_Y^* c^2 = M_Y c^2 + E_x$ is the mass energy of excited state of ^{31}P . E_x is the excitation energy which is defined as the difference between the ground state Q-value and the Q-value of the specific excited state. Different states, with corresponding energies, spins and parities, populated in ^{31}P can be observed in the excitation energy spectrum for $^{30}\text{P}(d, p)^{31}\text{P}$, as shown in Figure 4.8. The proton yields for lower excitation states are higher in the QQQ5s because of the angular distribution of the sd-shell states, and the proton yields for higher excitation states are higher in the super X3s because of the angular distribution of the pf-shell states. The excitation energy spectrum for the QQQ5 detectors with and without the target interaction point calculations, discussed in Section 4.2, is shown in Figure 4.9.

4.5 Elastic Scattering

Downstream of the CD_2 target, the ORRUBA barrel consisted of telescopes of the BB10 and the SX3 detectors for the particle identification of the elastically-scattered particles that are restricted below 90° in inverse kinematics. As shown in Figure 4.10, these telescopes were used for particle identification for elastically-scattered particles. The upper locus is elastically-scattered deuterons from the $^{30}\text{P}(d, d)^{30}\text{P}$ reaction, and the lower locus is elastically-scattered protons. The proton elastic scattering data will be analyzed in future for the ADWA differential cross-section calculations. The analysis of the $^{30}\text{P}(d, d)^{30}\text{P}$ reaction was performed to extract the normalization factor that is required for the conversion of the angular distribution to the differential cross-section.

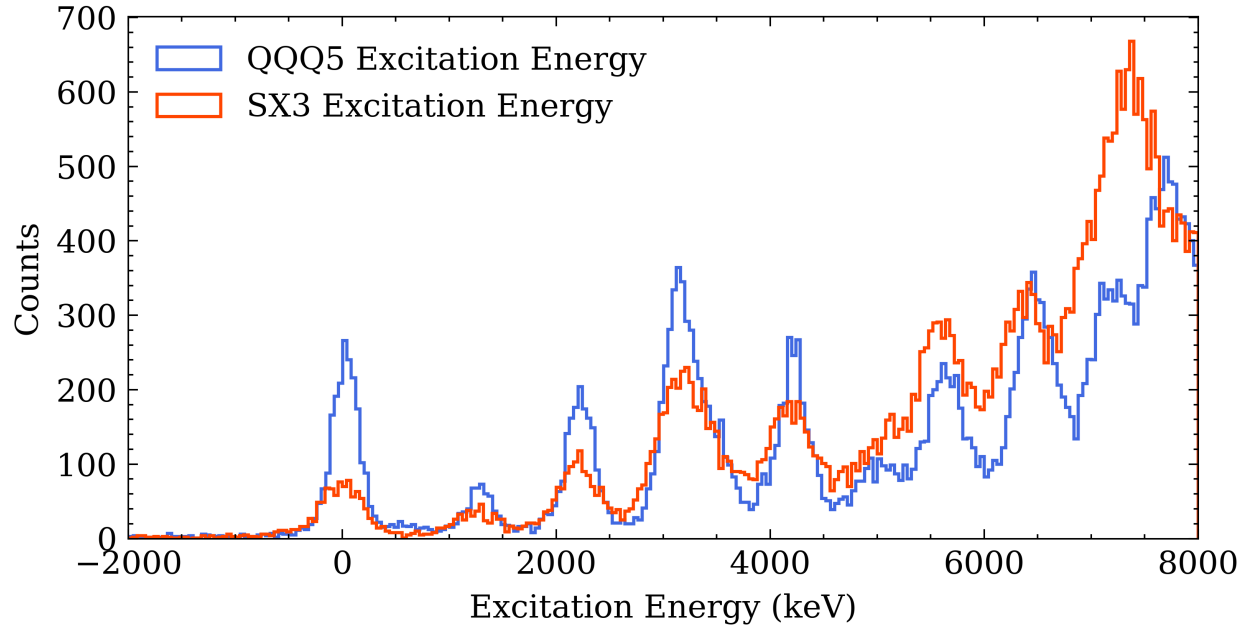


Figure 4.8: Excitation energy spectrum (gated on the IC PID and the TDC) for the $^{30}\text{P}(d, p)^{31}\text{P}$ reaction showing different states populated in ^{31}P . Protons measured in the QQQ5 detectors are indicated in blue, and super X3 detectors are indicated in red. The first three peaks correspond to the ground, 1266-keV, and 2234-keV states. Because of the tight level spacing, the higher excitation states were not resolved, which created unresolved single peaks.

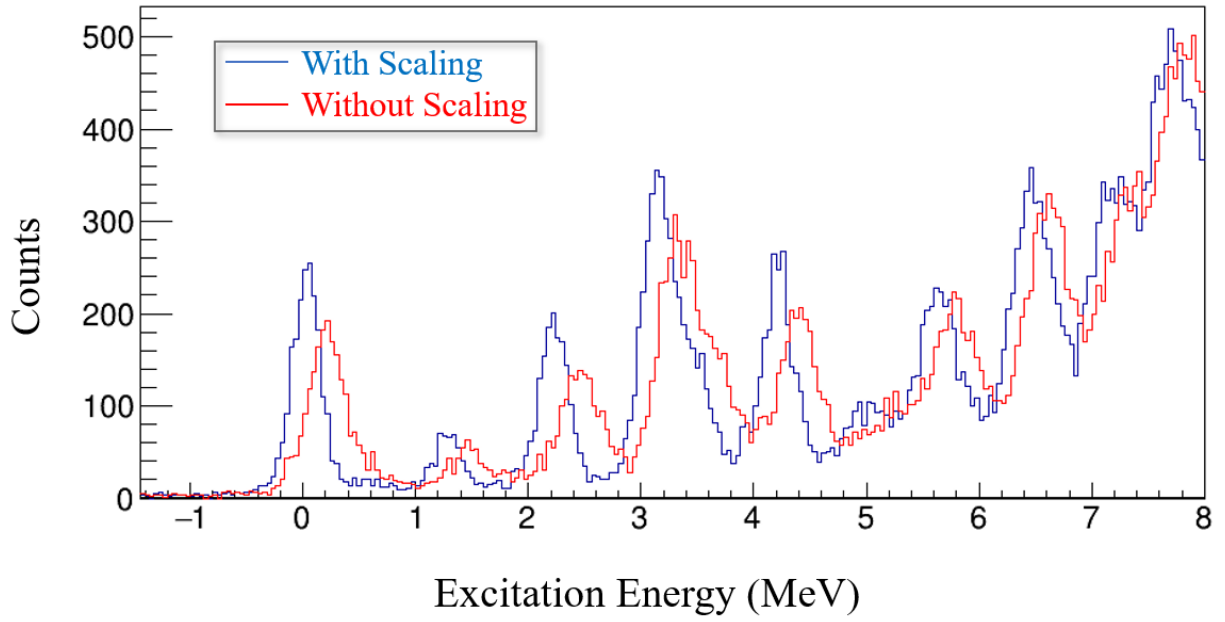


Figure 4.9: Excitation energy spectrum (gated on the IC and the TDC) for the $^{30}\text{P}(d, p)^{31}\text{P}$ reaction with and without the target interaction point calculation. The improvement in the resolution can be seen after using the target interaction point.

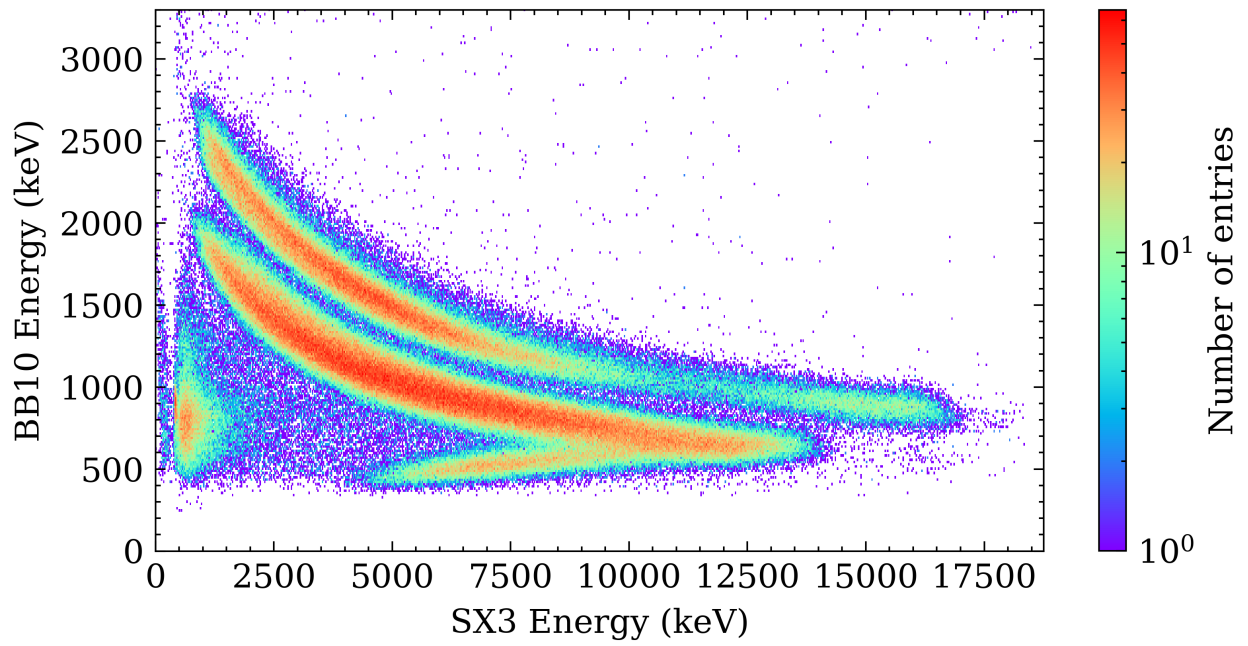


Figure 4.10: PID spectrum for the downstream barrel (gated on the IC and the IC TDC) where the upper locus represents deuterons and the lower locus represents protons

4.6 Particle- γ Coincidence

The energies of γ rays measured by GRETINA have different values than the transition energies because of the Doppler effect. The Doppler shifts depend on the velocities of recoil nuclei and angles between the recoil direction and the direction of de-exciting γ rays from the recoiling nuclei, and is corrected using the following equation:

$$E_{Transition} = E_{Measured} \frac{1 + \beta \cos \theta_\gamma}{\sqrt{1 + \beta^2}}, \quad (4.8)$$

where θ_γ represents the angle between the recoiling nuclei and the de-exciting γ rays and β is the ratio of the speed of the recoiling nuclei to the speed of light. The speed of the recoil was calculated event-by-event, allowing for an event-by-event Doppler correction.

In Figure 4.11, the particle- γ matrix before and after Doppler correction is shown. The vertical axis represents excitation energies extracted from the proton energy measured by the silicon detectors, which shows different states populated in the ^{31}P nucleus. The excited states decay either to other excited states, or directly to the ground state by emitting the γ rays represented by the horizontal axis. Before Doppler correction, the 511 keV background is prominent in the particle- γ matrix as shown in Figure 4.11a. After Doppler correction, the 511 keV background from stationary sources is spread, and several transitioning γ rays become prominent as shown in Figure 4.11b. The diagonal lines represent γ feedings to different discrete states in ^{31}P . Loci that lie on the black diagonal line corresponds to the population of excited states that decay via a single γ ray to the ground state of ^{31}P . Loci on the red diagonal line are events where a γ ray was emitted that feeds the 1266-keV state. Loci on the yellow diagonal line are events where a γ ray was emitted that feeds the 2233-keV state. Loci on the green diagonal line are events where a γ ray was emitted that feeds the 3415-keV state. Loci on the magenta diagonal line are events where a γ -ray was emitted that feeds the 4431-keV state. All transitions to the ground state, 1266-, 2233-, 3415- and 4431-keV states are circled in black, red, yellow, green and magenta respectively.

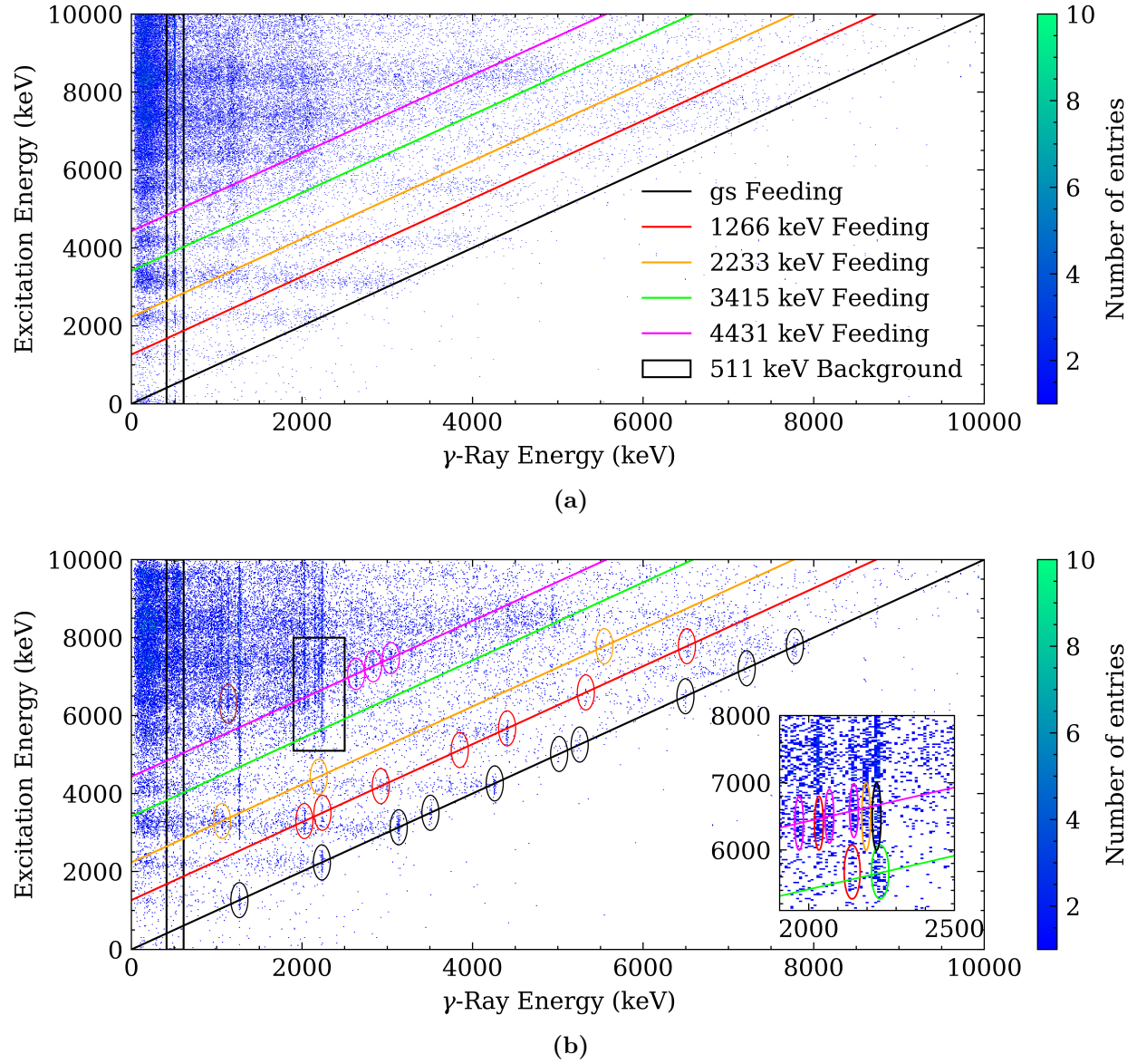
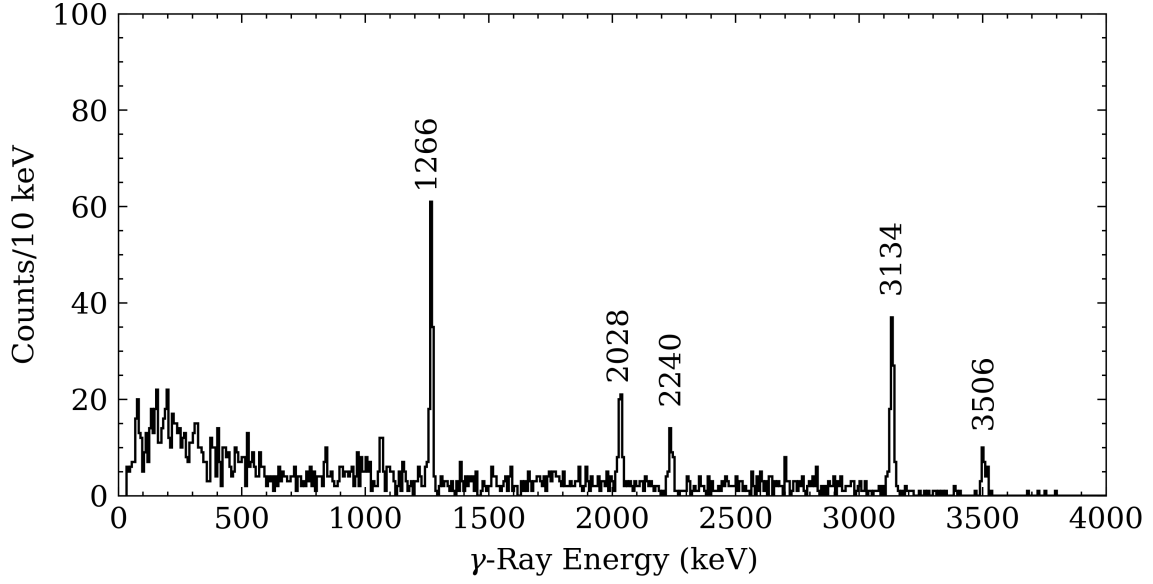


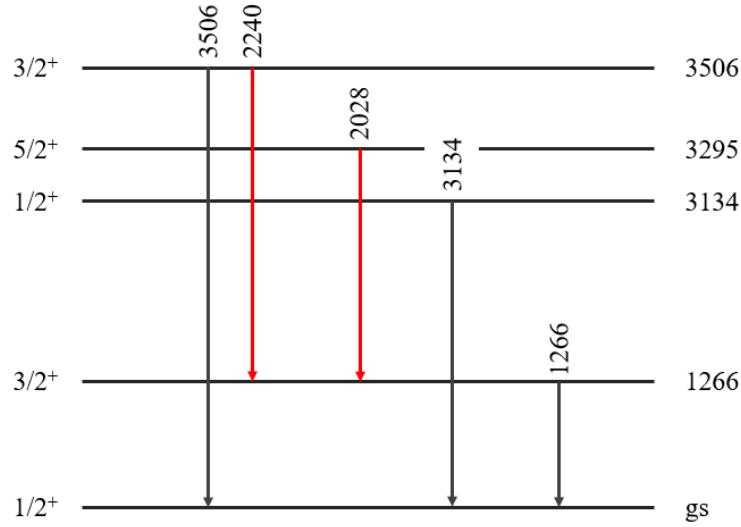
Figure 4.11: Two-dimensional histograms showing ^{31}P excitation energy versus γ -ray energy, gated on IC and TDC, before and after Doppler correction. The inset on the bottom-right represents expansion of the boxed section in 5000 keV to 8000 keV in excitation energy and 2000 keV to 2500 keV in γ -ray energy. (a) Particle- γ matrix before Doppler correction with the 511 keV background shown in a box and different diagonal lines representing feeding to different states (b) Particle- γ matrix after Doppler correction with broadened 511-keV background and several transitioning γ rays on different diagonal lines

Doppler corrected particle- γ matrix, and the γ -ray projection spectrum extracted from the particle- γ matrix over ranges of excitation energies were used to resolve the states in higher excitation region of ^{31}P . For each unresolved single peak in the excitation energy spectrum, shown in Figure 4.8, a γ -ray projection spectrum was extracted, and the energies of these transitioning γ rays were found by Gaussian fitting the peaks. For some transitions, γ -ray yields were not enough for Gaussian fit. In such cases, the center of the peaks were taken as γ -ray energies. The γ -ray projection spectrum for the unresolved peak in excitation energy range 2.6 MeV to 3.8 MeV is shown in Figure 4.12a. 3 states at 3134 keV, 3295 keV, and 3506 keV energies were observed in the unresolved peak in excitation energy range 2.6 MeV to 3.8 MeV. These states, and the transitioning γ rays are placed in a level scheme as shown in Figure 4.12b.

The γ -ray projection spectrum for the unresolved peak in excitation energy range 3.8 MeV to 4.6 MeV is shown in Figure 4.13a. 2 states at 4190 keV, and 4260 keV energies were observed in the unresolved peak in excitation energy range 3.8 MeV to 4.6 MeV. These states, and the transitioning γ rays are placed in a level scheme as shown in Figure 4.13b. Similarly the γ -ray projection spectrum for the unresolved peak in excitation energy range 4.6 MeV to 6 MeV is shown in Figure 4.14a. Although the yields of the γ rays at 3850 keV and 5015 keV are small, these transitions were considered to account for the population of the lower excitation states at 5015 keV and 5116 keV observed in the ^{31}P excitation energy spectrum shown in Figure 4.8. After considering these transitions, 4 states at 5015 keV, 5116 keV, 5256 keV and 5672 keV energies were observed in the unresolved peak in excitation energy range 4.6 MeV to 6 MeV. These states, and the transitioning γ rays are placed in a level scheme as shown in Figure 4.14b. The γ -ray projection spectrum for the unresolved peak in astrophysically important excitation energy range 6 MeV to 6.9 MeV is shown in Figure 4.15. 4 states at 6399 keV, 6496 keV, 6501 keV and 6594 keV energies were observed in astrophysically important region. These states, and their transitioning γ rays are placed in a level scheme as shown in Figure 4.16. The energies of all transitioning γ rays below 7 MeV are listed in Table 4.1.



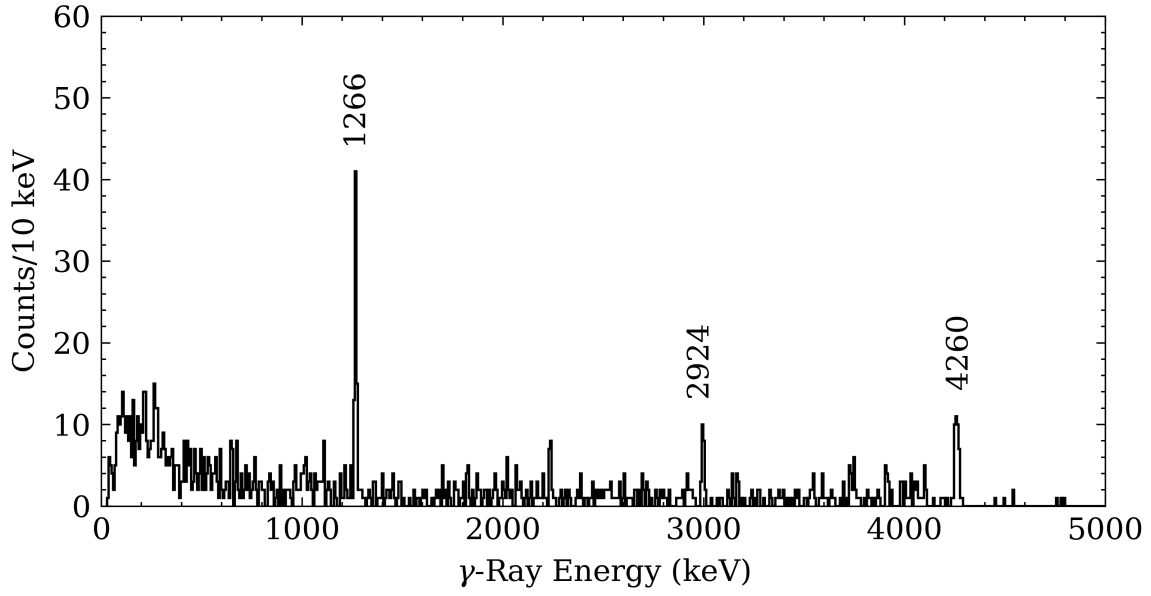
(a)



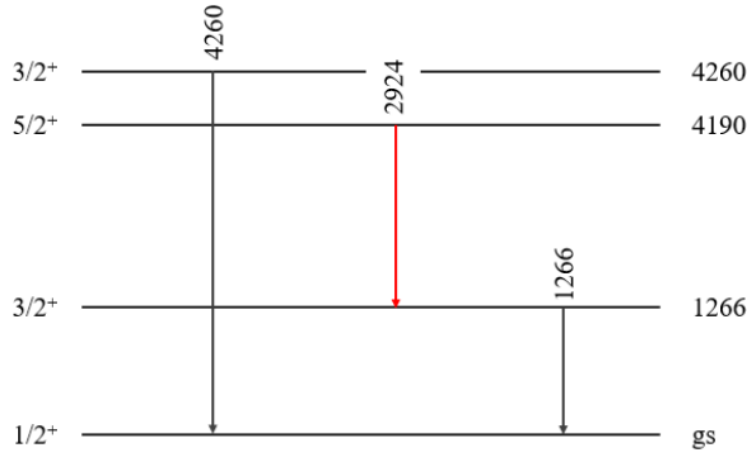
$^{31}\text{P}_{15}$

(b)

Figure 4.12: (a) γ -ray spectrum extracted from the particle- γ matrix for excitation energy range 2.6 MeV to 3.8 MeV. (b) Level scheme of ^{31}P with several transitioning γ rays from states in range 2.6 MeV to 3.8 MeV. γ -ray transitions to the ground state and 1266-keV state are represented by black and red vertical arrows respectively. The energies and J^π were adapted from [nnuc\(11\)](#).



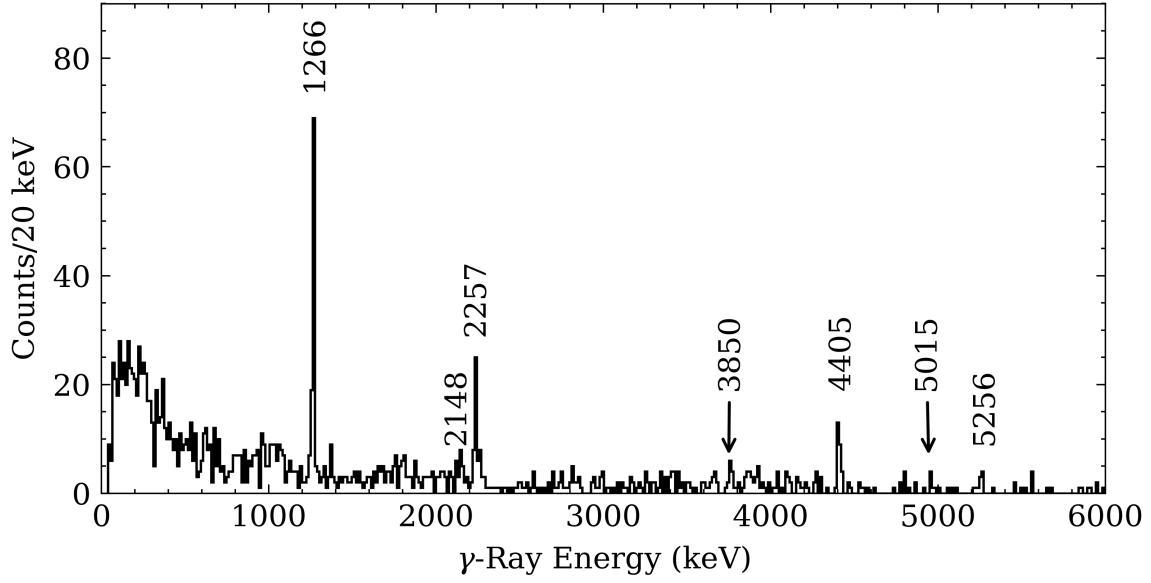
(a)



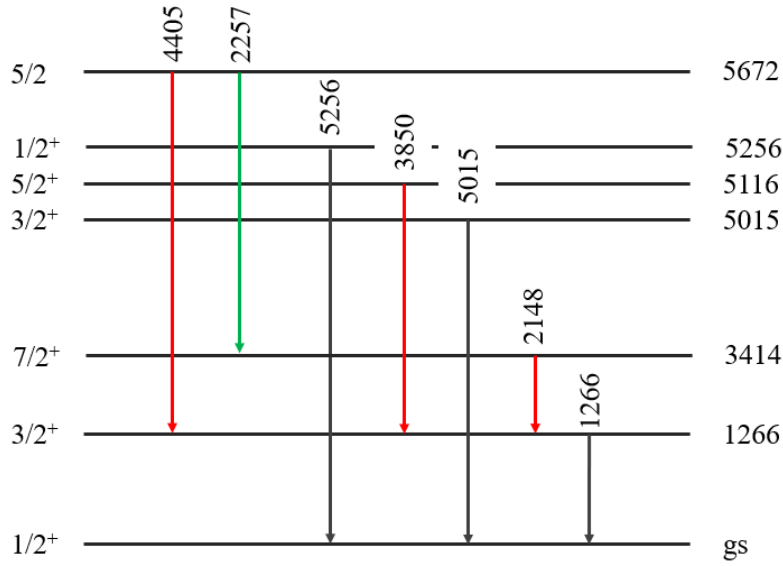
$^{31}\text{P}_{15}$

(b)

Figure 4.13: (a) γ -ray spectrum extracted from the particle- γ matrix for excitation energy range 3.8 MeV to 4.6 MeV. (b) Level scheme of ^{31}P with several transitioning γ rays from states in range 3.8 MeV to 4.6 MeV. γ -ray transitions to the ground state and 1266-keV state are represented by black and red vertical arrows respectively. The energies and J^π were adapted from [nnuc\(11\)](#).



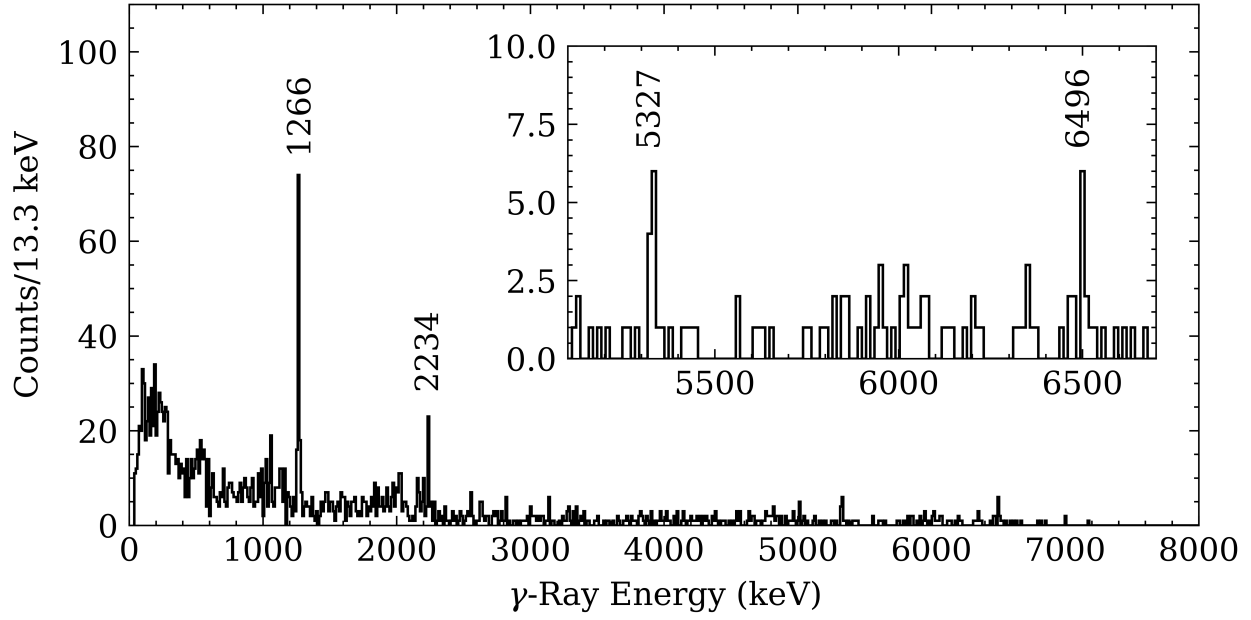
(a)



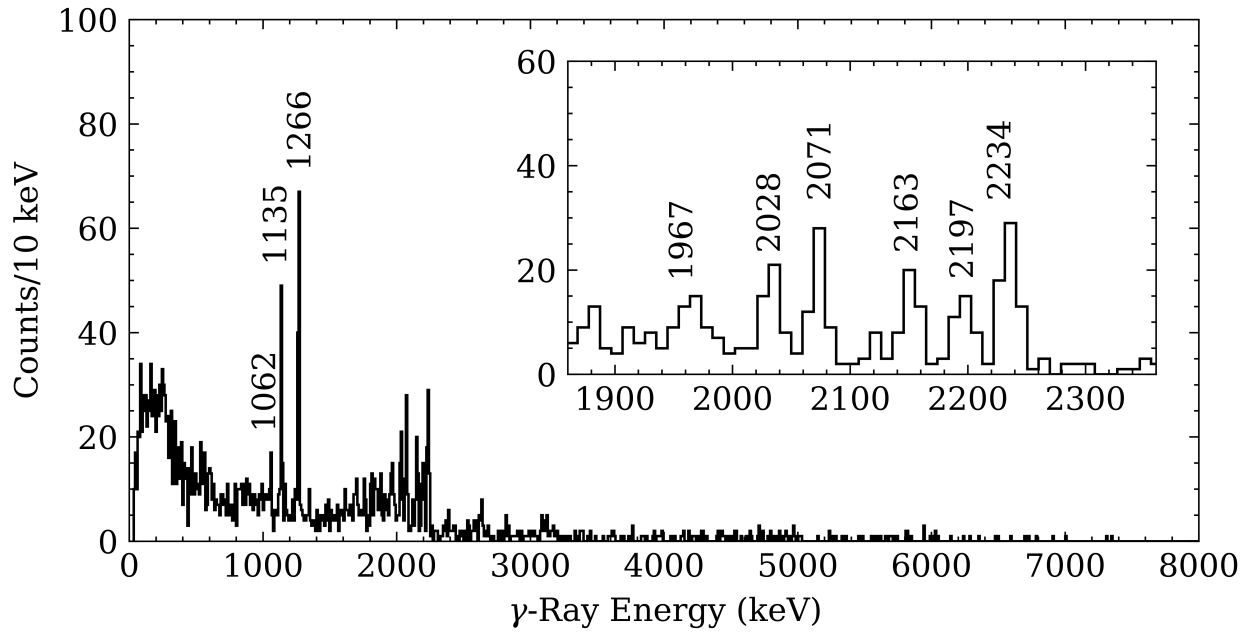
$^{31}\text{P}_{15}$

(b)

Figure 4.14: (a) γ -ray spectrum extracted from the particle- γ matrix for excitation energy range 4.6 MeV to 6 MeV. Transitions with low yields are represented by arrows. (b) Level scheme of ^{31}P with several transitioning γ rays from states in range 4.6 MeV to 6 MeV. γ -ray transitions to the ground state, 1266-keV, and 3414-keV states are represented by black, red and green vertical arrows respectively. The energies and J^π were adapted from [nndc\(11\)](#).



(a)



(b)

Figure 4.15: γ -ray spectrum extracted from the particle- γ matrix for astrophysically important excitation energy range 6 MeV to 6.9 MeV. (a) γ -ray spectrum coincident with protons detected in QQQ5 detectors. The inset represents the γ -ray spectrum expanded in γ -ray energy from 5.1 MeV to 6.7 MeV. (b) γ -ray spectrum coincident with protons detected in super X3 detectors. The inset represents the γ -ray spectrum expanded in γ -ray energy from 1.86 MeV to 2.36 MeV.

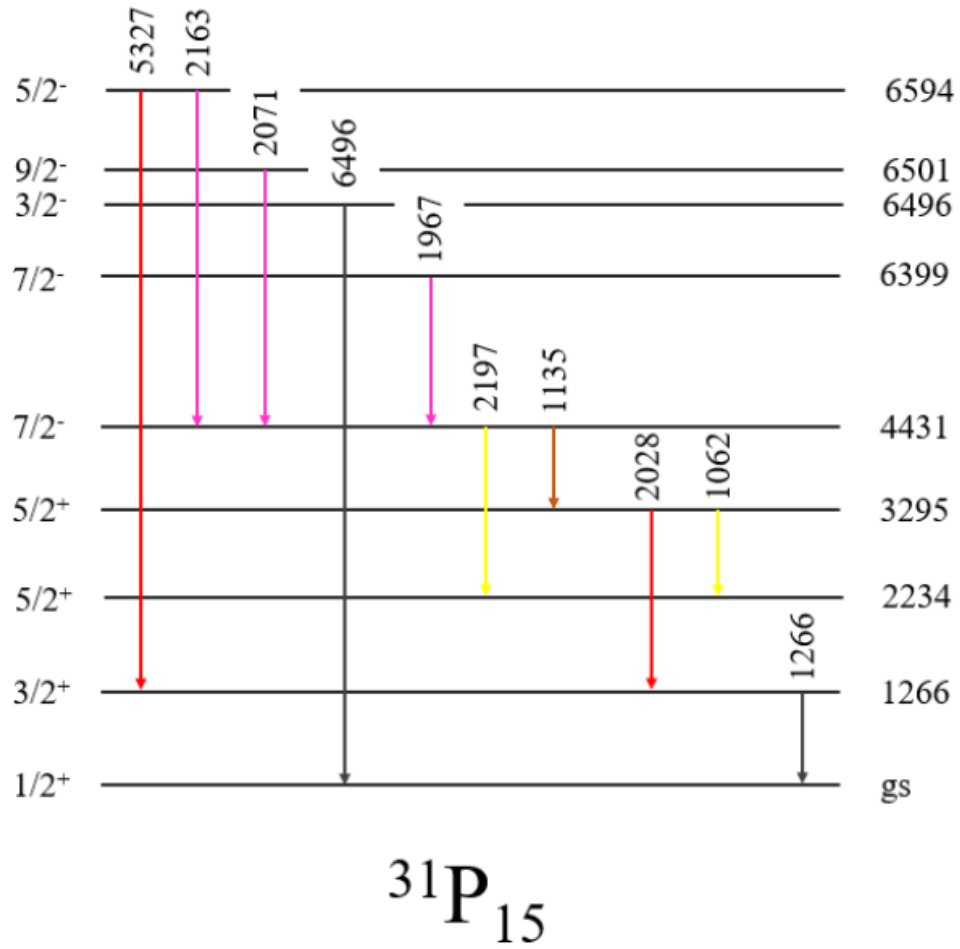


Figure 4.16: Level scheme of ^{31}P with several transitioning γ rays from states in astrophysically important excitation energy range. γ -ray transitions to the ground state, 1266-keV, 2234-keV, 3295-keV and 4431-keV states are represented by black, red, yellow, brown and magenta vertical arrows respectively. The energies and J^π were adapted from [nnuc\(11\)](#).

Table 4.1: List of transitioning γ rays originating from ^{31}P excitation energies below 7 MeV. The error bars represent uncertainties in the Gaussian fits

NNDC(11) Energy (keV)	Fitted Energy (keV)	Initial Level		Final Level	
		E (keV)	J^π (11)	E (keV)	J^π (11)
A. Ground State Transitions Line					
1266.1	$1267^{+0.9}_{-1.2}$	1266	$3/2^+$	gs	$1/2^+$
2233.6	$2233.3^{+0.5}_{-0.8}$	2233	$5/2^+$	gs	$1/2^+$
3134.3	$3132.6^{+1.0}_{-0.6}$	3134	$1/2^+$	gs	$1/2^+$
3506.1	$3507.8^{+1.8}_{-1.6}$	3506	$3/2^+$	gs	$1/2^+$
4260.4	$4259.5^{+1.4}_{-1.4}$	4260	$3/2^+$	gs	$1/2^+$
5014.9	5015	5015	$(3/2^+)$	gs	$1/2^+$
5256.8	$5257.2^{+2.8}_{-0.7}$	5256	$1/2^+$	gs	$1/2^+$
6496.1	$6496.8^{+1.6}_{-1.0}$	6496	$3/2^-$	gs	$1/2^+$
B. 1266-keV Level Feeding Line					
2028.8	$2031.8^{+1.4}_{-1.1}$	3295	$5/2^+$	1266	$3/2^+$
2239.8	$2238^{+1.2}_{-2.4}$	3506	$3/2^+$	1266	$3/2^+$
2924.7	2924	4190	$5/2^+$	1266	$3/2^+$
3849.6	3849	5116	$5/2^+$	1266	$3/2^+$
4405.6	$4406.6^{+1.9}_{-0.9}$	5672	$5/2$	1266	$3/2^+$
5327.6	$5329.1^{+1.2}_{-0.4}$	6594	$(5/2)^-$	1266	$3/2^+$
C. 2233-keV Level Feeding Line					
1061.6	1061	3295	$5/2^+$	2233	$5/2^+$
2197.0	2197	4431	$7/2^-$	2233	$5/2^+$
D. 3415-keV Level Feeding Line					
2257.4	2257	5672	$5/2$	3415	$7/2^+$
Cascade of 3415-keV Level					
2148.4	2148	3415	$7/2^+$	1266	$3/2^+$
1266.1	$1267^{+0.9}_{-1.2}$	1266	$3/2^+$	gs	$1/2^+$
E. 4431-keV Level Feeding Line					
1967.7	1967	6399	$7/2^{(-)}$	4431	$7/2^-$
2071.5	2071	6501	$9/2^-$	4431	$7/2^-$
2163.0	2163	6594	$(5/2)^-$	4431	$7/2^-$
Cascade of 4431-keV Level					
1135.6	1135	4431	$7/2^-$	3295	$5/2^+$
2197.0	2197	4431	$7/2^-$	2233	$5/2^+$
1061.6	1061	3295	$5/2^+$	2233	$5/2^+$
2028.8	$2031.7^{+1.3}_{-1.1}$	3295	$5/2^+$	1266	$3/2^+$
2233.6	$2233.3^{+0.5}_{-0.8}$	2233	$5/2^+$	gs	$1/2^+$
1266.1	$1267^{+0.9}_{-1.2}$	1266	$3/2^+$	gs	$1/2^+$

Chapter 5

Results and Discussion

5.1 Level Scheme

All the transitions in the particle- γ matrix were placed in the level scheme as shown in Figure 5.1. The horizontal lines represent different states populated in the ^{31}P nucleus. The energies of these states, labeled on the right side, and the angular momentum, labeled on the left side, are taken from NNDC(11). The black, red, yellow, brown, green and magenta vertical lines represent γ -ray transitions to the ground, 1266-keV, 2234-keV, 3295-keV, 3415-keV, and 4431-keV states respectively.

The ground state and 17 excited states of ^{31}P were observed. NNDC reports that the 5672-keV state has $J=5/2$, but the parity of the state is not mentioned. The determination of the parity of this state is discussed in Section 5.4.4. Four states, at energies 6399 keV, 6496 keV, 6501 keV, and 6594 keV, are of particular interest as these are the mirror states to known ^{31}S resonances that lie at energies relevant to nova burning. By extracting the spectroscopic factors of these states using the appropriate optical potential, and using mirror symmetry, the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ resonance strengths were determined, from which the astrophysical reaction rate was extracted.

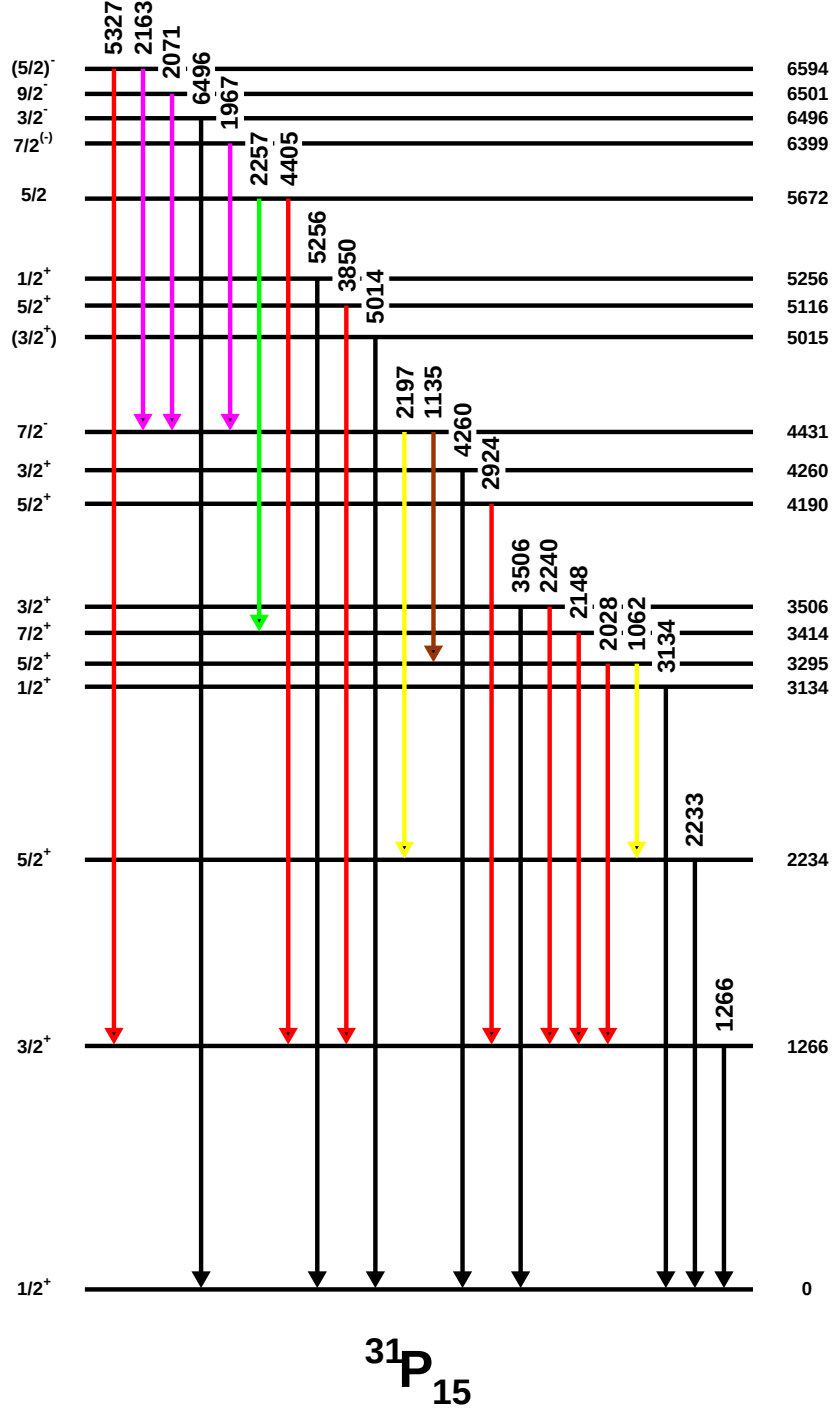


Figure 5.1: Level Scheme of ^{31}P with energies in keV. The energies of the states, labeled on the right side, and the angular momentum, labeled on the left side, are taken from NNDC(11). Transitions to the ground, 1266-keV, 2234-keV, 3295-keV, 3415-keV, and 4431-keV states are shown in black, red, yellow, brown, green and magenta respectively. Four states, at energies 6399 keV, 6496 keV, 6501 keV, and 6594 keV, are of the astrophysical interest.

5.2 The Optical Model

The optical model is a simple model in which nuclei are likened to cloudy crystal balls. Analogous to the behavior of the light, when a beam of particles strike them, the nuclei are partially absorbed, and partially scattered. The Schrödinger equation for a wave function, $\Psi(\vec{r}, t)$, that describes the nuclear system is given by(30):

$$i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}, t) = \frac{-\hbar^2}{2\mu} \nabla^2 \Psi(\vec{r}, t) + U(\vec{r}) \Psi(\vec{r}, t) \quad (5.1)$$

The complex potential, $U(r)$, can be written as the sum of real and imaginary parts as follows(30):

$$U(r) = V(r) + iW(r) \quad (5.2)$$

where the real part, $V(r)$, is responsible for the elastic scattering, and the imaginary part, $W(r)$, is responsible for the absorption from the elastic channel(30). For a reaction of type A(a,b)B with (A+a) entrance channel and (B+b) exit channel, optical potentials are used as entrance and exit channel potentials. A commonly used form of optical potential is given by:

$$U(r) = -V_r(r) - i(W_V(r) + W_S(r)) + V_{ls}(r)(\vec{L} \cdot \vec{\sigma}) + V_C(r) \quad (5.3)$$

The real volume potential, $V_r(r)$, is of the Woods-Saxon form given by:

$$V_r(r) = \frac{V_r}{1 + e^{\frac{R-R_r}{a_r}}} \quad (5.4)$$

where R_r and a_r are the radius and diffuseness parameters of the real volume potential. The imaginary volume potential, $W_V(r)$, is also of the Woods-Saxon form given by:

$$W_V(r) = \frac{W_r}{1 + e^{\frac{R-R_i}{a_i}}} \quad (5.5)$$

where R_i and a_i are the radius and diffuseness parameters of the imaginary volume potential. The imaginary surface potential, $W_S(r)$, is used to describe absorption by valence

nucleons on the surface. $W_S(r)$ is chosen as proportional to the derivative of the Woods-Saxon potential given by:

$$W_S(r) = -4ia_iW_S \frac{d}{dr} \left(\frac{1}{1 + e^{\frac{R-R_i}{a_i}}} \right) \quad (5.6)$$

where R_i and a_i are the radius and diffuseness parameters of the imaginary surface potential. The spin-orbit term, $V_{ls}(r)(\vec{L} \cdot \vec{\sigma})$ is given by:

$$V_{ls}(r)(\vec{L} \cdot \vec{\sigma}) = \frac{2V_{so}}{r} \frac{d}{dr} \left(\frac{1}{1 + e^{\frac{R-R_{so}}{a_{so}}}} \right) (\vec{L} \cdot \vec{\sigma}) \quad (5.7)$$

where R_{so} , a_{so} , and $\vec{L}$ are the radius, diffuseness, and angular momentum of the spin-orbit potential. The Coulomb term, $V_C(r)$, is included if the incident particle is charged. The optical model parameters can be determined locally by fitting the elastic scattering cross-sections for the nuclides of interests at relevant energies or globally by fitting large amount of elastic scattering data sets over a range of Z , A and E .

In Distorted-Wave Born Approximation (DWBA), the optical model is used to consider that the incoming and the outgoing plane waves are distorted by the nucleus. The spin-parity and the spectroscopic factors of the states populated in the ^{31}P nucleus were constrained by using the DWBA calculations code FRESKO(40).

The $^{30}\text{P}(d, d)^{30}\text{P}$ reaction DWBA calculations were performed using three optical potentials, namely Lohr-Haeberli(12), Perey-Perey(13), and Daehnick Global(14). The $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction DWBA calculations were performed using Perey-Perey(13) potential for the entrance channel, and Chapel-Hill(41) potential for the exit channel. The optical potential parameters are listed in Table 5.1. The neutron binding potential in the ^{31}P is of the Woods-Saxon form with radius and diffuseness parameters 1.25 fm and 0.65 fm respectively.

Table 5.1: Optical potential parameters for ($^{30}\text{P}+d$) entrance channel and ($^{31}\text{P}+p$) exit channel calculated with different global optical model parameterizations. These parameters are extracted from the code FRONT(1). V_r , W_s , W_r , and V_{so} are in MeV and R_r , a_r , R_i , a_i , R_{so} , a_{so} , and r_c are in fm.

Perey-Perey(13) for ($^{30}\text{P}+d$) entrance channel										
V_r	R_r	a_r	W_s	R_i	a_i	W_r	V_{so}	R_{so}	a_{so}	r_c
87.2305	1.15	0.81	18.2448	1.34	0.68	0.0	0.0	1.0	1.0	1.149
Lohr-Haeblerli(12) for ($^{30}\text{P}+d$) entrance channel										
101.7504	1.05	0.86	22.5792	1.43	0.6255	0.0	3.5	0.75	0.5	1.299
Daehnick Global(14) for ($^{30}\text{P}+d$) entrance channel										
88.5830	1.17	0.7362	12.2969	1.3250	0.7474	0.3197	3.4327	1.07	0.66	1.299
Chapel-Hill(41) for ($^{31}\text{P}+p$) exit channel										
47.5064	1.1784	0.69	6.4540	1.11963	0.69	2.1414	5.9	0.958	0.63	1.291

5.3 Normalization

Two methods were employed to determine the integrated beam-target product to determine absolute differential cross-sections. The first method involved the analysis of the $^{30}\text{P}(d, d)^{30}\text{P}$ channel by normalizing the (d, d) data to the (d, d) differential cross-section calculated in a DWBA formalism. The second method used a direct counting of the incident ^{30}P flux using prescaled self-triggered ionization chamber events.

5.3.1 Method I: Using Deuteron Elastic Scattering

The angular distribution, for the deuteron elastic scattering channel, obtained by gating over the deuterons in the particle identification plot in Figure 4.10, and dividing data into angular bins was converted to the differential cross-section using the following equation:

$$\frac{d\sigma}{d\Omega} = F \left(\frac{dN}{d\Omega} \right) \quad (5.8)$$

where F is the normalization factor, dN is the number of counts in an angular bin, and $d\Omega$ is the solid angle of the same angular bin. The normalization factor was calculated by normalizing the data points to DWBA calculations of the $^{30}\text{P}(d, d)^{30}\text{P}$ channel for three optical potentials using the FRESKO code(40) as shown in Figure 5.2, and the results are listed in the Table 5.2. The normalization was extracted using the lmfit library of python which implements least-squares minimization weighted by uncertainties(42).

5.3.2 Method II: Using The Ionization Chamber For Direct Counting Of Ions

Because a downscaled IC singles trigger was recorded, the total incident beam flux was measured directly. This measurement was combined with target thickness determined via α -particle energy loss to obtain the beam-target product needed for normalization. Differential

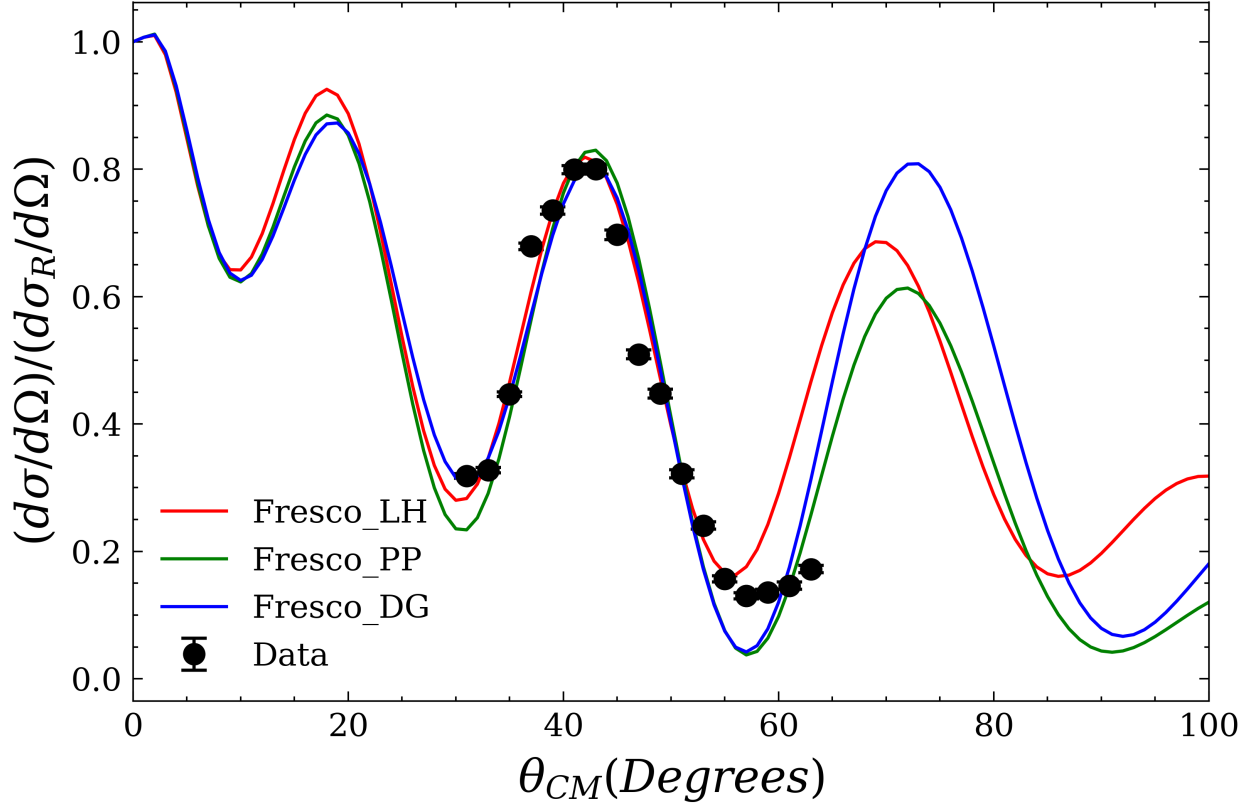


Figure 5.2: $^{30}\text{P}(d, d)^{30}\text{P}$ differential cross-section in the centre-of mass frame. The vertical axis shows the ratio of differential cross-section to Rutherford scattering cross-section. The black points are $^{30}\text{P}(d, d)^{30}\text{P}$ elastic scattering data points, and the red, green and blue solid lines are from the DWBA calculations with the Lohr-Haeberli(12), Perey-Perey(13), and Daehnick Global(14) potentials respectively

cross-sections can be obtained by using the following equation:

$$\frac{d\sigma}{d\Omega} = \frac{1}{N_B \times N_T} \left(\frac{dN}{d\Omega} \right) \quad (5.9)$$

where N_B is the total ^{30}P beam counts inside the graphical cut in the particle identification plot from the ionization chamber using the IC self triggers. N_T is the number of areal density of the CD_2 target. Comparing Equations 5.8 and 5.9, we see that the normalization is given by the following equation:

$$F = \frac{1}{N_B \times N_T} \quad (5.10)$$

N_T was determined using the α -particle energy loss in the target. To calculate N_B , data from the ionization chamber and the $^{30}\text{P}(d, d)^{30}\text{P}$ elastic scattering were analyzed using the same particle identification gate as used for (d, d) and (d, p) to subject both data to similar IC efficiency. Instead of counting N_B for the whole experimental data run-by-run, elastically-scattered deuterons were counted which were scaled to determine N_B . A total number of elastically-scattered deuterons, N_{el} , is proportional to the total number of ^{30}P beam particles and the areal density of the target. We can find the proportionality constant, K , using the following equation:

$$N_{\text{el}} = \frac{1}{K} \times N_B \times N_T \quad (5.11)$$

$$K = \frac{1}{N_{\text{el}}} \times N_B \times N_T \quad (5.12)$$

From Equations 5.10 and 5.12, the normalization constant can be evaluated in terms of K using the following equation:

$$F = \frac{1}{K \times N_{\text{el}}} \quad (5.13)$$

As shown in Table 5.2, the value of the normalization constant, F , was calculated at the start of the experiment, and at the end of the experiment to allow for degradation of the

Table 5.2: Cross-section normalization factors determined from DWBA calculations using three global Optical Model potentials and using IC with different runs. The uncertainties include statistical uncertainties while extracting deuteron and IC yields and fitting uncertainties in differential cross-sections in Figure 5.2. These errors are propagated to get errors for the average of two methods. The errors in the bottom row of the table simply shows the range of the Normalization calculated via different methods. Note that the errors exclude uncertainties in the areal density calculations.

Method I: Using Optical Model	
Potential	Normalization (<i>mb/counts</i>)
Perey-Perey	$2.40^{+0.022}_{-0.002} * 10^{-4}$
Lohr-Haeberli	$2.63^{+0.01}_{-0.006} * 10^{-4}$
Daehnick Global	$2.45^{+0.01}_{-0.006} * 10^{-4}$
Method II: Using Ionization Chamber	
Run Detail	Normalization (<i>mb/counts</i>)
First Two Runs	$2.38 \pm 0.006 * 10^{-4}$
Last Two Runs	$2.33 \pm 0.0059 * 10^{-4}$
Average of Two Methods	$2.42^{+0.005}_{-0.003} * 10^{-4}$
Average of Two Methods	$2.42^{+0.218}_{-0.098} * 10^{-4}$

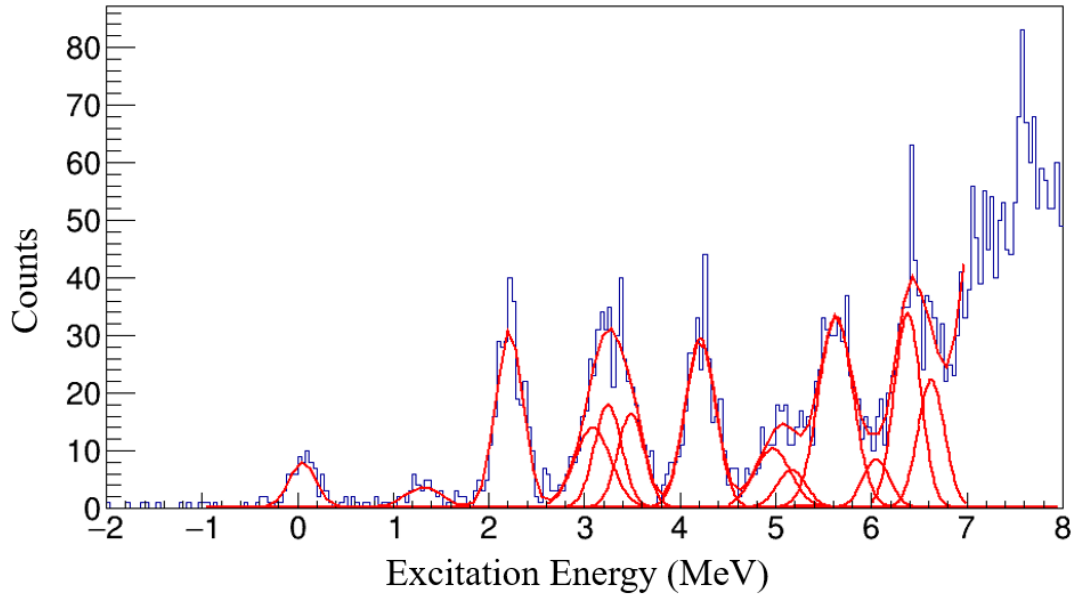
target, as the areal density of the target can degrade with time irradiated by the beam. The average normalization constant of the two methods, shown in Table 5.2, was used to convert the angular distributions to differential cross-sections.

5.4 Differential Cross Section

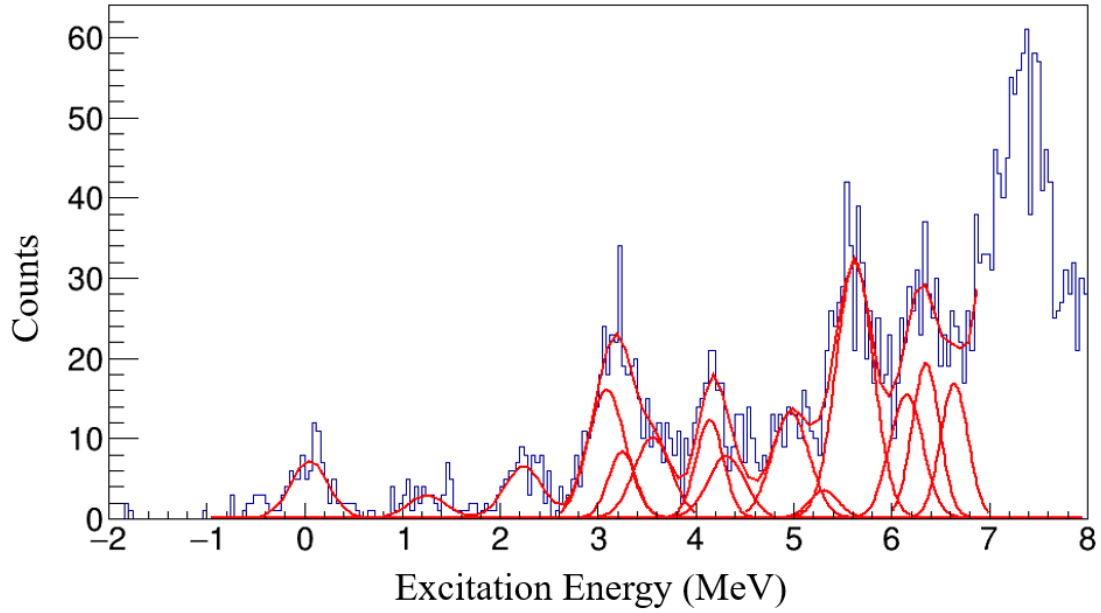
With the states in the level scheme, the excitation energy spectra were fitted with a Gaussian function for each state and the fusion evaporation from reactions on the carbon in the CH₂ target was included using the data from the runs with CH₂ target. To extract the angular distributions, the QQQ5 and super X3 detectors were divided into 3° angular bins as shown in Figure 5.3. The differential cross-sections were extracted by scaling the angular distribution using the normalization factor from Table 5.2. The spectroscopic factors were extracted by scaling the calculated DWBA differential cross-section from the FRESKO code to the measured differential cross section using the lmfit library of python(42), which implements least-squares minimization weighted by uncertainties. As a starting point, Perey-Perey and Chapel-Hill potentials were chosen as optical potentials. These potentials will be replaced with adiabatic potentials as discussed in Section 6.2.

5.4.1 Ground, 1266-keV, and 2234-keV states

The level spacing for the ground, 1266-keV, and 2234-keV states are larger than those for the higher excitation states. This allows differential cross-sections to be plotted for individual resolved states using only charged particle data. The differential cross-section plots for the ground, 1266-keV, and 2234-keV states are shown in Figures 5.4, 5.5, and 5.6 respectively. The ground state, and the 2234-keV state are populated with pure s-wave transfer, and pure-d wave transfer, with spectroscopic factors 0.52 ± 0.01 , and 0.4 ± 0.01 respectively. The 1266-keV state is populated with a mixture of s-and d-wave transfers with spectroscopic factors 0.04 ± 0.01 , and 0.09 ± 0.01 respectively.



(a)



(b)

Figure 5.3: Excitation energy spectrum for 3° angular bins in laboratory frame for upstream QQQ5 detectors and super X3 detectors fitted with multiple Gaussians for states up to 7-MeV. The amplitudes, centroids, widths are let to float within certain bounds for these fits. The fusion evaporation background is also included in the fit. (a) Excitation energy spectrum for 138° to 141° laboratory angular bin in upstream QQQ5 detectors. (b) Excitation energy spectrum for 111° to 1114° laboratory angular bin in upstream super X3 detectors.

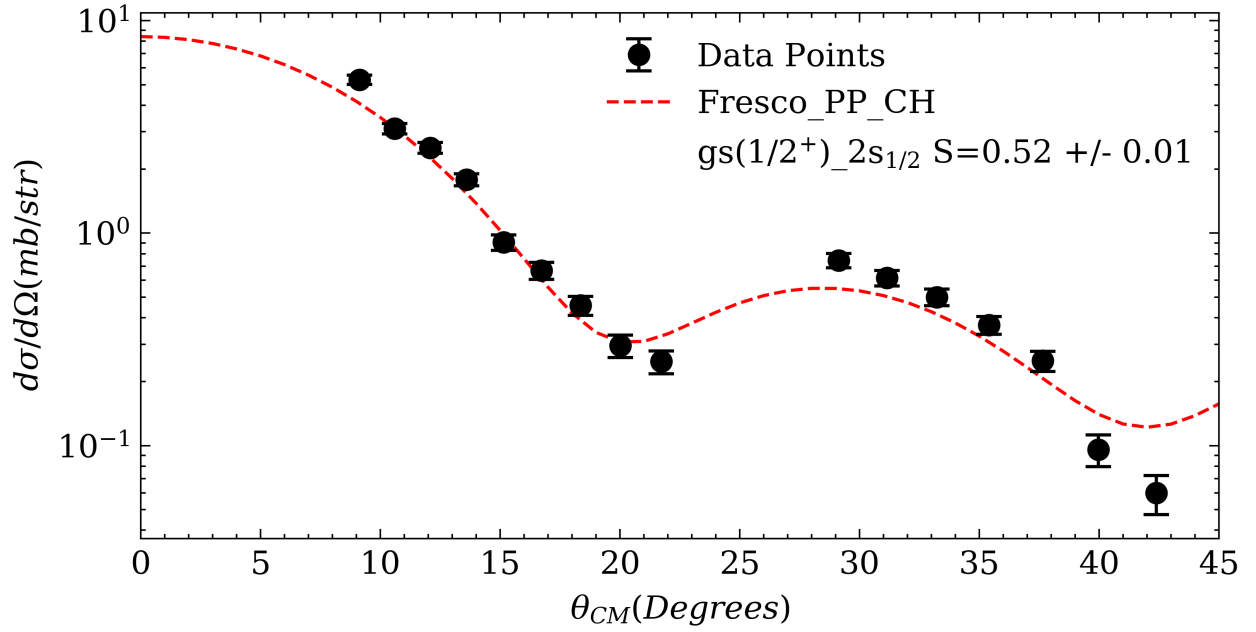


Figure 5.4: Differential cross-section of the ground state populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, and the dashed red line is from DWBA calculations. The ground state distribution can be described by pure s-wave transfer with a spectroscopic factor 0.52 ± 0.01 . The error bar represents uncertainties from the fitting procedure weighted by statistical uncertainties.

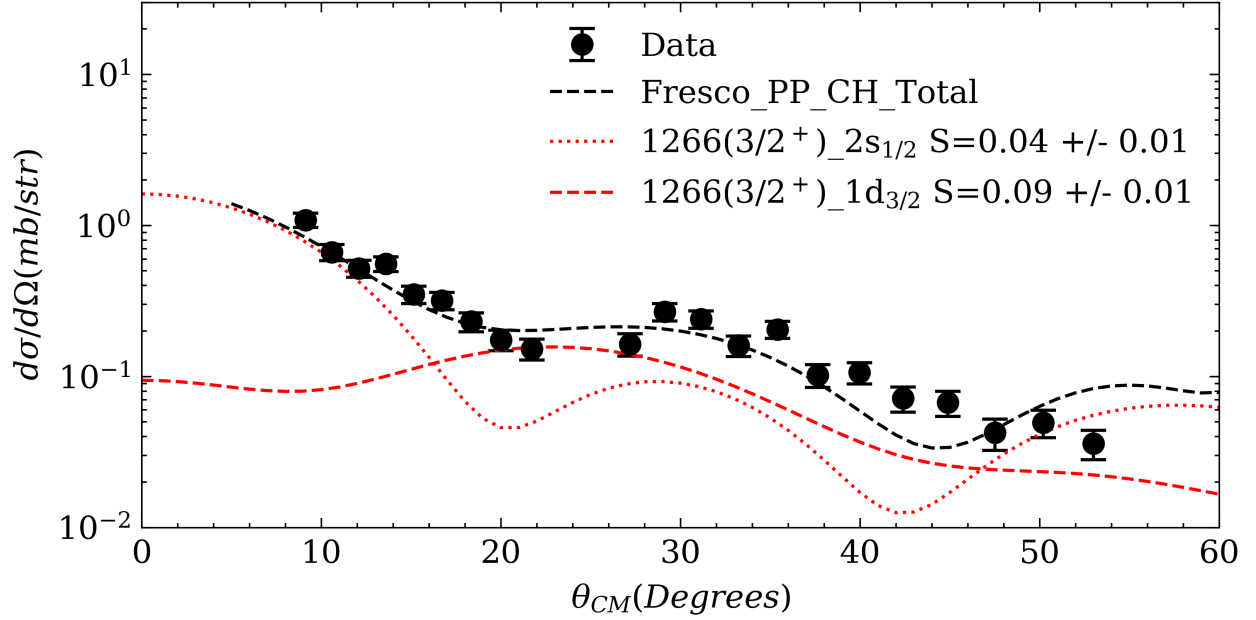


Figure 5.5: Differential cross-section of the 1266-keV state populated via the $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, and the dashed and the dotted red lines are from DWBA calculations for s-, and d-waves respectively. The dashed black line is the total contribution from these s-, and d-waves. The 1266-keV state has contributions from both s-, and d-, waves with spectroscopic factors 0.04 ± 0.01 and 0.093 ± 0.01 respectively. The error bar represents uncertainties from the fitting procedure weighted by statistical uncertainties.

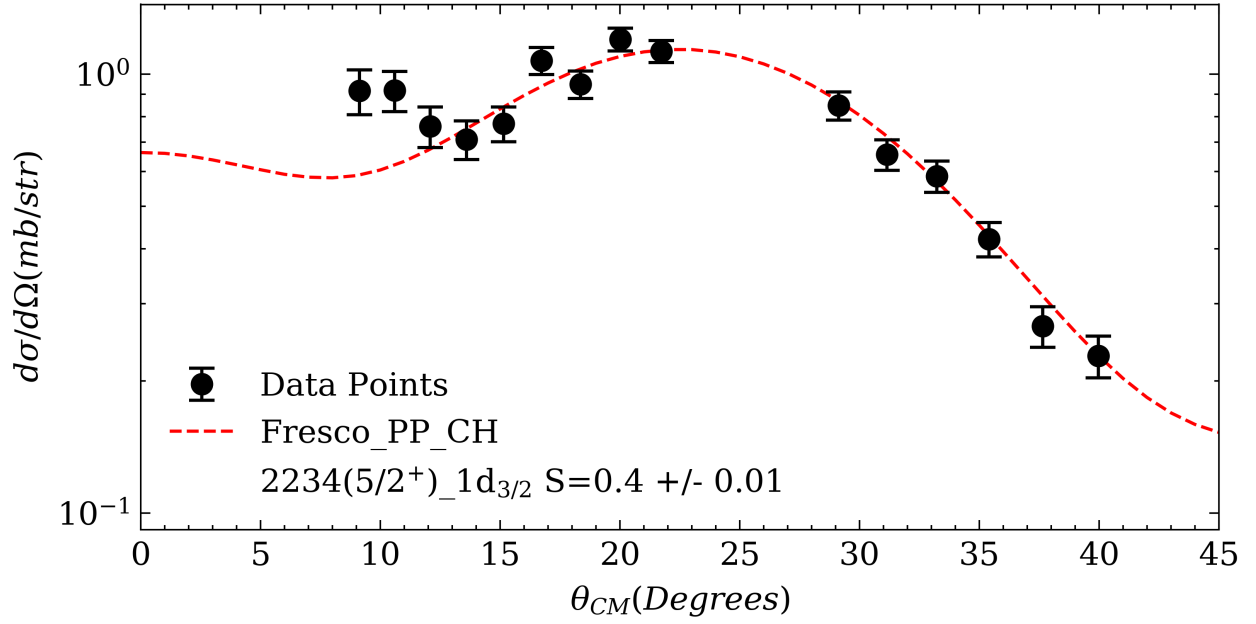


Figure 5.6: Differential cross-section of the 2234-keV state populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, and the dashed red line is from DWBA calculations. The 2234-keV state distribution can be described by pure d-wave transfer with a spectroscopic factor 0.40 ± 0.01 . The error bar represents uncertainties from the fitting procedure weighted by statistical uncertainties.

5.4.2 3134-, 3295-, and 3506-keV states

The level spacing for the 3134-keV, 3295-keV, and 3506-keV states were too small to resolve individual peaks. Because of this, the extraction of differential cross-sections and spectroscopic factors for the individual states was not trivial. The total differential cross-section for the single-unresolved peak is shown in Figure 5.7. The mixture of a s- and a d-wave transfers obtained from DWBA calculations nicely describes the measured differential cross-section. The scaling of this fit has unresolved contributions from the 3134-keV, 3295-keV and 3506-keV states.

5.4.3 4190-, and 4260-keV states

The 4190-, and 4260-keV states were also unresolved. The total differential cross-section for the single peak is shown in Figure 5.8. The mixture of an s-wave and a d-wave, obtained from DWBA calculations, nicely fits the measured differential cross-section. The contributions from the 4190-keV, and 4260-keV states are not separable.

5.4.4 5015-, 5114-, 5256-, and 5672-keV states

The total differential cross section for the unresolved peak for 5015-, 5114-, 5256-, and 5672-keV states are shown in Figures 5.9 and 5.10. As shown in Figure 5.9, the mixture of a s-wave and a d-wave did not fit the measured differential cross section in the higher centre of mass angles. The precise fit was obtained by adding contributions from p-, and f-waves as shown in Figure 5.10. The contribution from 5015-keV, and 5114-keV, 5256-keV, and 5672-keV states are not separable.

5.4.5 6399-, 6496-, 6501-, and 6594-keV states

The 6399-, 6496-, 6501-, and 6594-keV states were also unresolved. The total differential cross-section for the single peak is shown in Figure 5.11. The mixture of s-, d-, p-, and f-waves, obtained from DWBA calculations, nicely fits the measured differential cross section.

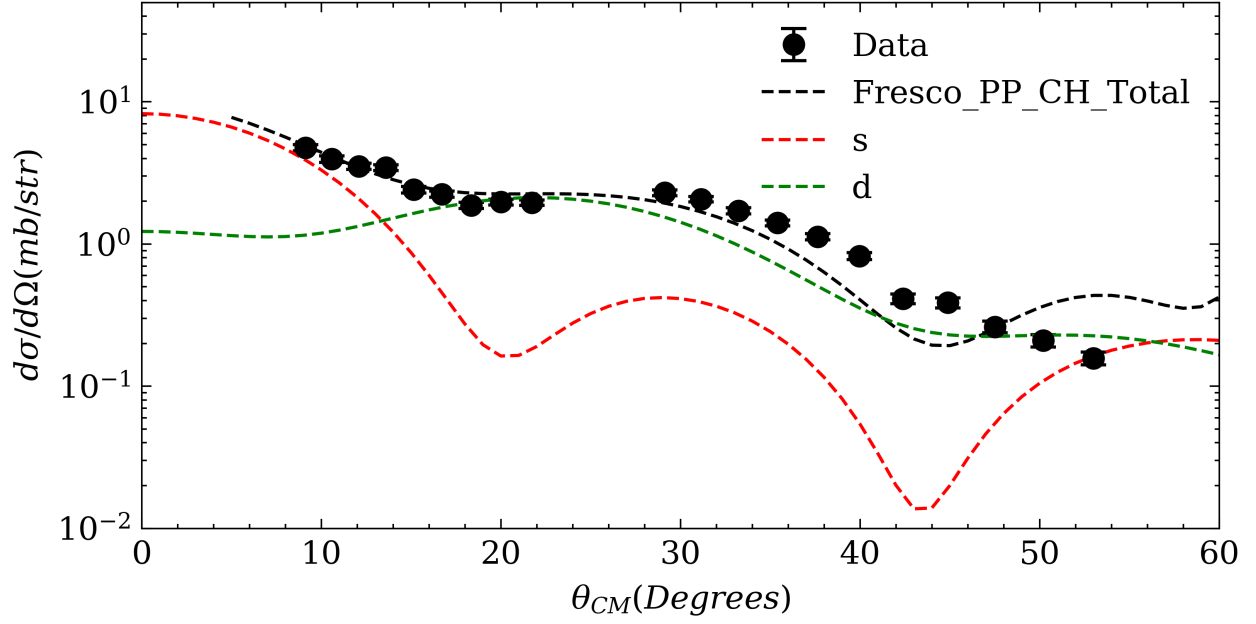


Figure 5.7: Differential cross-section of the 3134-keV, 3295-keV, and 3506-keV states populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction in center-of-mass frame. The black points are experimental data with statistical error bars, the dashed red and green lines are from DWBA calculations with s-, and d-wave respectively, and the dashed black line represents their sum. The fraction of the s- and d-wave contributions from the individual states is not resolved.

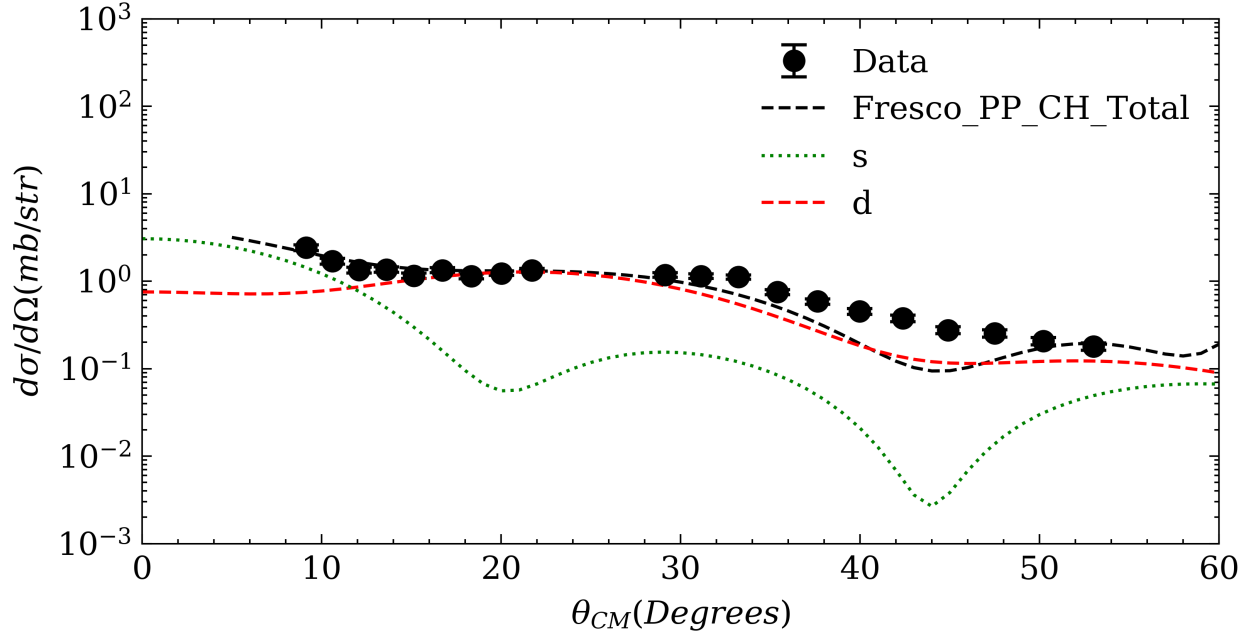


Figure 5.8: Differential cross-section of the 4190-keV and 4260-keV states populated via the $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dotted green and the dashed red lines are from DWBA calculations with s-wave and d-wave respectively, and the dashed black line represents their sum. The fraction of the s-wave and d-wave contributions from the individual states is not resolved.

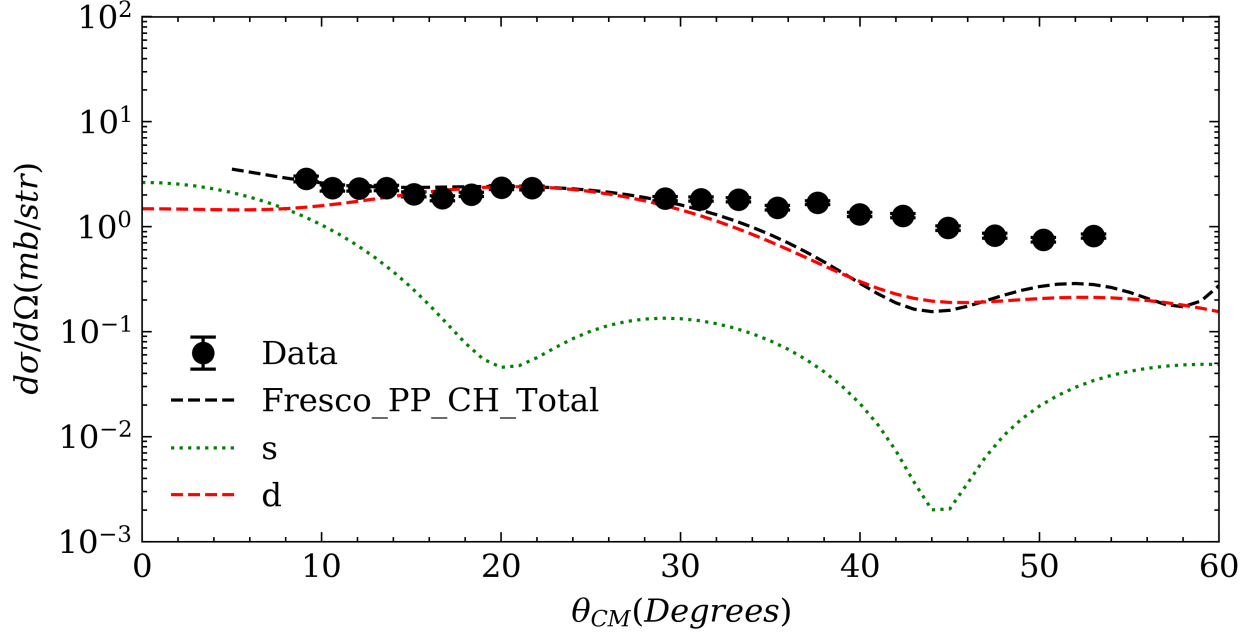


Figure 5.9: Differential cross-section of the 5015-keV, 5116-keV, 5256-keV and 5672-keV states populated via the $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dotted green and the dashed red lines are from DWBA calculations with s-wave and d-wave respectively, and the dashed black line represents their sum. In the higher centre of mass angle, the experimental data are above the total DWBA calculation line. This is described by adding contributions of p-, and f-wave as shown in Figure 5.10

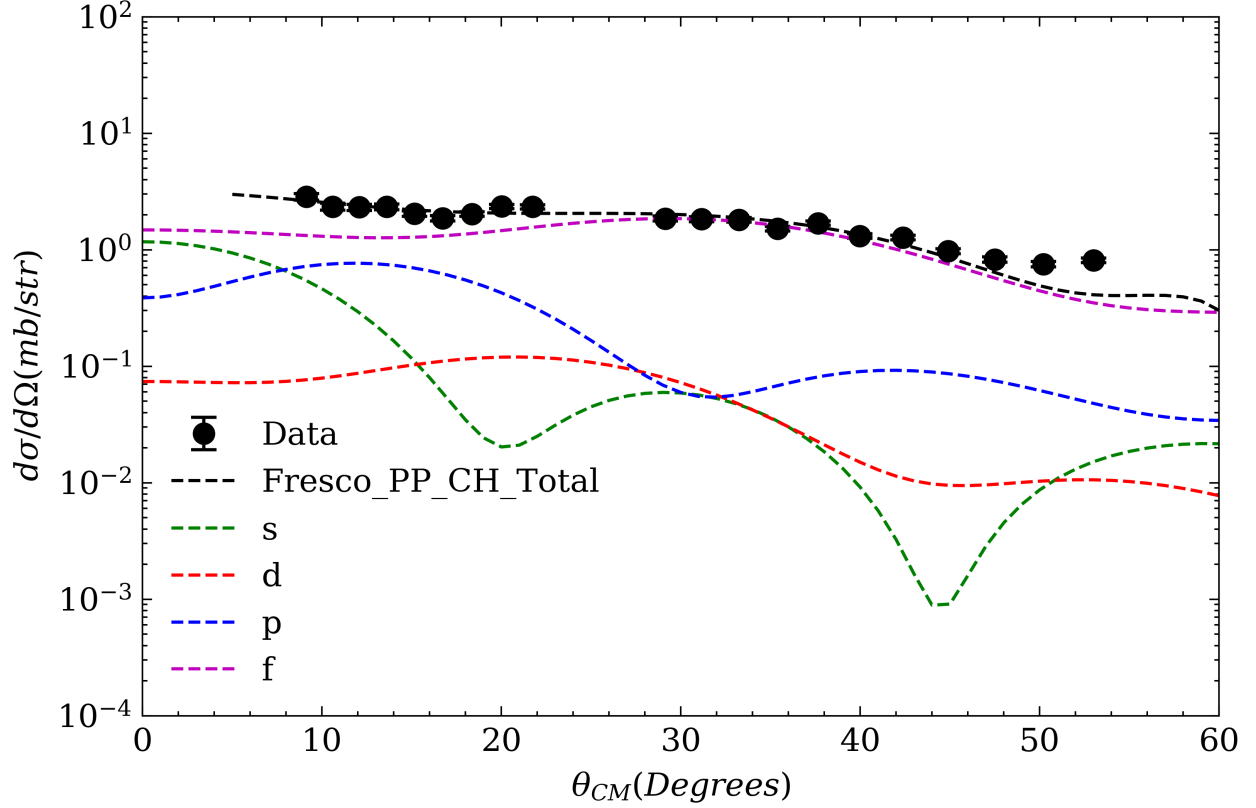


Figure 5.10: Differential cross-section of the 5015-keV, 5116-keV, 5256-keV and 5672-keV states populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dashed green, red, blue and magenta lines are from DWBA calculations with s-wave and d-wave, p-wave and f-wave respectively, and the dashed black line represents their sum. With the contribution of p-, and f-wave, the fit looks correct for high centre-of-mass angles. The fraction of the s-wave, d-wave, p-wave and f-wave contributions from the individual states is not resolved.

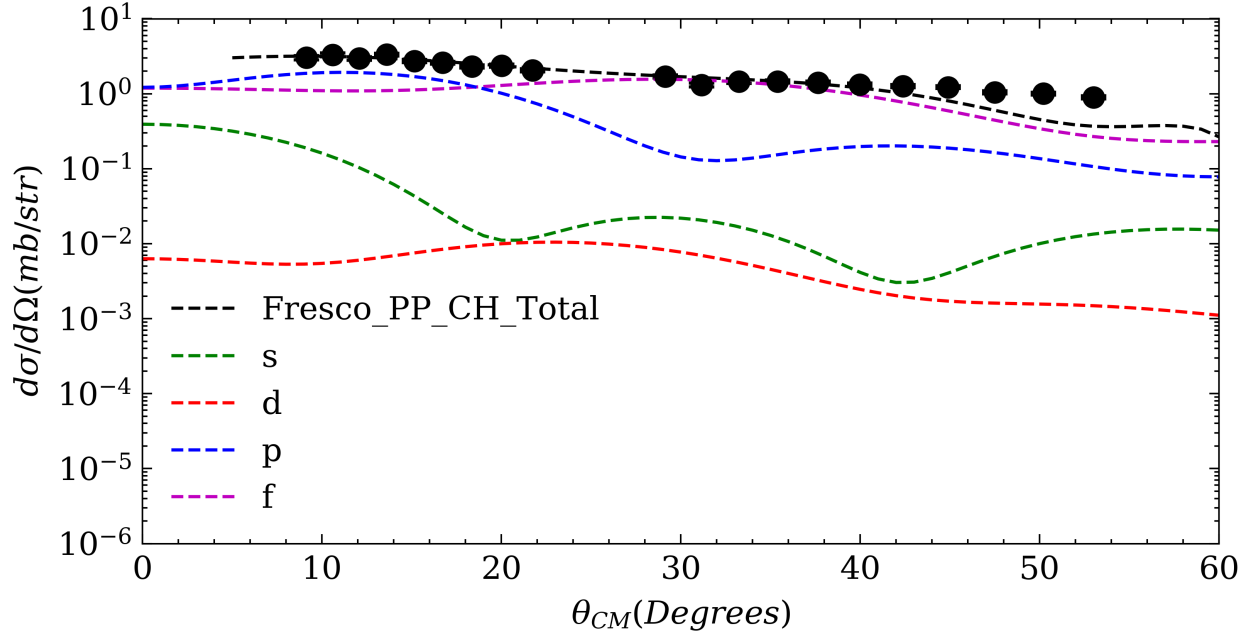


Figure 5.11: Differential cross-section of the 6399-keV, 6496-keV, 6501-keV and 6594-keV states populated via the $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dashed green, red, blue and magenta lines are from DWBA calculations with s-, d-, p-, and f-waves respectively, and the dashed black line represents their sum. The fraction of the s-wave, d-wave, f-wave and p-wave contributions from the individual states is not resolved.

The contribution from 6399-keV, 6496-keV, 6501-keV, and 6594-keV states are not separable. To resolve the spectroscopic factors for unresolved states with transfer to all possible orbitals, following steps were carried out:

1. γ -ray efficiency was used to constrain yields of each state.
2. γ -gated particle angular distributions were used to constrain contributions from all possible orbitals.

5.5 Using GRETINA Efficiency Calibration To Resolve Individual States

A ^{56}Co γ -ray source was used to calibrate the efficiency of GRETINA as shown in Figure 5.12. A relative efficiency was measured, and was scaled using the 1266-keV, and 2234-keV γ rays from the first two excited states of the ^{31}P nucleus to obtain the absolute efficiency. The plot was fitted with a power series, which was used to extract the emitted γ -ray counts from measured γ -ray counts. After efficiency correction, the γ rays were used to extract spectroscopic factors for individual states.

5.5.1 3134-, 3295-, and 3506-keV state

The γ -ray yields from the 3134-keV, 3295-keV, and 3506-keV states were corrected for efficiency, and their individual contributions to the single peak were calculated as shown in Table 5.3. These contributions were used to constrain the fit procedure to extract the spectroscopic factors of individual states from the total yields as shown in Figure 5.13. As 3295-keV state is a definite d-wave with 25% contribution to the total yields, the spectroscopic factor for this state is 0.31 ± 0.03 . The 3134-keV, and 3506-keV states have 48% and 27% contributions to the total yields. But those contributions arise from both s-, and d-waves. γ -gated particle angular distributions were used to constrain the contribution of the s- and d-waves in the 3134-keV and 3506-keV states, which were used to

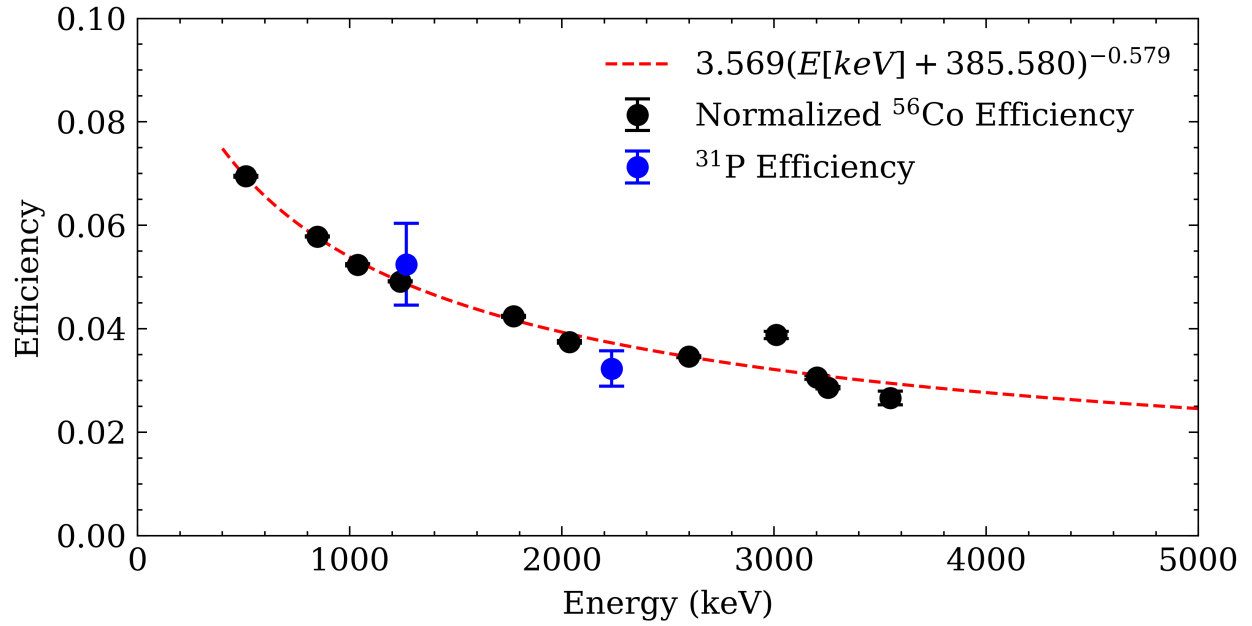


Figure 5.12: GREYINA efficiency as a function of γ -ray energy. The black points are from the ^{56}Co source, and blue points are from 1266-keV and 2234-keV γ rays from ^{31}P with statistical error bars. The dashed red line is the fit function obtained by fitting the data points using least-squares minimization.

Table 5.3: Individual contributions of 3134-keV, 3295-keV, and 3506-keV states

E_x (keV)	Shell	Contribution (%)
3134	$2s_{1/2}1d_{3/2}$ mixture	48
3295	$1d_{3/2}$	25
3506	$2s_{1/2}1d_{3/2}$ mixture	27

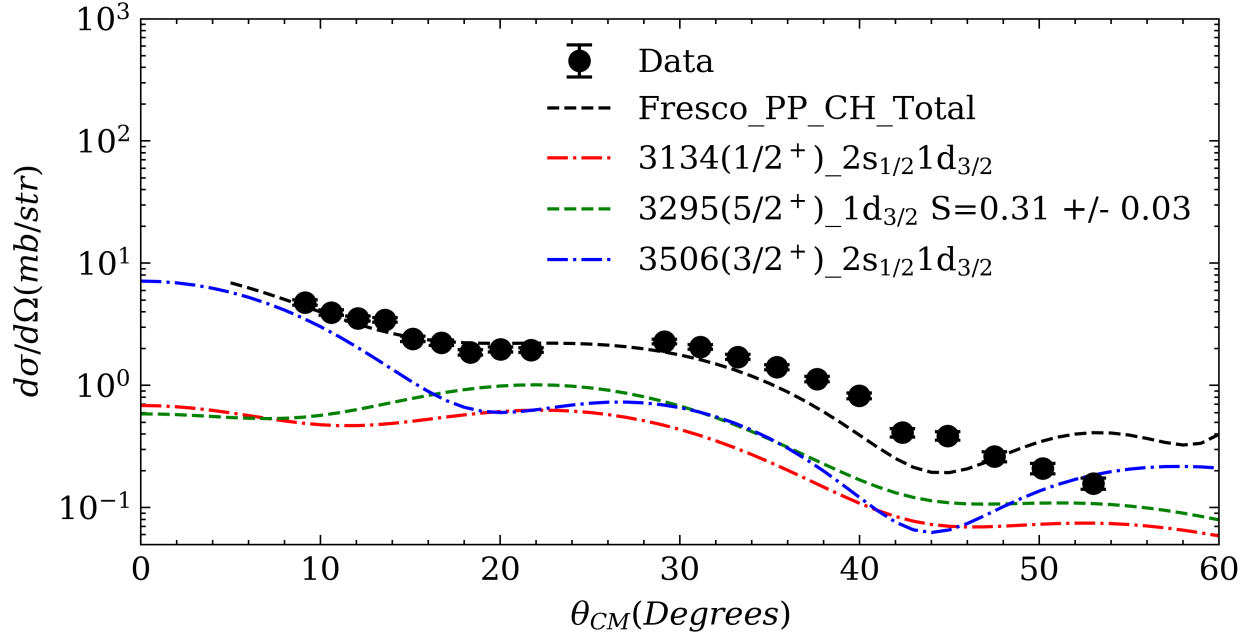


Figure 5.13: Differential cross-section of the 3134-keV, 3295-keV, and 3506-keV states populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dashed-dotted red, dashed green, and dashed-dotted blue lines are from DWBA calculations for the 3134-keV, 3295-keV, and 3506-keV and the dashed black line represents their sum. As the 3295-keV state is a definite d-wave, the spectroscopic factor for this state is 0.31 ± 0.03 . The error bar represents uncertainties from the fitting procedure weighted by statistical uncertainties. The 3134-keV state, and the 3506-keV state has 48% and 27% contribution to the total yields, but the contributions of the s-wave and d-wave in these states are not separable.

extract spectroscopic factors for s-, and d-waves for 3134-keV and 3506-keV states as shown in Figures 5.14 and 5.15 respectively. With constraints on the individual contributions from the 3134-keV and 3506-keV states for s-wave and d-wave, the spectroscopic factors for 3134-keV s-wave, 3134-keV d-wave, 3506-keV s-wave, and 3506-keV d-wave are 0.20 ± 0.08 , 0.39 ± 0.09 , ≤ 0.11 , and 0.3 ± 0.05 respectively.

5.5.2 4190-, and 4260-keV states

The γ rays emitted from the 4190-keV state, 4260-keV state were corrected for efficiency, and their individual contribution to the single peak were calculated as shown in Table 5.4. These contributions were used to constrain the fit procedure to extract spectroscopic factors of individual states from the total yields as shown in Figure 5.16. As the 4190-keV state is a definite d-wave with 12% contribution to the total yields, the spectroscopic factor for this state is 0.07 ± 0.01 . The 4260-keV has 88% contribution to the total yields. As the shapes of s- and d-waves are very distinct, the s- and d-wave contributions were constrained with the fit, and their spectroscopic factors are 0.04 ± 0.02 and 0.47 ± 0.04 respectively.

5.5.3 5015-, 5116-, 5256-, and 5672-keV states

The γ rays emitted from the 5015-keV, 5116-keV, 5256-keV, and 5672-keV states were corrected for efficiency, and their individual contributions to the single peak were calculated as shown in Table 5.5. These contributions were used to constrain the fit procedure to extract the spectroscopic factors of individual states from the total yields as shown in Figure 5.17. As the 5116-keV state is a definite d-wave with 4% contribution to the total yields, the spectroscopic factor for this state is 0.04 ± 0.003 . The 5015-keV, 5256-keV, 5672-keV states have 5%, 8% and 83% contribution to the total yields. With the shapes of p- and f-waves being very distinct for 5672-keV state, the p- and f-wave contributions were constrained with the fit, and their spectroscopic factors are 0.02 ± 0.001 and 0.77 ± 0.07 respectively. The 5672-keV state is the lowest energy negative parity state that was observed

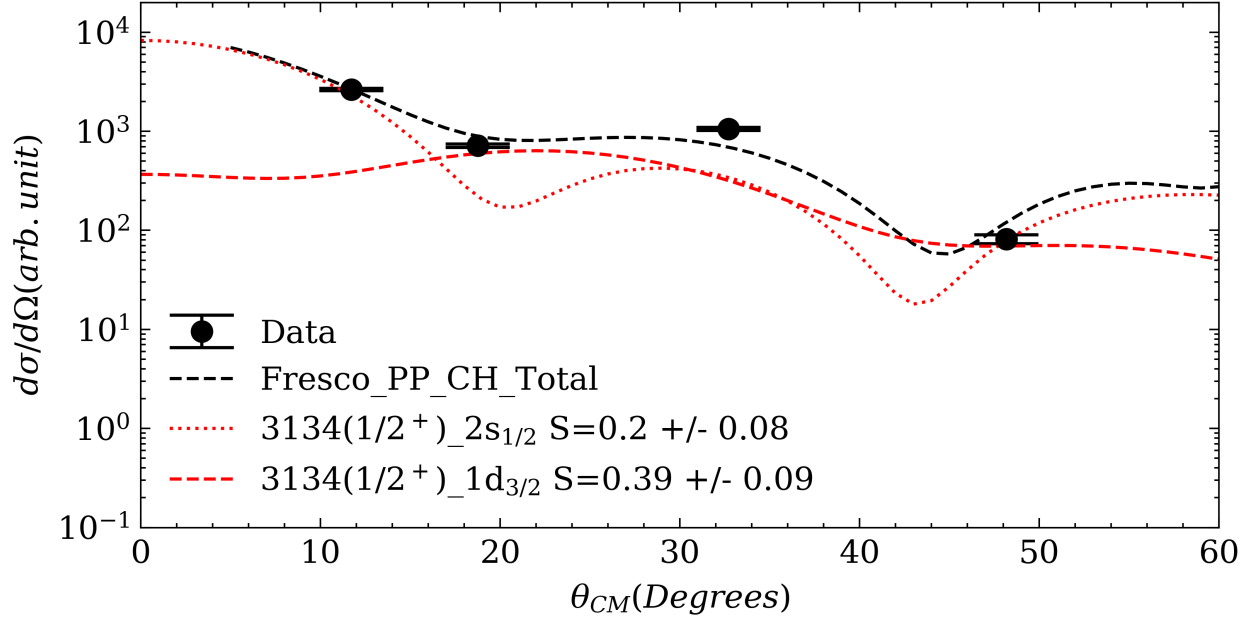


Figure 5.14: γ -gated angular distribution of the 3134-keV state populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction of the center-of-mass frame. The black points are experimental data with statistical error bars, the dotted, and dashed red lines are from DWBA calculations for s-wave and d-wave respectively, and the dashed black line represents their sum. The spectroscopic factors for s-, and d-waves are 0.20 ± 0.08 and 0.39 ± 0.09 respectively. The error bars represent uncertainties from the fitting procedure weighted by statistical uncertainties.

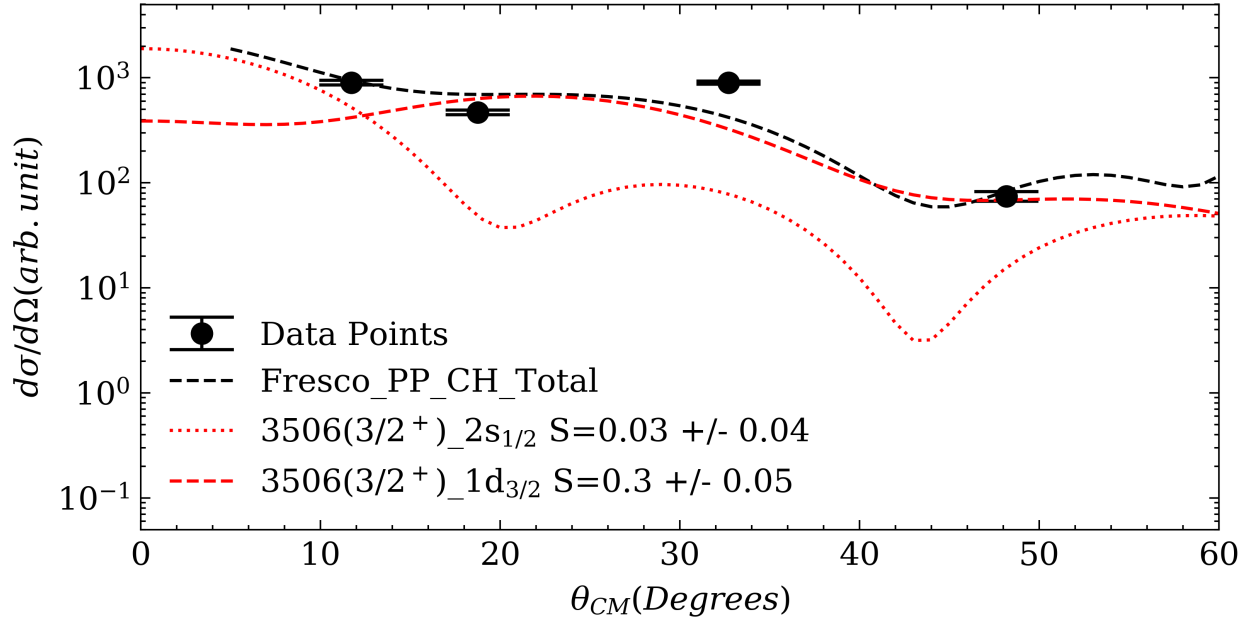


Figure 5.15: γ -gated angular distribution of the 3506-keV state of the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction. The black points are experimental data with statistical error bars, the dotted, and dashed red lines are from DWBA calculations for s-wave and d-wave respectively, and the dashed black line represents their sum. The spectroscopic factors for s-, and d-waves are $0.03^{+0.04}_{-0.00}$ and 0.3 ± 0.05 respectively. The error bars represent uncertainties from the fitting procedure weighted by statistical uncertainties.

Table 5.4: Individual contribution of 4190-keV, and 4260-keV states

E_x (keV)	Shell	Contribution (%)
4190	$1d_{3/2}$	12
4260	$2s_{1/2}1d_{3/2}$ mixture	88

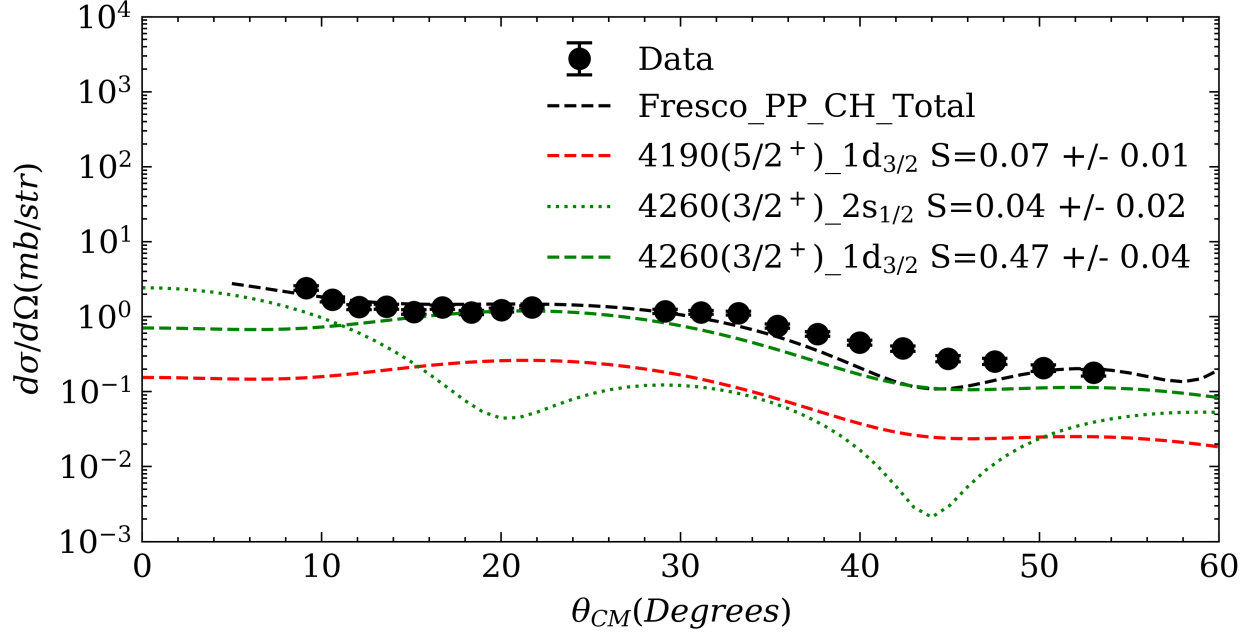


Figure 5.16: Differential cross-section of the 4190-keV, and the 4260-keV states populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dashed red, the dotted green and the dashed green lines are from DWBA calculations for 4190-keV d-wave, 4260-keV s-wave and 4260-keV d-wave, and the dashed black line is their sum. The 4190-keV state is a definite d-wave with spectroscopic factor 0.07 ± 0.01 . The 4260-keV state has contributions from both s-, and d-waves with spectroscopic factors 0.04 ± 0.02 and 0.47 ± 0.04 respectively. The error bars represent uncertainties from the fitting procedure weighted by statistical uncertainties.

Table 5.5: Individual contribution of 5015-keV, 5116-keV, 5256-keV and 5672-keV states

E_x (keV)	Shell	Contribution (%)
5015	$2s_{1/2}1d_{3/2}$ mixture	5
5116	$1d_{3/2}$	4
5256	$2s_{1/2}1d_{3/2}$ mixture	8
5672	$2p_{3/2}1f_{7/2}$ mixture	83

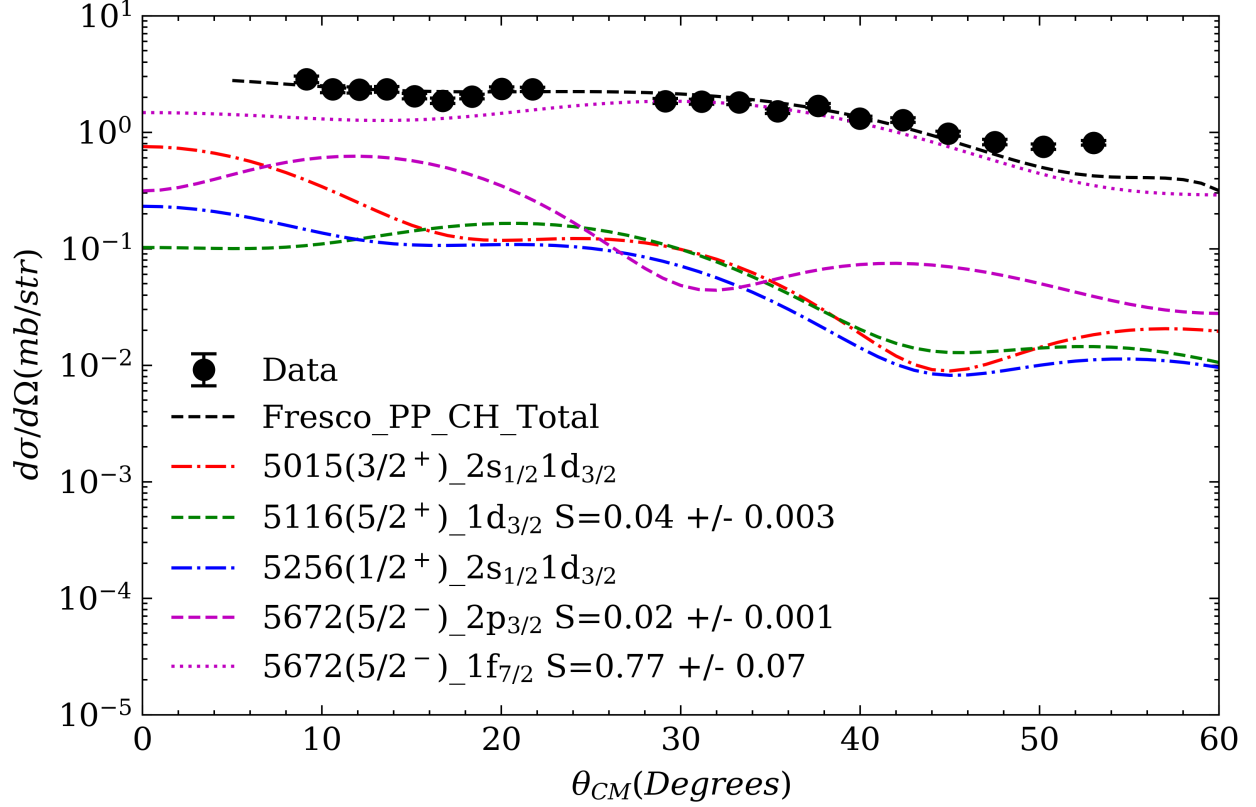


Figure 5.17: Differential cross-section of the 5015-keV, 5116-keV, 5256-keV and 5672-keV states populated via the $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dashed-dotted red, dashed green, dashed-dotted blue, dashed magenta and dotted magenta lines are from DWBA calculations for 5015-keV, 5116-keV, 5256-keV, 5672-keV states with p-wave and 5672-keV state with f-wave, and the dashed black line represents their sum. 5116-keV state is a definite d-wave with spectroscopic factor 0.04 ± 0.003 . 5672 keV state has p- and f-wave contributions with spectroscopic factors 0.02 ± 0.001 and 0.77 ± 0.07 respectively. The error bars represent uncertainties from the fitting procedure weighted by statistical uncertainties. 5015-keV and 5116-keV states have 5% and 4% contributions respectively, but the fractions of the s-wave and the d-wave contributions in them are not separable.

in this measurement. The contribution to the 5015-keV, and 5256-keV states arises from both s-, and d-waves. The γ -gated particle yields were not enough for the angular distribution of the 5015-keV state. So the individual contributions from s-wave and d-wave were not constrained for this state. However, γ -gated particle angular distributions were used to constrain the contributions of the s-, and d-waves in the 5256-keV state as shown in Figure 5.18. With these, the spectroscopic factors for 5256-keV s-wave, 5256-keV d-wave are 0.08 ± 0.01 , and $0.001^{+0.01}_{-0}$ respectively.

5.5.4 6399-, 6496-, 6501-, and 6594-keV states

The γ -gated angular distribution of the 6496-keV state is shown in Figure 5.19. The d-wave transfers obtained from DWBA calculations nicely describes the measured angular distribution.

The γ rays emitted from the 6399-keV, 6496-keV, 6501-keV, and 6594-keV states were corrected for efficiency, and their individual contribution to the single peak were calculated as shown in Table 5.6. These contributions were used to constrain the fit procedure to extract the spectroscopic factors of individual states from the total yields as shown in Figure 5.20. As 6399-keV and 6501-keV states are definite f-waves with 17% and 19% contribution to the total yields, the spectroscopic factors for these states are 0.1 ± 0.01 and 0.11 ± 0.01 respectively. The 6496-keV state has 13% contribution to the total yields. The angular distribution shown in Figure 5.19 suggests that the angular distribution is dominated by the d-wave transfers. With this, the spectroscopic factors for the 6496-keV s-wave, and 6496 d-wave are 0.01 ± 0.001 and 0.06 ± 0.02 respectively. The 6594-keV state has 51% contribution to the total yields. With this, the spectroscopic factors for the 6594-keV f-wave, and 6594-keV p-wave are 0.25 ± 0.02 , and 0.05 ± 0.01 respectively. The spectroscopic factors of all the states populated in the ^{31}P are listed in the Table 5.7.

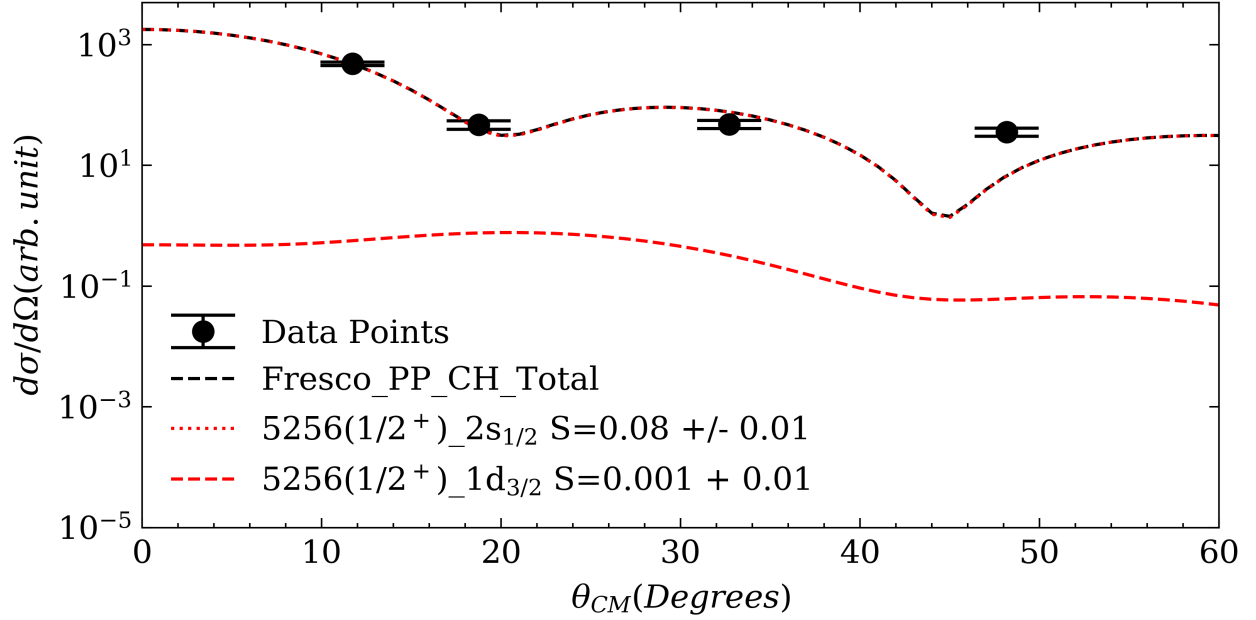


Figure 5.18: γ -gated angular distribution of the 5256-keV state populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dotted red, dashed red lines are from DWBA calculations for s-wave and d-wave respectively, and the dashed black line represents their sum. The spectroscopic factors for s-, and d-waves are 0.08 ± 0.01 and $0.001^{+0.01}_{-0.00}$ respectively. The error bars represent uncertainties from the fitting procedure weighted by statistical uncertainties.

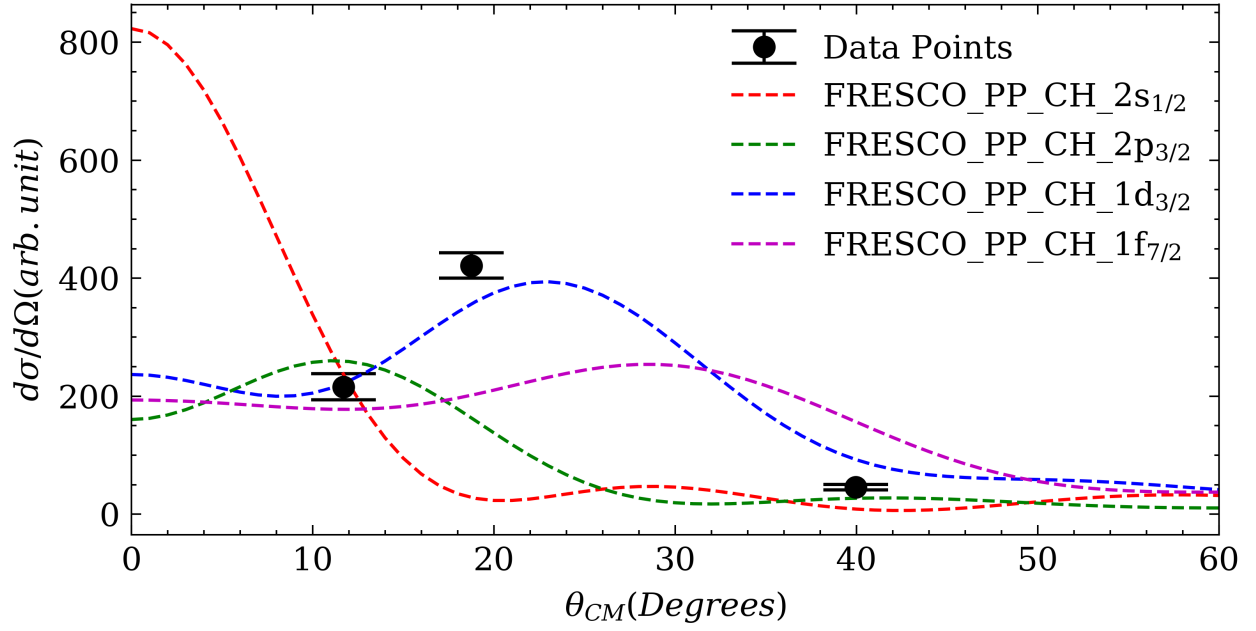


Figure 5.19: Angular distribution of the 6496-keV states populated via the $^{30}\text{P}(d, p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dashed red, green, blue and magenta lines are from DWBA calculations for s-, p-, d-, and f-waves.

Table 5.6: Individual contribution of 6399-keV, 6496-keV, 6501-keV and 6594-keV states

E_x (keV)	Shell	Contribution (%)
6399	$1f_{7/2}$	17
6496	$2s_{1/2}1d_{3/2}$ mixture	13
6501	$1f_{7/2}$	19
6594	$2p_{3/2}1f_{7/2}$ mixture	51

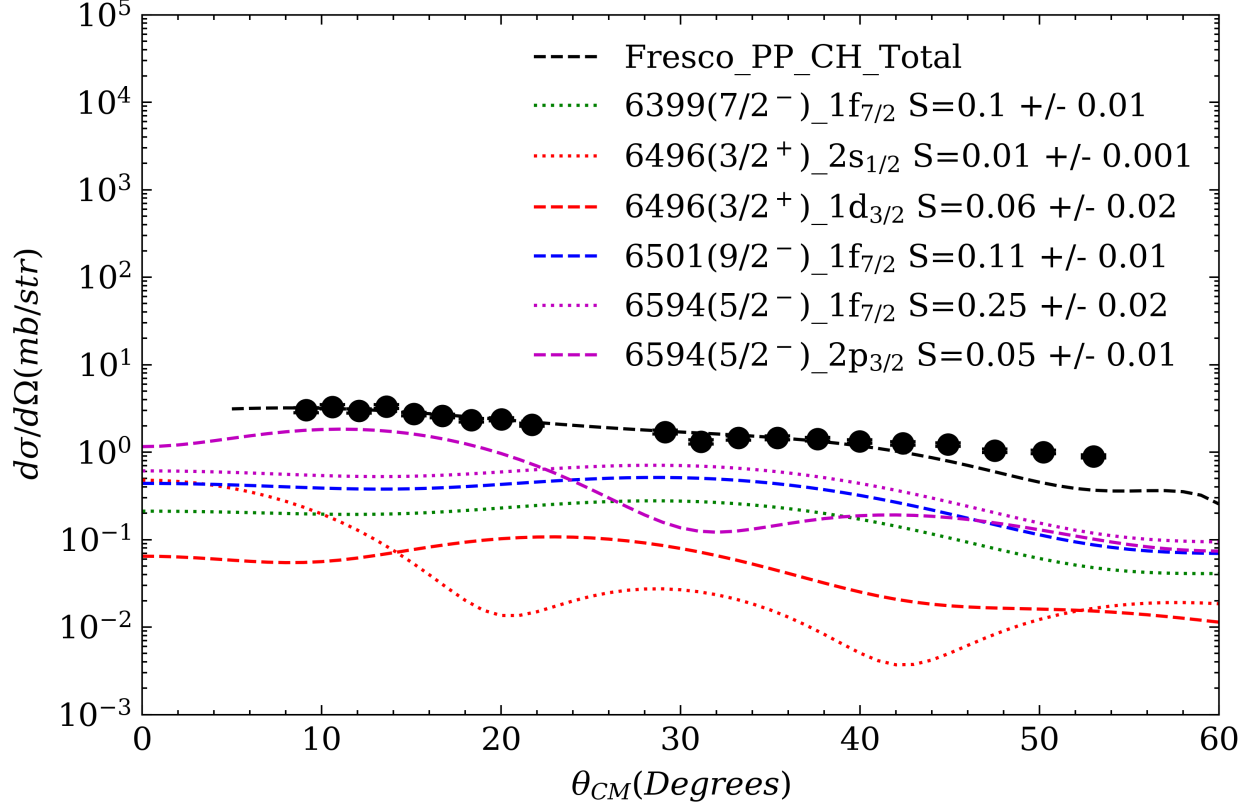


Figure 5.20: Differential cross-section populated of the 6399-keV, 6496-keV, 6501-keV and 6599-keV states populated via the $^{30}\text{P}(d,p)^{31}\text{P}^*$ reaction in the center-of-mass frame. The black points are experimental data with statistical error bars, the dotted green, dotted red, dashed red, dashed blue, dotted magenta and dashed magenta lines are from DWBA calculations for 6399-keV f-wave, 6496-keV s-wave, 6496-keV d-wave, 6501-keV f-wave, 6594-keV f-wave, and 6594-keV p-wave and the dashed black line represents the total. 6399-keV and 6501-keV states are definite f-waves with spectroscopic factors 0.10 ± 0.01 , and 0.11 ± 0.01 respectively. The spectroscopic factors for 6496-keV s-wave and 6496-keV d-wave are 0.01 ± 0.001 and 0.06 ± 0.02 . The spectroscopic factors for 6594-keV f-wave and 6594-keV p-wave are 0.25 ± 0.02 and 0.05 ± 0.01 . The error bars represent uncertainties from the fitting procedure weighted by statistical uncertainties.

Table 5.7: Spectroscopic factors of the states populated in the ^{31}P nucleus following the $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction measurement. The errors represent uncertainties from the fitting procedure weighted by statistical uncertainties. The spectroscopic factors for 5015-keV state were not resolved for s- and d-waves because of low γ -ray yields.

State	J^π (11)	Shell	Extracted S
gs	$1/2^+$	$2s_{1/2}$	0.52 ± 0.01
1266 keV	$3/2^+$	$2s_{1/2}$	0.04 ± 0.01
		$1d_{3/2}$	0.09 ± 0.01
2234 keV	$5/2^+$	$1d_{3/2}$	0.40 ± 0.01
3134 keV	$1/2^+$	$2s_{1/2}$	0.20 ± 0.08
		$1d_{3/2}$	0.39 ± 0.09
3295 keV	$5/2^+$	$1d_{3/2}$	0.31 ± 0.03
3506 keV	$3/2^+$	$2s_{1/2}$	0.03 ± 0.04
		$1d_{3/2}$	0.3 ± 0.05
4190 keV	$5/2^+$	$1d_{3/2}$	0.07 ± 0.01
4260 keV	$3/2^+$	$2s_{1/2}$	0.04 ± 0.02
		$1d_{3/2}$	0.47 ± 0.04
5015 keV	$3/2^+$	$2s_{1/2}$ and $1d_{3/2}$	-
5116 keV	$5/2^+$	$1d_{3/2}$	0.04 ± 0.003
5256 keV	$1/2^+$	$2s_{1/2}$	0.08 ± 0.01
		$1d_{3/2}$	0.001 ± 0.01
5672 keV	$5/2^-$	$2p_{3/2}$	0.02 ± 0.001
		$1f_{7/2}$	0.77 ± 0.07
6399 keV	$7/2^-$	$1f_{7/2}$	0.1 ± 0.01
6496 keV	$3/2^+$	$2s_{1/2}$	0.01 ± 0.001
		$1d_{3/2}$	0.06 ± 0.02
6501 keV	$9/2^-$	$1f_{7/2}$	0.11 ± 0.01
6594 keV	$5/2^-$	$2p_{3/2}$	0.05 ± 0.01
		$1f_{7/2}$	0.25 ± 0.02

5.6 Mirror Symmetry

The ^{31}S mirror assignments of the 6399-keV, 6496-keV, 6501-keV and 6594-keV states in ^{31}P were performed based on the γ -decay branches of these states. These branches were compared to the ones observed in previous studies by Doherty *et al.*(8) and Kankainen *et al.*(9).

5.6.1 Mirror of 6399-keV state

In the present ^{31}P spectroscopic study, the $7/2^-$ state at 6399 keV decays to $7/2^-$ state at 4431 keV, which subsequently decays to $5/2^+$ state at 3295 keV and $5/2^+$ state at 2234 keV as shown in Figure 5.1. Based on the strong transition from $7/2^-$ state at 6160 keV to $7/2^-$ state at 4450 keV in ^{31}S , which subsequently decays to $5/2^+$ state at 3284 keV and $5/2^+$ state at 2234 keV, 6160-keV state in ^{31}S was assigned as the mirror of 6399-keV state in ^{31}P . This agrees with the mirror assignments performed by Doherty *et al.*. Kankainen *et al.* reported $S(l = 3) = 0.036 \pm 0.013$ for this state, which is ~ 2.5 times smaller than the spectroscopic factor reported in the present study.

5.6.2 Mirror of 6501-keV state

In this study, the $9/2^-$ state at 6501 keV decays to the $7/2^-$ state at 4431 keV, which subsequently decays to $5/2^+$ state at 3295 keV and $5/2^+$ state at 2234 keV as shown in Figure 5.1. Based on the transition from $9/2^-$ state at 6377 keV to $7/2^-$ state at 4450 keV in ^{31}S , which subsequently decays to $5/2^+$ state at 3284 keV and $5/2^+$ state at 2234 keV, 6377-keV state in ^{31}S was assigned as the mirror of 6501-keV state in ^{31}P . This agrees with the mirror assignments performed by Doherty *et al.* and Kankainen *et al.*. The spectroscopic factor obtained from the present study is $S(l = 3) = 0.11 \pm 0.01$, and Kankainen *et al.* reported $S(l = 3) = 0.051 \pm 0.017$ for this state, which is ~ 2 times smaller than the spectroscopic factor reported in the present study.

5.6.3 Mirror of 6594-keV state

The $5/2^-$ state at 6594 keV predominantly decays to $3/2^+$ state at 1266 keV as shown in Figure 5.1. Based on the transition from $5/2^-$ state at 6357 keV to $3/2^+$ state at 1248 keV in ^{31}S , 6357-keV state in ^{31}S was assigned as the mirror of 6594-keV state in ^{31}P . This agrees with the mirror assignments performed by Doherty *et al.*, and Kankainen *et al.* reported an upper limit of 0.011 for $l=1$. The spectroscopic factor obtained from the present study is $S(l=3)=0.25 \pm 0.02$. The high spectroscopic factor associated with a $l=3$ transfer is in agreement with the shell model prediction by Brown *et al.* (35).

5.6.4 Mirror of 6496-keV state

In this study, the 6496-keV state directly decays to the $1/2^+$ ground state as shown in Figure 5.1. The study by Doherty *et al.* assigns the 6327-keV state as its mirror in ^{31}S . Their study observed 5078-keV γ -ray transition from the 6327-keV state to the 1248-keV state in ^{31}S . Based on the γ -ray angular distribution of 5078-keV transition, they assigned $J=3/2$ for the 6327-keV state. Because of lack of a positive parity state in its mirror, ^{31}P , they assigned $J^\pi=3/2^-$ for the 6327-keV state in ^{31}S , and 6496-keV state in ^{31}P . The $^{32}\text{S}(d,t)^{31}\text{S}$ measurement by Irvine *et al.* adopts this spin and parity assignment (43). The $^{31}\text{P}(^3\text{He},t)^{31}\text{S}$ measurement by Wrede *et al.* also assigned $J^\pi=3/2^-$ for the 6327-keV state in ^{31}S based on nearby mirror states in ^{31}P (37).

The angular distribution of tritons obtained from the $^{31}\text{P}(^3\text{He},t)^{31}\text{S}$ measurement by Parikh *et al.* suggests $J^\pi=1/2^+$ for the 6329-keV state and $J^\pi=3/2^+$ for the 6356-keV state as shown in Figure 5.21 (15). Furthermore, the ^{31}Cl β -decay measurement by Bennett *et al.* suggests $J^\pi=3/2^+$ for 6390-keV state in ^{31}S (39). In this study, we extracted a positive parity for the 6496-keV state in ^{31}P . Because of the evidence of positive parity states in this measurement, and studies by Parikh *et al.* (15), and Bennett *et al.* (39), the negative parity assigned by Doherty *et al.* (8), Irvine *et al.* (43), and Wrede *et al.* (37) can be questioned.

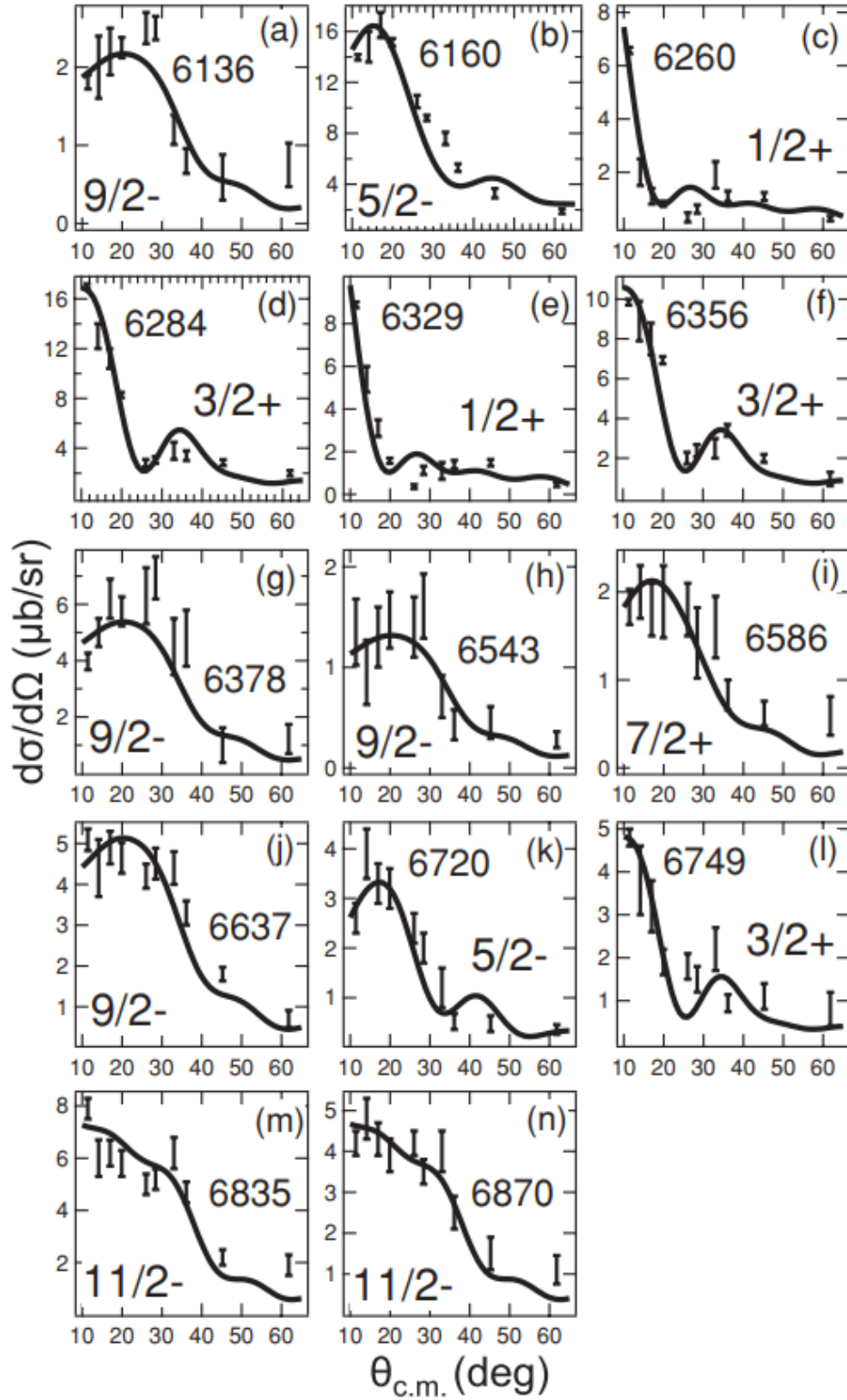


Figure 5.21: Angular distribution of tritons measured with $^{31}\text{P}(^3\text{He},t)^{31}\text{S}$ reaction by Parikh *et al.* (15).

Furthermore, the study by Doherty *et al.* (8) observed a 5078-keV γ -ray transition from the 6327-keV state to the 1248-keV state in ^{31}S . This transition was not observed in the study by Kankainen *et al.*. Instead, they observed the 6327-keV transition to the ground state. No measurement has seen both γ -ray transitions, and there is no information about the branching ratios. The assumption that these two γ rays are the transitioning γ rays from the same state at 6327 keV can also be questioned.

There have been a number of recent complementary experiments performed aiming to better constrain the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ rate, the preliminary results of which will be consulted to further guide the interpretation of the $^{31}\text{S}/^{31}\text{P}$ mirror systems. A follow-up experiment was performed at the NSCL (44), using the newly commissioned GADGET detector to reduce backgrounds and increase sensitivity to proton branches in states populated through beta decay. They measured a very weak proton branching ratio $8.3(1.0)\text{e-6}$ for the 260-keV resonance. Because the lifetime and gamma width of this resonance is not known, the absolute width is not experimentally constrained, so a total width was obtained using shell model calculations for the gamma widths. The lack of observation of the mirror to this state in the $^{30}\text{P}(d,p\gamma)^{31}\text{P}$ experiment can be used to place upper limits on the spectroscopic factors, and hence absolute proton width.

A more recent fusion evaporation experiment has been performed at ATLAS using GRETINA and the FMA to study γ -decay branches from ^{31}S states. Unlike the previous experiment (8) this experiment did not require γ - γ coincidences, so should be sensitive to the ground state branches that were missing from the previous experiment. These data will help confirm mirror assignments between the $^{31}\text{S}/^{31}\text{P}$ systems. Finally, a $^{28}\text{Si}(^6\text{Li},t)^{31}\text{S}^*(p)$ experiment has recently been performed using the Enge split-pole spectrometer at Florida State University, in which decay protons were detected in the Silicon Array for Branching Ratio Experiments (SABRE). Though this experiment did not see decay branches below about 500-keV resonance energy, the angular distributions and decay branches from the higher lying resonances will provide another test of spin assignments of ^{31}S states, which can

be used to constrain ^{31}P mirror assignments. However, in this dissertation, we calculated the resonance properties, and $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate by assuming the ^{31}S mirror state of 6496-keV state in ^{31}P in two cases: the 6327-keV state and the 6390-keV state.

The $^{31}\text{P}/^{31}\text{S}$ mirror assignments are shown in Figure 5.22. The resonance energies of these states were calculated by subtracting the proton separation energy from the excitation energies. The spectroscopic factors for these resonances in ^{31}S were assigned assuming the scaling from the spectroscopic factors in ^{31}P to be 1. The spectroscopic factors from the present study, and the study by Kankainen *et al.* are listed in Table 5.8.

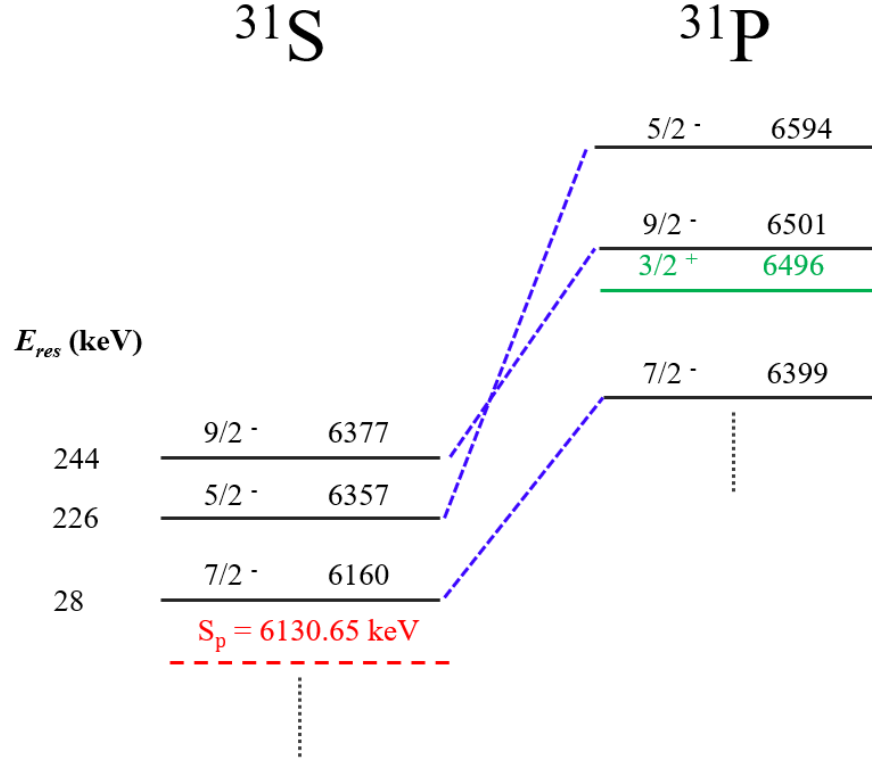


Figure 5.22: $^{31}\text{P}/^{31}\text{S}$ mirror assignments in the excitation energy range of astrophysical interest following the $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ reaction measurement. The ^{31}S mirror of $3/2^+$ 6496-keV state in ^{31}P is not finalized yet, and we calculated the resonance properties, and $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate by assuming the ^{31}S mirror state of 6496-keV state in ^{31}P in two extremes: 6327-keV state and 6390-keV state. All energies are in keV.

Table 5.8: Spectroscopic factors of the four resonances affecting the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate. The errors represent uncertainties from the fitting procedure of spectroscopic factors extraction.

$^{31}\text{P } E_x$ (keV)	$^{31}\text{S } E_x$ (keV)	E_{res} (keV)	J^π (11)	Shell	Kankainen <i>et al.</i> S (9)	Extracted S
6399	6160.2	27.6	$7/2^-$	$1f_{7/2}$	0.036 ± 0.013	0.1 ± 0.01
6496	6326.8-6390.4	196.15-259.7	$3/2^+$	$2s_{1/2}$ $1d_{3/2}$	0.023 ± 0.012 for $2p_{3/2}$	0.01 ± 0.001 0.06 ± 0.02
6594	6357.0	226.41	$5/2^-$	$2p_{3/2}$ $1f_{7/2}$	≤ 0.011 -	0.05 ± 0.01 0.25 ± 0.02
6501	6375.6	244.9	$9/2^-$	$1f_{7/2}$	0.051 ± 0.017	0.11 ± 0.01

Chapter 6

Conclusion

The $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction acts as a bottleneck for classical nova nucleosynthesis beyond $A=30$ in ONe novae. Also, the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate directly affects the isotopic ratio of $^{30}\text{Si}/^{28}\text{Si}$, which is an important nova identifier in the analysis of pre-solar grains. To use the elemental ratios of O/S, S/Al, O/P and P/Al as nuclear thermometers for classical novae, the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate needs to be constrained. Because of the unfeasibility of the direct measurement of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction at relevant astrophysical energies, an indirect method was used which measured the $^{30}\text{P}(d, p\gamma)^{31}\text{P}$ transfer reaction with a radioactive ^{30}P beam at 8 MeV/A at Argonne National Laboratory using the newly commissioned GODDESS system.

Several γ -ray transitions in the ^{31}P level scheme were confirmed in this study. The negative parity assignment of the 5672-keV state is among several important results from this work. For the first time, this study observed an $l=3$ transfer with a very high spectroscopic factor as predicted by the shell model calculation by Brown *et al.* (35). The most important result is the observation of $3/2+$ 6496-keV state in ^{31}P . Apart from this, we observed 3 other states in the astrophysically important region. The single-proton spectroscopic structure and resonance structure of these astrophysically important resonances in ^{31}S were constrained via mirror symmetry.

6.1 Resonant Reaction Rate

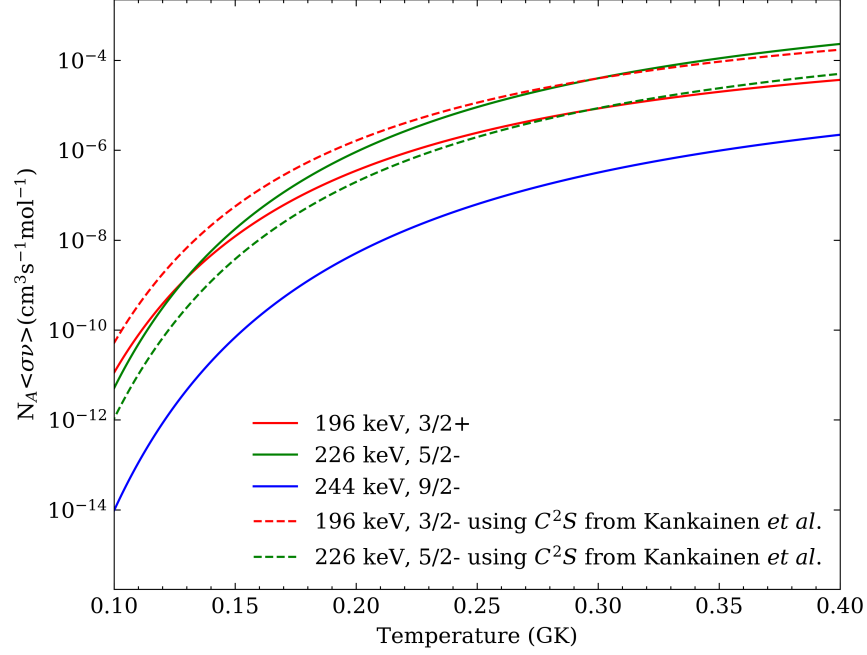
As discussed in the Section 2.4, the resonance strengths of low-lying, narrow and isolated resonances can be constrained from the single-particle widths, and the spectroscopic factors. The single-particle widths for the four resonances were constrained using R-matrix calculations, and the spectroscopic factors extracted in this work, the reaction rates over the relevant temperature for the ONe novae were extracted as shown in Figure 6.1.

The reaction rate for the individual resonances is higher than those reported by Kankainen *et al.* (9) because of higher spectroscopic factors extracted in this work. The $9/2^-$ 244-keV resonance has a very small contribution to the reaction rate as shown in Figure 6.1. If we assume that the $3/2^+$ 6496-keV state in ^{31}P corresponds to 196-keV resonance in ^{31}S , this resonance does not dominate the reaction rate in lower temperature region as reported by Kankainen *et al.* as shown in Figure 6.1a. However, if we assume that the $3/2^+$ 6496-keV state in ^{31}P corresponds to the 260-keV resonance in ^{31}S , this resonance will dominate the reaction rate in the higher temperature region as shown in Figure 6.1b. To precisely constrain the reaction rate, the assignment of the ^{31}S mirror corresponding to the $3/2^+$ 6496-keV state in ^{31}P is critical. We are currently working to make this mirror assignment.

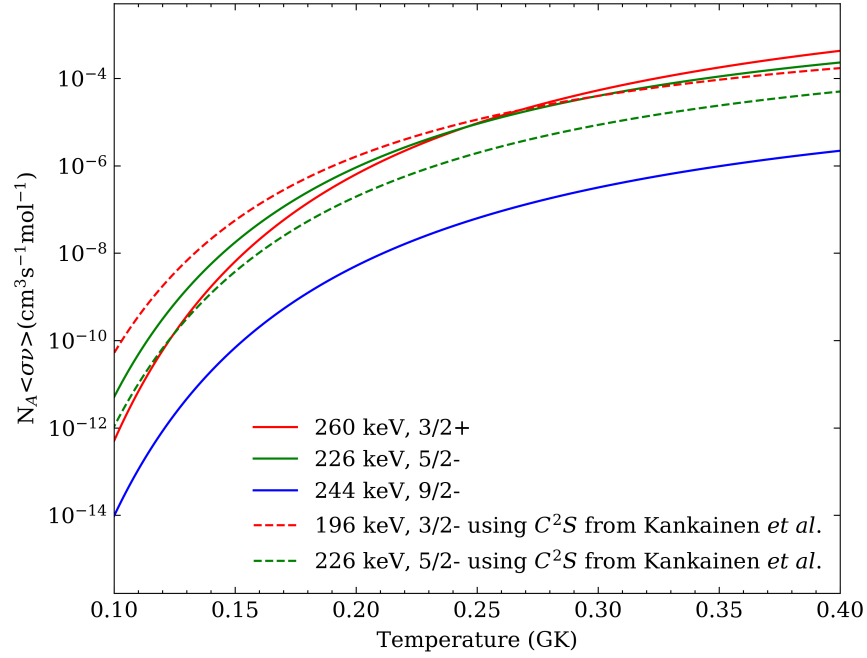
6.2 Future Work Before Publication

6.2.1 GRETINA Efficiency Simulation

GRETINA efficiency calculations, discussed in Section 5.5, were used to extract the spectroscopic factors of different states. The efficiency calibration, performed with a ^{56}Co γ -ray source, which has no photo-peaks above 3.5 MeV. The accuracy of the efficiency fit function in the higher γ -ray energy is being tested using a Geant4 simulation named UCGretina(45).



(a)



(b)

Figure 6.1: Resonant reaction rate as a function of temperature for astrophysically important resonances. Dashed red, and green lines are adopted from the study by Kankainen *et al.*(9). (a) Reaction rate assuming that the 3/2+ 6496-keV state in ^{31}P corresponds to 196-keV resonance in ^{31}S . (b) Reaction rate assuming that the 3/2+ 6496-keV state in ^{31}P corresponds to 260-keV resonance in ^{31}S .

6.2.2 Differential Cross Section

The differential cross sections, and the spectroscopic factors were extracted using the Distorted Wave Born Approximation (DWBA) calculations. To account for the deuteron breakup, DWBA calculations are not adequate. Adiabatic Wave Approximation (ADWA) calculations are being performed with appropriate optical potentials. Except for that, different possibilities of angular momentum transfers are also being considered while extracting the spectroscopic factors.

6.2.3 Mirror Symmetry

The assignment of ^{31}S mirror corresponding to the $3/2^+$ 6496-keV state in ^{31}P , and three other resonances are critical to constrain the reaction rate. There have been a number of recent complementary experiments performed aiming to better constrain the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ rate, the preliminary results of which will be consulted to further guide the interpretation of the $^{31}\text{S}/^{31}\text{P}$ mirror systems. The spectroscopic factors for the mirror states in the ^{31}S will be calculated using the shell model embedded in the continuum (SMEC) formalism. Currently, the spectroscopic factors for the mirror states are assigned without scaling the spectroscopic factors.

6.2.4 Resonant Reaction Rate

After precise calculations of the resonance properties, the resonant reaction rate for individual resonances will be calculated and compared with the previous measurements.

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