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<td>Degree</td>
<td>博士 (学術)</td>
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<td>Date of Degree</td>
<td>2012-09-25</td>
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<td>Resource Type</td>
<td>Thesis or Dissertation / 学位論文</td>
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<td>Report Number</td>
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<td><a href="http://www.lib.kobe-u.ac.jp/handle_kernel/D1005640">http://www.lib.kobe-u.ac.jp/handle_kernel/D1005640</a></td>
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Create Date: 2017-12-20
Doctoral Dissertation

Charge state distribution of $^{16}\text{O}$ from $^4\text{He} \left(^{12}\text{C},^{16}\text{O}\right) \gamma$ of astrophysical interest

July 2012

Graduate School of Science, Kobe University

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Abstract

In nuclear astrophysics, the fusion reaction $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ takes place in helium burning phase, where $^{12}\text{C}$ is produced by the $3\alpha$ process. The reaction rate of $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ at the relevant Gamow peak, $(E_0=0.3 \text{ MeV for } T=2\times10^8 \text{K})$, determines the abundances of carbon and oxygen at the end of helium burning. This, in turn, strongly influences the nucleosynthesis of elements up to the iron ion and evolution of star, such as supernova explosion and white dwarf creation. Thus, $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ plays an important role in helium burning phase.

At present, cross section of $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ at stellar energy is unknown precisely. In order to obtain the total recoil oxygen yield in laboratory, charge state fractions of recoil oxygen through helium gas have to be understood. However, energetic oxygen ions traversing a helium gas undergo a series of electron capture and loss. For sufficiently thick helium gas, a large number of collisions must occur for the ion to establish an equilibrium charge state distribution. For a thin helium gas, charge state fractions take a non-equilibrium distribution due to insufficient collision. Thus, we perform the experimental measurement and theoretical calculation to obtain the charge state fraction of recoil oxygen.

Firstly, we performed measurements in the charge-state distribution for $^{16}\text{O}$ ion in helium gas with energies of 7.2 MeV, 4.5 MeV and 3.45 MeV. Charge state distributions (CSDs) in equilibrium distribution are obtained. Experimental result show Gaussian distribution, and semi-empirical formulas are applied to fit mean charge state and distribution width. Thus, the evolutions of charge state fractions against projectile energy are plotted using Gaussian distribution.

Furthermore, we calculate the equilibrium charge state distribution in theory. Ionization cross section and capture cross section in ion-atom collision are calculation by plane wave born approximation and continuum distorted wave approximation, respectively. Evolutions of charge state fractions against target thickness are simulated. In equilibrium distribution, we compare theoretical results with experimental data. After correction with density effect, theoretical results agree with experimental data.
In order to obtain the CSD of recoil oxygen in $^4\text{He}$, we simulate the CSD evolution of recoil oxygen created in $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$. Several electron assumptions are suggested to determine the initial charge state of recoil oxygen just after the fusion reaction. The simulation provides good agreement with experimental data, and suggests that recoil oxygen ions only contain the electrons from the carbon. Finally, charge state non-equilibrium distribution of recoil oxygen in helium gas is simulated under assumption of without electron capture. Taking into account these non-equilibrium distributions, we estimate charge fraction of recoil oxygen at measured energies ($E_{\text{cm}}=2.4, 1.5, 1.15$ MeV) under various capture assumptions. It is first to perform estimation of charge fraction of recoil oxygen using cross section of charge exchange. With these results, cross sections of fusion reaction can be measured precisely.
Chapter 1 Introduction

The origin of the chemical elements has long been a grand challenge for astrophysics. Hydrogen and helium elements were produced in the early stage of the Big Bang. All other elements are produced in various kinds of stellar processes. Nuclear reaction in nuclear astrophysics influences nucleosynthesis and evolution of star. In helium burning phase, \(^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma\) reaction has a large significance to understand these processes.

The nuclear reaction \(^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma\) takes place in helium burning after \(3\alpha\rightarrow^{12}\text{C}\) reaction. The abundance ratio of \(^{12}\text{C}/^{16}\text{O}\) in the end of helium burning affects later stages of evolutions of stars and nucleosynthesis. Therefore knowledge of the reaction rates of \(3\alpha\rightarrow^{12}\text{C}\) and \(4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma\) is very important because the abundance ratio \(^{12}\text{C}/^{16}\text{O}\) is determined by two reactions. The reaction rate of \(3\alpha\rightarrow^{12}\text{C}\) is known 15% accuracy. However, the reaction rate of \(4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma\) has not been precisely known yet. Thus experimental determination of \(4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma\) reaction cross section is very important in astrophysics. The efforts have been done in order to obtain the cross section by measuring recoil \(^{16}\text{O}\) produced from \(4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma\) reaction at the Kyushu University Tandem Laboratory for 18 years. In experiment, recoil \(^{16}\text{O}\) pass through target and charge state of \(^{16}\text{O}\) ions show a distribution as a result of electron capture and loss in the collisions with the target atoms. Since the cross section is very small and signal to background ratio is as small as \(10^{-18}\), only one charge state of recoil oxygen could be measured. Therefore, to determine cross section with precision of 10%, the charge state distribution of recoil oxygen must be known.
1.1 Nuclear reaction in stars

1.1.1 Nuclear reaction rate in astrophysics and nuclear reaction in laboratory

The goal of nuclear astrophysics is to evaluate reaction rate relevant to stellar environment, by use of theoretical or experimental methods. Astrophysical reaction rate of a nuclear reaction depends on both the cross section and the number of particle encounters in a star. Therefore, reaction rate include information from both nuclear physics (the cross section $\sigma$) and stellar models (the stellar density and temperature). Considering encounter of two particles $i$ and $j$, the reaction rate is expressed as follows [1]:

$$ r_{ij} = \sigma N_i J_j $$  \hspace{1cm} \text{(1.1)}

where $\sigma$ is the energy dependent cross section, $N$ is the number density of particles per unit volume, and $J$ is the flux, $J_j = vN_j$, where $v$ is the relative velocity between particles $i$ and $j$, then,

$$ r_{ij} = \sigma vN_i N_j $$ \hspace{1cm} \text{(1.2)}

In a star the relative velocity is distributed in a Maxwell-Boltzmann distribution $\phi(v)$, with normalization $\int \phi(v)dv = 1$ and the total thermonuclear reaction rate is given by

$$ r_{ij} = N_i N_j \int v\sigma(v)\phi(v)dv = N_i N_j \langle \sigma v \rangle $$ \hspace{1cm} \text{(1.3)}

For identical particle, trivial correction should be taken into account so as to avoid double counting:

$$ r_{ii} = \frac{N_i N_j}{(1 + \delta_{ij})} \langle \sigma v \rangle $$ \hspace{1cm} \text{(1.4)}

Maxwell-Boltzmann distribution of velocity could be written as follows:

$$ \phi(v)dv = \left(\frac{u}{2\pi kT}\right)^{3/2} \exp(-uv^2 / 2kT)4\pi v^2 dv $$ \hspace{1cm} \text{(1.5)}

Equation 1.5 gives the probability that the relative velocity has a value between $v$ and $v+dv$. The Boltzmann constant is given by $k=8.6173 \times 10^{-5}$eV/K, $T$ is the temperature, and $u$ is
the reduced mass: \( u = \frac{m_i m_j}{m_i + m_j} \). With relations \( E = uv^2/2 \) and \( dE/dv = uv \), velocity distribution can be written as an energy distribution:

\[
\phi(v)dv = \phi(E)dE = \left(\frac{u}{2\pi kT}\right)^{3/2} e^{-E/kT} 4\pi \frac{2E}{u} \frac{dE}{u} \sqrt{\frac{u}{2E}}
\]

\[
= \frac{2}{\sqrt{\pi}} \frac{1}{(kT)^{3/2}} \sqrt{E} e^{-E/kT} dE
\]

For the reaction rate per particle we obtain:

\[
< \sigma v > = \int v\phi(v)\sigma(v)dv = \int v\phi(E)\sigma(E)dE
\]

\[
= \left(\frac{8}{\pi u}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int E\sigma(E)e^{-E/kT}dE
\]

The nuclear cross section was parameterized by Bethe and Gamow based on the general principles of quantum mechanics as (see appendix 1):

\[
\sigma(E) = \frac{S(E)}{E} \times e^{-2\pi\eta}
\]

where \( \eta \) is the Sommerfeld parameter: \( \eta = \frac{Z_i Z_f e^2}{\hbar v} \). \( S(E) \) is called “astrophysical S-factor”.

The astrophysical S-factor represents effects of intrinsic nuclear reaction and is determined experimentally.

Equation (1.8) is also expressed in terms of “Gamow energy” \( E_G \) as:

\[
\sigma(E) = \frac{S(E)}{E} \exp\left(-\left(\frac{E}{E_G}\right)^{1/2}\right)
\]

\[
E_G = (2\pi Z_i Z_f \alpha^2 \frac{\mu c^2}{2} \alpha = \frac{e^2}{hc}
\]

where \( \alpha \) is the fine structure constant. The reaction rate is rewritten by substituting equation (1.9) for the cross section:

\[
< \sigma v > = \left(\frac{8}{\pi u}\right)^{1/2} \frac{1}{u^{1/2} (kT)^{1/2}} \int S(E)\exp\left(-\frac{E}{kT}\right)\left(\frac{E}{E_G}\right)^{1/2}dE
\]

For the non-resonant reactions, \( S(E) \) is nearly constant. Assuming that \( S(E) \) is constant, the integrand has a sharp peak called “Gamow peak” at around the energy \( E_0 \), which is competitive result of both penetration factor and Maxwell-Boltzmann distribution, as shown in the figure 1.1:
\[ E_0 = \left( \frac{E_G^{1/2} kT}{2} \right)^{2/3} \]  \hspace{1cm} 1.11

We expand exponential function at \( E_0 \) and get:

\[ \exp(-\frac{E}{kT} - \frac{E_G^{1/2}}{E}) \approx \exp(-\frac{3E_0}{kT} - \frac{E - E_0}{\Delta E_0}) , \]  \hspace{1cm} 1.12

where, \( \Delta E_0 \) is the full width at half maximum of the Gamow peak,

\[ \Delta E_0 = \left( \frac{4}{3} kT E_0 \right)^{1/2} . \]

Hence:

\[ <\sigma v > = \frac{2}{\sqrt{\pi(kT)^3}} \Delta E_0 S(E_0) \exp\left(\frac{-3E_0}{kT}\right) \]  \hspace{1cm} 1.13

The energy dependence of the reaction rate is actually determined by the measurement of the cross section or S-factor in the laboratory.

![Gamow peak](image)

*Figure 1.1: Gamow peak comes from the competing results of penetration factor and Maxwell-Boltzmann factor. Two dashed lines are a Maxwell-Boltzmann factor and a penetration factor. [1]*

Next, we introduce elements abundance in stars and hydrogen and helium burning.

The existence and distribution of the chemical elements in cosmos is a consequence of nuclear processes. These processes have taken place in the Big Bang and subsequent thermonuclear reactions in stars and interstellar medium. Now, they are being studied theoretically, experimentally and observationally. Figure1.2 shows abundances of the chemical elements in the solar system. Hydrogen and helium were clearly far more abundant...
than any of the other elements. The mass of all the rest is less than 2% of the mass of the solar system. In the remaining stellar-produced elements, the abundance of element decreases with atomic number, when they have even or odd atomic numbers.

![Figure 1.2: Abundances of the chemical elements in the solar system. Hydrogen and helium are most common, from the Big Bang. The next three elements (Li, Be, B) are rare because they are poorly synthesized in the Big Bang and also in stars.][2]

Stellar nucleosynthesis occurs in stars during the process of stellar evolution and elements burning. Stars are the nuclear furnaces in which H and He are fused into heavier nuclei. It is responsible for the generation of elements from carbon to iron by nuclear fusion processes, which occurs by proton-proton chain in stars cooler than the Sun (figure 1.3), and by the CNO cycle in stars more massive than the Sun (figure 1.4). In pp chain, branch pp I takes place with a frequency of 86%. The remainder of the time one has the ppII and ppIII branches, with associated neutrino losses. One notes that the neutrinos released in pep reaction (figure 1.4) are far more energetic than in pp chain. Hydrogen burning starts at 10^7 K temperature at central region. The lifetime of a star is determined by star mass. For massive stars roughly 90% of their lifetime is spent in the hydrogen burning and lest in helium burning [3].
Figure 1.3: Overview of the proton-proton chain reaction sequence [4]

Figure 1.4: Overview of the CNO-I, II, III cycle. The helium nucleus is released in three cycles [4].

CNO-I: $^{12}\text{C} \rightarrow ^{13}\text{N} \rightarrow ^{13}\text{C} \rightarrow ^{14}\text{N} \rightarrow ^{15}\text{O} \rightarrow ^{15}\text{N} \rightarrow ^{12}\text{C}$

CNO-II: $^{15}\text{N} \rightarrow ^{16}\text{O} \rightarrow ^{17}\text{F} \rightarrow ^{17}\text{O} \rightarrow ^{14}\text{N} \rightarrow ^{15}\text{O} \rightarrow ^{15}\text{N}$

CNO-III: $^{17}\text{O} \rightarrow ^{18}\text{F} \rightarrow ^{18}\text{O} \rightarrow ^{15}\text{N} \rightarrow ^{16}\text{O} \rightarrow ^{17}\text{F} \rightarrow ^{17}\text{O}$
When hydrogen in a stellar core burns out, core contraction of star causes the temperature and density to increase further. When temperature is high up to $2 \times 10^8$ K and density reaches to $10^2$ to $10^4$ g/cm$^3$, helium burning takes place. Figure 1.5 shows the process of helium burning from helium to $^{20}$Ne creation. In the helium-burning phase, there are two important nuclear reactions: the $3\alpha$ reaction and the subsequent $^4$He($^{12}$C, $^{16}$O)$\gamma$ reaction. The ratio of these two reaction rates determines the $^{12}$C/$^{16}$O ratio after helium burning and consequently both the amounts of $^{12}$C and $^{16}$O, and of the heavier nuclides built from these nuclei.

![Diagram of Helium Burning Processes](image)

*Figure 1.5: Helium burning processes stop at $^{20}$Ne creation, there are two important reactions: $3\alpha$ reaction and $\alpha + ^{12}$C reaction [4]*

### 1.1.2 $^{12}$C/$^{16}$O ratio and $^4$He($^{12}$C, $^{16}$O)$\gamma$ reaction

In process of helium burning, the star is red giant. The further evolution of the star is influence by the ratio of carbon to oxygen ($^{12}$C/$^{16}$O), which could result in different iron core masses before the beginning of the final supernova collapse and explosion. In turn, the different iron core affects the relative probabilities of different types of supernova remnants. For instance, if $3\alpha \rightarrow ^{12}$C reaction rate is much faster than $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate, then no $^{16}$O is produced in helium burning. If it is the other way, no $^{12}$C is produced.
Figure 1.6: Burning phases of each nucleus and onion-like structure of a 25 solar masses star prior to its supernova explosion. [4-6]

Figure 1.6 shows the nucleus burning states and onion like structure of star in 25 solar masses star. The core of star is Fe nucleus and outer layer is enveloped by hydrogen nucleus in a 25 solar masses star. Studies in thermonuclear element burning indicate that if the mass fraction of $^{12}\text{C}$ at the end of helium burning is smaller than around 15% of its original fraction [7], then carbon burning and neon burning will not take place. As a result, the star will directly go to the oxygen burning. Furthermore, the neon burning as a function of the S-factor for $^{4}\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction is simulated in a 25 solar masses star[7]. Several assumptions of $^{4}\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction rate are suggested to simulate product of $^{20}\text{Ne}$. The results reveal that the star will not produce $^{20}\text{Ne}$ if the cross section of the $^{4}\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction is twice as large as the suggested value [8,9]. As a result, the carbon burning essentially stopped. These oxygen rich stars and carbon rich stars will be created, which may lead to collapse into a black hole and leave behind a neutron star, respectively [7].

Thus, the relative amounts of carbon and oxygen at helium burning play an important role of the initial conditions for the next phase element burning and star evolution. In burning processes, heavier elements up to Fe are synthesized. The abundances of elements, and evolution of massive stars such as supernovae explosion, critically depend on $^{4}\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction rate.

Therefore, we have to know the ratio of $^{12}\text{C}/^{16}\text{O}$ at the end of helium burning (within 10% precision) to understand evolution of star and the heavy nucleosynthesis.
1.1.3 S-factor measurement of $^4$He($^{12}$C, $^{16}$O)$\gamma$ reaction in the Laboratory

Reaction rate is mainly determined by the value of the cross section (or S factor) at the thermonuclear stellar energy ($E_0$). Helium burning temperature occurs at $2 \times 10^8 \, K$. According to equation 1.11, the energy at Gamow peak is calculated to be $E_0 \pm \Delta E_0/2 = 315 \pm 43 \, KeV$. Thus, $^4$He($^{12}$C, $^{16}$O)$\gamma$ reaction takes place nearly around 300 KeV in stars.

Astrophysical S-factor are nearly constant around the stellar energy in most other cases in nuclear astrophysics, therefore the S-factor can be extrapolated from higher energy in laboratory.

However, $^4$He($^{12}$C, $^{16}$O)$\gamma$ reaction exits in the different situation. In figure 1.7, an energy level diagram of oxygen is displayed along with S-factor of $^4$He($^{12}$C, $^{16}$O)$\gamma$. The S-factor value near stellar energy changes rapidly. This effect is a consequence of resonant capture at different oxygen energy level. In astrophysics, the relevant reaction rates are governed by a resonant nuclear state in many cases, which can contribute significantly to the reaction rate at low energies. Several important resonant reactions occur at 1$^-$ state (9.585 MeV), 1$^-$ state (7.117 MeV) and 2$^+$ state (6.917 MeV). The reaction rates at 300keV are influenced by these resonant reactions. The contributions from the low energy tail of the broad 9.585 MeV(1$^-$ state) resonance are few. But the high energy tails of two sub-threshold resonances at 7.117 MeV (1$^-$ state) and 6.917 MeV (2$^+$ state) influence the reaction rate strongly. Present measurements of reaction rate cannot be extended to such low energies (~300keV) due to existence of strong Coulomb barriers (around 3.1 MeV). Extrapolations to the stellar energy region from high energy region might become possible. Therefore, experiments at really low energy are desirable in order to obtain reliable extrapolation cross section.
1.2 KUTL measurement in $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reactions

The experimental efforts over the last decades were spent on the observation of the capture gamma rays, including one experiment that used the coincident detection of the $^{16}\text{O}$ recoils [12-20]. A major disadvantage of measuring gamma ray is the large background.

Due to the low cross section and various background sources, useful gamma ray data but still inadequate precision were limited to the energy range of $E_{cm}=1.0$ to 3.2 MeV in center of mass system. Because the efficiency for detecting a charged particle is in general higher than that of the $\gamma$ ray, it is possible that the excitation function will be extended down to 0.7 MeV by a detection of $^{16}\text{O}$ recoils.

At present, we have measured $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reactions successfully at $E_{cm}=2.4$ MeV and 1.5MeV, as marked with red points in figure 1.8. We plan to measure cross section at $E_{cm}=1.15$, 1.0, 0.85, and 0.7MeV, (the red lines in figure 1.8) so as to extrapolate result precisely to stellar energy 0.3MeV.
In our measurement, inverse kinetics is used and recoils oxygen is detected. Experimental facility is shown in figure 1.9. It is based on 10MV tandem accelerator, including sputtering ion source, beam line, acceleration tube, windowless gas target and recoil mass separator.

It is very difficult to perform the measurement at low energy due to Coulomb barrier existence. Reaction cross sections decrease rapidly. Figure 1.10 shows a decrease trend of cross section at low energy, which is estimated under an assumption of S-factor to be a constant. Therefore, reaction events become very rare at low energy. At 0.7MeV, the ratio of $^{16}\text{O} / ^{12}\text{C}$ is around $10^{-18}$. In order to reach the precision of 10%, we have to increase the reaction yield and reduce background. Some efforts have been made.

1. $^{12}\text{C}$ beam intensity. $^{12}\text{C}$ beam has been pulsed to make Time of Flight (TOF) measurement. At present, beam intensity is around 100nA. At low energy measurement (<1.0MeV), strong intensity is necessary. Therefore, one method of accel-decel strong focus operation has been developed [21]. Finally, about 100 times more intense beam (~10µA) can be accelerated by the accel-decel method.

2. Blow-in windowless gas target. Windowless gas target has been designed. For He gas target, it can realize high center pressure (up to 24 Torr) at room temperature, and sufficient thickness (>75 Torr·cm). [22]

3. Background Reduction. The ratio of signal (recoil $^{16}\text{O}$) to background particles (mainly $^{12}\text{C}$) should be as small as $10^{-18}$. In $^{4}\text{He}(^{12}\text{C},^{16}\text{O})\gamma$ reactions, background...
originates from scattered and sputtered $^{12}\text{C}$ ions generated by the $^{12}\text{C}$ beam hitting objects such as the target frame, beam pipes, magnet poles, and the ED electrode. We developed a recoil mass spectrometer (RMS) and Long time chopper to separate $^{16}\text{O}$ recoils from the $^{12}\text{C}$ beam. They can realize $10^{-16}$ level of reduction of background [23]. Recently, ion chamber is under development and expected to realize the reduction of $10^{2--3}$ further.

![Figure 1.9: Layout of Kyushu University Tandem Laboratory (KUTL)](image1)

![Figure 1.10: Cross section of $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reactions decrease rapidly at low energy. Under an assumption of S-factor to be a constant [1]](image2)
1.3 Charge state distribution of recoil oxygen

Recoil $^{16}$O ions in a selected charge state are counted at the end of the beam line. In order to obtain reaction cross section, one must know the total numbers of recoil particles.

Electromagnetic recoil mass separators in inverse kinematics are used to investigate nuclear reactions of astrophysical interest. In such apparatus, only one charge state of the heavy recoil product can be transmitted for a given separator setting. Thus, in order to determine the yield from a reaction accurately, the each charge state fraction must be known precisely. The fraction distribution depends on ion energy, thickness of target, initial projectile charge state, and combination of projectile and target.

Projectile with a specific charge state through target will shows the charge state distribution due to charge exchange (electron loss and electron capture). With the change of thickness of target, the charge state distribution (CSD) varies from non-equilibrium distribution to equilibrium distribution.

For instance, figure 1.11 shows the CSD evolution against the target thickness. When the thickness of target is smaller than $2.0 \times 10^{17}$ atoms/cm$^2$, it shows a non-equilibrium distribution. If the projectile travels further, it reaches an equilibrium distribution and charge state fractions remain the same.

![Figure 1.11: Charge state fractions as a function of target thickness for 7.2MeV $^{16}$O$^{1+}$ beam in helium. The curves are from simulation result.](image)

Figure 1.11: Charge state fractions as a function of target thickness for 7.2MeV $^{16}$O$^{1+}$ beam in helium. The curves are from simulation result.
In $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reactions, recoil oxygen present different charge state when coming out of gas target. Such CSD of the recoils depends on the location in the target where in the target they were created: those created toward the upstream end pass through the most gas, so they are the most likely to take equilibrium CSD. However, CSD of recoils created near the end of target takes non-equilibrium distribution, after through the remaining gas. Recoil ions in non-equilibrium distribution amount to a certain fraction of total recoils at our measured energy. This situation is illustrated in figure 1.12.

Therefore, the thesis’s work is to estimate the fraction of $^{16}\text{O}^{q+}$ by experiment and theoretical simulation precisely. Experimentally, we measure charge state distribution at 7.2, 4.5 and 3.45 MeV. Oxygen beam is injected to helium gas target with the sufficient thickness. Each charge state fraction is counted at the end of beam line. Theoretically, calculations are performed by considering the collision process of ion with an atom in order to reproduce the charge state distribution obtained by the experiment stated above. Relevant theories are used to calculate charge exchange cross section. On the other hand, for the non-equilibrium distribution, one model is used to simulate the fraction distribution evolution against target thickness. Several assumptions of electron capture from target are suggested to solve charge state of recoil oxygen just after fusion reaction. Finally, we estimate charge fraction of recoil oxygen at our measured energy ($E_{cm}=2.4$, 1.5 and 1.15 MeV).

![Figure 1.12: recoil oxygen created at geometrical location of target in $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction takes equilibrium distribution and non equilibrium distribution.](image)
Reference

[1] Hiroshi OBA, Kyushu University, 2007 Doctor thesis: Direct measurement of nuclear astrophysical reaction $^{4}$He($^{12}$C, $^{16}$O)$\gamma$ cross section near stellar temperature


Chapter 2 Theory of Charge exchange process

Charge-exchange of a projectile is the result of electron capture and loss processes which arise from the projectile and target atom collision. The studies of charge-exchange processes attracted a lot of attention, not only because they provide important information about atomic collision and other processes in complex atomic systems, but also because of the numerous requirements for practical uses, such as accelerators[1], positron-emission tomography[2], tumor treatment with heavy ion[3], and heavy-ion driven inertial fusion[4]. Especially with the availability of energetic beams of ions in different charge states from particle accelerators, the studies have been performed considerably, both theoretically and experimentally.

Experimentally, the charge state distribution mainly focused on heavy ion, such as Kr\(^+\), Xe\(^+\), Pb\(^+\), and U\(^+\), and C-foil and gas target, according to the accelerator demand [5-7]. Furthermore, cross sections of charge exchange have also been published [8, 9]. Some experimental techniques have been developed which give detailed insights into specific charge-exchange processes [10]. The observation of photons emitted in radiative electron capture is possible and coincidence techniques allow the measurement of differential electron capture cross sections [11, 12].

Theoretically, cross sections of change exchange can be calculated with some approximations [13-15]. However, the complexity of these atomic collision systems makes such theoretical predictions very unreliable, especially at middle and low energy. Several semi-empirical or empirical formula have been derived from experimental data, however, their application is usually limited to a certain domain, for example, a certain energy range, and certain projectile and target species[16,17].

The lack of an adequate theory requires a deep understanding of charge exchange before a sufficient and detailed investigation. Next, we give a description of charge exchange process and charge state distribution.
2.1 Description of Charge-exchange process

When energetic ions traverse over the matter, charge exchange between ion and matter atom takes place frequently due to ion-atom collision. Charge exchange mainly consists of following processes, as shown in figure 2.1:

1. Electron loss (ionization)

For electron loss by charge exchange, electron of energetic ion could be ionized through collision with target atom. In this process, projectile $Z^{q+}$ loses $m$ electrons and form $Z^{(q+m)+}$. The charge state of projectile increases by $m$, as follows:

$$Z^{q+} + A \rightarrow Z^{(q+m)+} + A^+ + me^- \quad m \geq 1 \quad 2.1$$

2. Electron capture.

When projectile $Z^{q+}$ captures $m$ electrons from target atom $A$, its charge state will decrease by $m$ and $Z^{(q-m)+}$ ions are created, as follows:

$$Z^{q+} + A \rightarrow Z^{(q-m)+} + A^{m+} \quad m \geq 1 \quad 2.2$$

Besides electron ionization and capture processes, electron excitation and de-excitation also happen in ion-atom collision, as follows

$$Z^{q+} + A \rightarrow Z^{q++} + A \quad 2.3$$

$$Z^{q++} + A \rightarrow Z^{q+} + A \quad 2.4$$

Furthermore, it should be noted electron in excited state may decay to ground state or be ionized by subsequent collision with target atom. This process occurs mainly in dense matter, such as solid target and high density gas target. It is called density effect. We will discuss it in theoretical calculation.
Charge changing processes can be described briefly by cross section $\sigma_{qq'}$ as

$$N_{q'} = N_q \cdot x \cdot \sigma_{qq'}$$  \hspace{1cm} (2.5)

where $N_q$ is the number of ions in charge state $q$ before the collision, $N_{q'}$ the number of ions that change to charge state $q'$ after the collision, and $\sigma_{qq'}$ is cross section for the change from charge state $q$ to $q'$, in unit of cm$^2$. The thickness of the target $x$, is the number of target atoms per cm$^2$ along the path of ion in the target. For a gas target, thickness using ideal gas law can be expressed as:

$$x = (N_A LP) / RT$$ \hspace{1cm} (2.6)

Where $N_A$ is Avogadro’s number, $L$ the length of the gas cell, $P$ is the gas pressure in the cell, $R$ is the gas constant, around 8.314(J/mol·K) and $T$ the temperature of the gas cell. For $T=25^\circ C$ (at room temperature):

$$x = 3.24 \times 10^{16} \cdot L(cm) \cdot P(Torr) \ [\text{atom} / \text{cm}^2]$$
2.2 Equilibrium charge state

In processes of charge exchange, charge states of projectile decrease or increase. Charge state fraction evolution $F_q(x)$ of projectile ions with a certain charge $q$ passing through a target ($x$ being the target thickness) can be solved by a set of differential equations [18].

$$\frac{dF_q}{dx} = \sum_{q'} F_{q'}(x) \sigma_{q'q} - F_q(x) \sum_{q'} \sigma_{qq'}$$  \hspace{1cm} 2.7

$$\sum_q F_q = 1$$  \hspace{1cm} 2.8

where $x$ is the penetration depth and $\sigma_{qq'}$ is the charge-changing cross sections from $q$ to $q'$. Charge change cross sections, including capture cross section and ionization cross section, are functions of the projectile species and velocity, and the target species

$$\sigma_{q,q'} = \sigma_{q,q'}(v, Z_p, Z_T)$$  \hspace{1cm} 2.9

where $v$ is the projectile velocity, and $Z_p, Z_T$ is the atomic number of projectile and target, respectively. With a complete set of cross section, equation 2.7 can be solved and charge state fractions vary from non-equilibrium to equilibrium distribution with target thickness. Target thickness thus is an important parameter in determining the charge state distribution. Especially in non-equilibrium distribution region, charge fractions charge rapidly with target thickness. From formula 2.6, target thickness is proportional to both target length and target pressure.

Because of the complexity of charge exchange, single electron effect as the simplest case is usually taken into account, which indicates capture and loss of single electron. The probability of multiple electrons changing in a single collision has generally been assumed to be very small and negligible. The ratio of $\sigma_{q,q-2}/\sigma_{q,q-1}$ amounts to less than ~8% for $^{14}$N and $^{16}$O ions at around 0.05MeV/u in hydrogen gas target [19]. And it is a general observation that the ratio decreases as the projectile energy increases. Also multiple electrons capture process with $n>2$ is only expected to occur when the target atoms contain at least more than
n electrons, which is impossible for hydrogen and helium gas target. Furthermore, multiple electrons capture was mainly observed at highly charge ions with slow velocity (~keV). Thus, one electron capture and ionization in oxygen-helium collision are main processes in comparison with the multiple electron process.

When projectiles pass through target in sufficient thickness and repeat a large number of collisions, charge state fractions can finally reach in equilibrium distribution. Thus charge state equilibrium distribution is established at $x \to \infty$, namely $dF_q/dx=0$. Under single electron change exchange assumption ($|q - q'| = 1$), equation 2.7 can be reduced to the following simple expression:

$$F_q \sigma_{q,q+1} - F_{q+1}\sigma_{q+1,q} = 0$$  \hspace{1cm} \text{2.10}

Equation 2.10 is equilibrium distribution expression. In equilibrium distribution, there are two useful parameters to describe the distribution feature: mean charge state $\bar{q}$, and distribution width $d$. The mean charge state is obtained from the measured charge state fractions:

$$\bar{q} = \sum_q qF_q$$  \hspace{1cm} \text{2.11}

where $q$ is the charge state of ion and $F_q$ is the charge state fraction. The distribution width $d$, can be calculated as follows:

$$d = \left[ \sum_q (q - \bar{q})^2 F_q \right]^{1/2}$$  \hspace{1cm} \text{2.12}

where $\bar{q}$ is the mean charge state, $q$ is the charge state and $F_q$ is the charge state fraction.

The mean charge state and distribution width are useful to predict the charge state fraction by Gaussian distribution formula.

Figure 2.2 shows the charge state fractions of carbon ions as a function of target thickness. When target thickness is small, charge state fractions change with target thickness, which is reflected on mean charge state and charge fraction difference. At (a) and (b) region, mean
charge states are 1.95 and 2.62, respectively. When target thickness is increased, starting at (c) the charge state distribution and mean charge does not change anymore since the target has reached a critical thickness and the charge state fractions have attained equilibrium [20]. If the target thickness is further increased, the measured charge fraction will remain the same distribution. Equilibrium charge state distributions are independent on the charge state of projectile.

As shown in figure 2.2, the charge state fractions show Gaussian distribution, which can be written in the Gaussian formula as:

\[
F_q = \frac{1}{d \sqrt{2\pi}} \exp\left[-\frac{(q - \bar{q})^2}{2d^2}\right],
\]

where \(q\) is the charge state, \(\bar{q}\) is the mean charge state and \(d\) is the distribution width. Since Gaussian can draw the charge state distribution then we could be able to predict the charge state fractions in equilibrium distribution. Based on equations 2.13, a reliable method to determine the distribution width \(d\) and the mean charge state \(\bar{q}\) is necessary. Thus, many works have been performed to build semi-empirical formulas with a large number of experimental data. Using these empirical formulas, the distribution width and mean charge state can be calculated. However, it should be noted that these semi-empirical formulas represent little physical background. They are obtained through a large number of data. Next, we briefly introduce the frequently cited empirical formulas.
Figure 2.2: Charge fractions as a function of target thickness for carbon through nitrogen gas. It shows non-equilibrium (a, b) and equilibrium (c) distribution. At (a), (b), and (c), mean charge state are 1.95, 2.62, and 2.75, respectively. At (c), corresponding to equilibrium distribution, mean charge state does not charge with target thickness [20].
2.3 Semi-empirical formula of equilibrium distribution

Schiwietz model [21]

In order to search for a more accurate scaling of the mean charge states, a multi-parameter least-square fit has been developed by Schiwietz et al., which is based on a large number of experimental data (about 840 experimental data points) as shown in figure 2.3. The expression is given as:

\[-q = Z_p \left[ \frac{8.29 x + x^4}{0.06 + 4 + 7.4x + x^4} \right]\] 2.14

where \(Z_p\) is the atomic number of projectile, and \(x\) is the scaling variable parameter, defined as:

\[x = c_1 (\tilde{v} / c_2 / 1.54)^{1+1.83/Z_p} \] 2.15

\[c_1 = 1 - 0.26 \exp \left[ -\frac{Z_T}{11} \right] \exp \left[ -\frac{(Z_T - Z_p)^2}{9} \right]\] 2.16

\[c_2 = 1 + 0.030 \tilde{v} \ln(Z_T)\] 2.17

\[\tilde{v} = Z^{-0.543} v / v_B\] 2.18

where \(Z_T\) is the atomic number of the target, and \(v_B\) is Bohr velocity.

For protons and helium ions this model is valid for the value of \(v / v_B\) above 2 and for all other ions, the ratio of \(v / v_B\) is above 0.4. It is found there are significant deviations at slower projectiles. Furthermore, it should be noted that resonance effects and shell-structure effects have been taken into account in this model.
Betz Model [22]

H.D Betz built empirical formula for mean charge state based on experimental data of fast ions ($Z_p \geq 10$, $5 \text{ MeV} < E < 80 \text{ MeV}$):

$$q = Z_p \left[ 1 - C \exp\left( -v / (v_B Z_p^\gamma) \right) \right]$$  \hspace{1cm} (2.19)

where, $Z_p$ is the atomic number of the projectile, $v$ is the projectile velocity, $v_B$ is the Bohr velocity and fitting parameters $C$ and $\gamma$ are determined empirically for each projectile and target combination. For gas target, $C \approx 1$ and $\gamma \approx 2/3$ gives a reasonable estimation of mean charge state.

At present, there are several semi-empirical formulas for distribution width $d$, but each of them is valid only within a certain domain. Dmitriev and Nikolaev estimated distribution width as follows [23]:

$$d = d_1 Z_p^w$$  \hspace{1cm} (2.20)

where parameter $d_1$ and $w$ have been determined semi-empirically to be 0.32 and 0.445 in nitrogen and argon gas, and be 0.38 and 0.40 in solids. Later, Dmitriev and Nikolaev developed a formula for solid targets as [24]:

Figure 2.3: Mean relative charge state in solid targets as a function of velocity scaling parameter $x$ [21].
\[
d = d_2 \left\{ \frac{q}{1 - \left( \frac{q}{Z_p} \right)^{1/k}} \right\}^{1/2}
\]

where, \(d_2\) and \(k\) were determined to be 0.5 and 0.6, respectively. This has been proved to be a useful approximation by Ryding et al. [25] and Wittkower et al. [26] for heavy ions stripped in oxygen gas and in carbon foil at energy below 20 MeV. However, for fast ions, equation 2.21 generally gives unsatisfactory results. Other expressions have been given independently by other researchers. However, the data of experimental distribution width often scatter considerably.

Charge exchange is a complicated many-body collision process and a theory is not yet available to predict the charge state distribution accurately. For semi-empirical formulas, it is useful to predict equilibrium charge state distribution within applied energy region before experiment. But they are limited to a certain domain. Furthermore, empirical formulas are unable to apply to non-equilibrium distribution, which strongly depends on charge state of projectile and target thickness. So, theoretical calculations are still desirable for charge exchange and charge state distribution.

### 2.4 Theoretical calculation model

The model of charge state distribution of ion beams passing through matter requires the knowledge of charge exchange cross sections, i.e., electron ionization, capture, excitation and de-excitation. In the following, we discuss briefly the calculation models on the basis of collision dynamics between ions and atoms.

#### 2.4.1 ETACHA Calculation

ETACHA model is developed to simulate charge state distribution of swift ions in the MeV/u range passing through the foil target [27]. This model is based on an independent electron model taking into account electron loss, capture, excitation and de-excitation from \(n=3\) shell and to all sub-shells. At present, ETACHA code can calculate the \(F_q(x)\) for the
projectile ions with atomic number less than 28 (1s to 3d shells). In this model, evolution equation 2.7 was computed as a function of target thickness. For charge exchange cross section, Born approximation is used to calculate excitation and ionization cross section, the Eikonal approximation is used to calculate non-radiative electron capture, and the Bethe-Salpeter formula for radiative electron capture is applied. ETACHA mode is useful to obtain charge state evolution for light ions up to Ar. Figure 2.4 presents the simulation result of ETACHA for Ar^{17+} in carbon. ETACHA calculation can explain the measured result well for the energy range of 10–100 MeV/u.

2.4.2 CHARGE Calculation

CHARGE code is developed [28] based on the three charge-state model developed by Allison [29]. It is applied to high energy region (>100MeV/u) and heavy projectiles (Z>30). The cross sections for projectile ionization are calculated by non-relativistic plane wave approximation, Slater screening constants are used to calculate electron screening effect [30]. Both non-radiative electron capture (NRC) and radiative electron capture (REC) cross section are considered. NRC cross section is calculated using the Stobbe formula [31]. REC cross section is obtained by summing over the n <10 for projectile and n<3 for target. Furthermore, double electron capture and double ionization processes are taken into account to correct charge exchange cross section. Figure 2.5 shows the charge state distribution of Au^{69+} and U^{68+} impinging on Al foil.

Besides, there are some other theoretical models, like that GLOBAL [28], and 4-state model [32], all of them have a certain limitations of application. GLOBAL and CHARGE are more suitable for high energy (>100MeV/u) and high Z projectile. In our measured energy region, they could lead to a big deviation from experimental results.

Therefore, to develop an appropriate theoretical calculation, valid for low energy and low Z heavy ion is necessary.
Figure 2.4: Charge state distributions between experiment and ETACHA calculation for 13.6 MeV/u Ar$^{17+}$ ion in carbon. Curves are from ETACHA simulation [27]

Figure 2.5: CHARGE calculation results (curves) and experimental data (points). X axis is number of projectile electron. Y axis is charge state fraction. Left: 1000 MeV/u Au$^{69+}$ on 11-mg/cm$^2$ Al. Right: 955 MeV/u U$^{68+}$ ions on 1.13 mg/cm$^2$ Al. [28]
Reference

Chapter 3 Experimental facilities

In this chapter, experimental facilities are described. Experiments are performed at the Kyushu University Tandem Laboratory (KUTL). For the present work the ion source, tandem accelerator, windowless gas target and associated detectors that are needed for charge state distribution measurements are explained in more detail in the following sections. Figure 3.1 displays the current layout of the KUTL. There are two experimental rooms and three beam courses, and the available course is selected by changing current of the steering magnet.

3.1 Ion Source – SNICS Ⅱ and Tandem Accelerator

Cesium sputtering ion sources are now the most widely used negative ion sources in tandem accelerator laboratories. At present, we use a single cathode ion source named SNICS Ⅱ.

Mixture of carbon and Fe is packed in the Cu cup. The cesium boiler and the cesium are heated so that cesium vapor enters the ion source. The flow of cesium into the source is controlled by adjusting the temperature of the boiler. The boiler temperature of about 200°C and a line temperature of about 100°C seem to work well. The cesium metal placed in a reservoir bottle become vapor, and filled in the chamber enclosing area between the cathode and the ionizer, as shown in figure 3.2. A Refrigerator is used to prevent the sputter cathode from being heated up.

The ionizer is a coiled sheath heater consisted of tantalum sheath and conductor that is heated by electric current, typically 25~26A. The sputter cathode is held at 5 kV negative with respect to the ionizer. After a cesium atom is ionized by contact with the hot coil, it is attracted to the cathode. The energetic cesium ions sputter atoms from the surface of the cathode. Some of these sputtered atoms collide with cesium atoms near the cathode, and become negative ions by capturing electrons.
The sputtered ions are transported to a pre-accelerator tube with accelerating by an extractor electrode. The beam energy before pre-accelerator is ~15 kV. A focus electrode is placed at the back of extractor electrode to minimize the beam spread. The voltage of 8–9 kV is applied to the electrode.

The cathode can be withdrawn through an air lock so that it can be changed without venting the entire source.

Schematic view of the SNICS II, including reservoir, cathode, ionizer, and extractor is shown in figure 3.2, and the operation parameters are given in table 3.1.

Table 3.1. Operation parameters of SNICS II

<table>
<thead>
<tr>
<th>Ionizer voltage</th>
<th>Cathode voltage</th>
<th>Extractor voltage</th>
<th>focus voltage</th>
<th>Beam current:</th>
</tr>
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<tr>
<td>25A</td>
<td>-5kV</td>
<td>-15kV</td>
<td>-9 kV</td>
<td>~20μA</td>
</tr>
</tbody>
</table>
Figure 3.1: Plan view of Kyushu University Tandem Laboratory.
The negative ion beam produced by the SNICS II is transported to the tandem accelerator. At the first stage of acceleration, the negative ions drift toward the center of the accelerator (named center terminal) to which the positive voltage (generating voltage (GV)) is applied. When the beam ions pass through a stripper consisting of the carbon foil or N₂ (or O₂) gas at the terminal center, the charge state of the beam ions changed to the positive. The second stage of acceleration is where the positively charged ion beam accelerates away from the generating voltage.

The charge state and energy of the accelerated ions are analyzed by the 90 degree dipole magnet (analyzing magnet), and the final energy of the beam can be written as:

$$E(\text{MeV}) = V_T(q + 1)$$

where $V_T$ is the generated voltage (GV) in $10^6 \text{ Volt}$ and $q$ is the positive charge state of the beam exiting the stripping region. The maximum GV is 10MV.

Figure 3.3 and 3.4 show the schematic drawing of tandem and tandem’s picture at KUTL, respectively.
3.2 Beam Transport system and RMS

The accelerated beam, as mentioned in the previous section, is sent directly into a 90° dipole analyzing magnet where the beam direction is changed and the components are analyzed. The magnetic rigidity of the ion beam is written as

\[ \overline{B\rho} = \overline{P} / q \]

Where \( B \) is the magnetic field, \( \rho \) is the radius of curvature of the magnet in meters, \( P \) and \( q \) are the momentum and the charge state of the ion, respectively.

Beyond the accelerator all other beam line components are used for the purpose of
beam transport and tuning. These elements are used for focusing, steering, and monitoring beam. Figure 3.5 shows the experimental layout. The start of the experiment is at the SNICS ion source. Then the path of the ion beam continues through the accelerator and is bent around a dipole magnet to get directed into the astrophysics beam line. Finally, the ion beam arrives at the target chamber. Background particles are rejected by RMS and recoils oxygen ions are detected by SSD at focal plane 2 (F2).

The recoil mass separator (RMS) consists of two dipole magnets (D1 and D2), an electric deflector (ED), four quadrupole magnets (Q1, Q2, Q3 and Q4), two sextupole magnets (SX1 and SX2), and a multi-pole magnet. The arrangement of the magnets and other components are shown in figure 3.6. There are two focal planes F1 and F2. In CSD experiment, the beam is focused and stopped at the F1 plane and its charge is measured by Faraday cup 3. In the cross section measurement of astrophysics experiments, the background particles are rejected at F1 and F2 plane, respectively.

Figure 3.5: Set up of $^4$He ($^{12}$C, $^{16}$O) $\gamma$ experiment. Charge state distribution measurements are also performed at this platform.
3.3 Beam monitor and Faraday cups

There are two types of beam monitors used for measuring charge state fractions. The one is the target silicon solid state detector (Target-SSD), and the others are Faraday cups. Both of the monitors are installed in the RMS and used for monitoring the beam current. The practical usage of the monitors is briefly presented in following, as shown in figure 3.7.

In the nuclear physics experiments, the Target-SSD detector is commonly used to know the energies as well as the timing of the particle incidences on the detector.

During that measured period the beam intensity dose not remain constant. Each charge state has to be measured individually. Thus, the usage of SSD is important in order to monitor and estimate the beam current by counting the elastically scattered particles from the gas target placed at the front of the RMS.

In our measurement, three faraday cups are used to measure the beam charge. Faraday cup 1 (FC1) in front of gas target is used to measure the incident beam current. Faraday cup 2 (FC2) in the behind of the gas target is used to measure the beam current after charge exchange. Faraday cup 3 (FC3) installed at the F1 plane of RMS is used to
measure the current of single charge state. The fraction of charge state can be determined from the ratio of current collected by FC3 and the count of scattered particles detected by Target-SSD.

![Figure 3.7: Measurement setting of charge state distribution. Faraday cups (FC1, FC2, and FC3) and SSD are shown.](image)

### 3.4 Windowless gas target

#### 3.4.1 Target box and structure

A blow-in type windowless helium gas target has been developed at KUTL, which has been used in the experiment of the astrophysics-nuclear reaction.

A gas target is commonly used with window foils, whose thickness is typically more than 1 mg/cm$^2$ so as to endure gas pressure of more than 10 Torr. When a primary beam passes through the window foil, such a thin foil is easily broken. As a result, gas leakage takes place. Furthermore, since the charge exchange could happen again on the exit foil, measurement result will be deteriorated seriously.

However, a windowless gas target has several difficulties such as low target thickness, very complicated structure, and necessity of a pumping system with high pumping speed. A gas target having very thin window foils is ideal if it is available. In previous work, we have examined a very thin carbon foil and a thin silicon nitride foil for the window. It was found that a carbon foil of 20 μg/cm$^2$ (100 nm in thickness) and 10 mm in diameter is broken at gas pressure of 3 Torr and helium gas easily penetrates through the foil [3].

Thus, a windowless gas target was developed in blow-in model, as shown in figure 3.8. The target gas is blown into the center room symmetrically from walls of two tunnels and...
the gas is stagnated. The gas pressure become high at the center room and sharply low with distant from the center. Compared to a blow-out gas target, in which target gas is injected into the target room perpendicularly to the beam axis, blow-in gas target can realizes higher target pressure. Figure 3.9 shows two running modes and pressure profile. Obviously, for He and N₂ gas, target running in blow in mode can reach higher pressure than blow out mode.

**Figure 3.8:** Upper drawing: the central of gas target. It runs at blow in mode. Gas is stagnated in the room to realize high pressure. SSD monitor is used to measure the scattered particles from the gas target. Lower picture: external pictures of gas target.
Whole length of target is 44 mm and the center target cell is 25 mm, which can be operated at the maximum pressure 24 Torr at room temperature. The gas flowing out of the cell is limited by an entrance and exit circular aperture of diameter 2.5 mm and 4.3 mm, respectively. Target cell is enclosed by two layers stainless steel to stop gas flowing into the vacuum of beam line. Their entrance and exit is shown in figure 3.8.

The reliable monitor of beam intensity is expected to be elastic scattering of beam particle from the target atoms. So, Target-SSD, looking at the center of the gas, is installed in the gas cell at 35°.

*Figure 3.9: Blow out mode and blow in mode. For He and N₂ gas, pressure profile at blow in mode can realize higher pressure.*
Figure 3.10: Whole structure of target, including inlet, outlet aperture and differential vacuum pump system.

TMP: turbo-molecular pump, MBP: mechanical booster pump, DP: diffusion pump
Φ 20, Φ 10, Φ 6, Φ 12 and Φ 30 represent aperture size in diameter with 20mm, 10mm, 6mm, 12mm and 30mm, respectively.

3.4.2 Target differentially pump

Extended gas target system, is shown in figure 3.10. The differential pump system consists of a central inner pumping stage and outer pump stage.

The outer pump stage includes two Turbo-molecular pumps (TMP A and TMP E) in upstream and two Turbo-molecular pumps in downstream (TMP B and TMP C).

For pump state in the target cell, P2 Region and P3 Region were evacuated by mechanical booster pumps MPB1 and MBP2 with pumping speed of 1200 m$^3$/h, and P4 Region was evacuated by a turbo molecular pump TMP D with pumping speed of 1500 m$^3$/h. Pumping speed and corresponding pressure for each region is listed in table 3.2.

A needle valve controls the loading of gas into the cell, and the gas pressure is measured by a capacitance gauge within 1%.

Table 3.2: Pressure of each region (Torr) and pump speed (m$^3$/h).
The value of P1 represents helium gas pressure at the target center.

<table>
<thead>
<tr>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
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<th>TMP C</th>
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<td>1200</td>
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<td>3000</td>
</tr>
</tbody>
</table>
Reference

[3] Doctoral thesis: Direct measurement of nuclear astrophysical reaction \(^4\text{He}(^{12}\text{C}, \ ^{16}\text{O})\gamma\) cross section near stellar temperature, 2007 Hiroshi Oba, Kyushu University
Chapter 4 Experimental results and discussions

Various experimental studies have been performed for various ion and target combinations covering a wide range of energies. Several reviews and tables have accumulated the data for equilibrium charge state distribution (CSD) for Be, B, and C ions through carbon foils [1-6]. However, measurements of CSD of $^{16}$O through helium gas in low energy (<10MeV) are few. The CSD of $^{16}$O is important in the present measurement of $^{12}$C+$\alpha$→$^{16}$O+$\gamma$, astrophysical nuclear fusion reaction with a thick windowless helium gas target.

In this chapter, we describe experimental procedures. Before the measurement, experimental setups were adjusted by measuring some important parameters, including slit adjustment, beam transmission rate test, and ratio of target monitor count and Faraday cup 3 charges. Equilibrium CSD of oxygen through helium gas are measured at $E(^{16}$O)=7.2, 4.5, and 3.45 MeV ($E_{cm}$=2.4 MeV, 1.5 MeV, and 1.15MeV). We discuss Gaussian distribution of experimental data. Mean charge state and distribution width are fitted using the empirical models. Finally, energy dependence of CSD is plotted according to empirical models.

4.1 Experimental procedures

Figure 4.1 represents CSD measuring system from gas target to focal plane 1 (F1). The symbols in figure 4.1 have been explained in figure 3.6 and 3.7 of section 3.2. The incident ions move along the beam line and through the windowless helium gas target. Recoil helium particles are measured by Target-SSD, which acts as a target monitor. After charge exchange with helium atom, incident beam is sent directly into a Recoil Mass Separator (RMS) where ions of different charge states are separated electrically by ED and magnetically by D1, and only one charge-state ion is guided to Faraday cup 3 (FC3). For each charge state measurement, we have to adjust the parameters of RMS in order to reject the unexpected particles.
4.1.1 Slit adjustment

In order to improve reliabilities in our measurements, several tests have been performed before the measurement of CSD. First, we explained the adjustment of slit width which needs repeated tests so as to obtain the optimum value.

Before each charge state fraction measurement, we adjust slit width by measuring beam charge in FC3 and the target monitor count. Figure 4.2 shows beam charge in FC3 divided by the charge in FC2 against slit width before O$^{3+}$ measurement at 3.45 MeV. Beam charge increased rapidly with slit width at first. It indicates that more particles came to FC3 with the increase of slit width. Then, the beam current became stable and a plateau appeared. Finally beam current increased again with the increase of slit width indicating that ions of different charge state came to FC3. Therefore, plateau indicates that the product ions with specific charge state can be separated well by adjusting slit width. The optimum slit width is set at the middle of plateau. As seen in figure 4.2, the width was determined in 30mm at right slit and 20mm at left slit. Using this method, slit widths were adjusted for each measurement.

Figure 4.1 Setup for CSD measurements from target to FC3. Slits are adjusted to stop unexpected particles. Three Faraday cups: FC1, FC2 and FC3. SSD: target Si solid state detector; ED: electric deflector; D1: magnetic deflector; F1: focal plane 1.
Figure 4.2: Value of Faraday cup 3 against slit width. This plot is for O$^{3+}$ measurement at 3.45 MeV. The optimum width was set 30mm at right slit, and 20mm at left slit.

4.1.2 Transmission rate

The structure of target is shown in figure 4.3. The inlet size is 2.5 mm in diameter, and outlet is 4.3mm in diameter. The aim of design is to confine gas without window foils and realize high pressure. The beam size was less than 2.1mm in diameter. We thus have to confirm that the beam can pass through the target cell without loss. Transmission rate test is done before each charge state measurement. It was performed without gas. Beam current was measured by FC1 in front of the target, (see figure 4.1). Then beam current through the target was measured by FC2 downstream the target. The transmission rate, FC2/FC1 was obtained. Table 4.1 shows the measured result at E= 3.45, 4.5, 7.2 MeV. Almost, the ratios were around 100%. Therefore, we confirmed that beam can pass through the target without loss.
Figure 4.3: The structure of target. Size of inlet and outlet is 2.5mm and 4.3 mm, respectively.

Table 4.1. Transmission rate test at 3.45, 4.5, 7.2 MeV ($E_{cm}$=1.15, 1.5, 2.4 MeV)

<table>
<thead>
<tr>
<th>Charge state</th>
<th>FC2/FC1 3.45MeV</th>
<th>FC2/FC1 4.5MeV</th>
<th>FC2/FC1 7.2 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+</td>
<td>1.01</td>
<td>---</td>
<td>----</td>
</tr>
<tr>
<td>2+</td>
<td>0.998</td>
<td>1.008</td>
<td>1.005</td>
</tr>
<tr>
<td>3+</td>
<td>1.005</td>
<td>1.006</td>
<td>0.996</td>
</tr>
<tr>
<td>4+</td>
<td>0.996</td>
<td>1.008</td>
<td>1.003</td>
</tr>
<tr>
<td>5+</td>
<td>1.035</td>
<td>0.999</td>
<td>1.001</td>
</tr>
<tr>
<td>6+</td>
<td>0.997</td>
<td>0.997</td>
<td>0.997</td>
</tr>
</tbody>
</table>

4.1.3 Target monitor and FC3

At the present experiment, we used a Faraday cup and a silicon detector as the beam monitor. The monitor detector (Target-SSD) installed in the target system detected He recoils scattered by the $^{16}$O beam, (see figure 4.3). The change of beam intensity could be monitored well by the count of SSD. In measurement, charge state fractions couldn't be measured at once but had to be measured individually. However, the beam intensity didn't remain constant throughout measurement. Even in such case, the ratio of SSD count to beam charge in FC3 was stable throughout measurement. A clear helium spectrum was obtained by SSD as shown in figure 4.4. The ratios of SSD count to FC3 charge are plotted in figure 4.5, which were performed at 3.45 MeV. As is seen in figure 4.5, the ratios are different for different charge state. In 6 times measurement, the ratios are stable for each charge state within relative error of 5%. By this detection method, the stability of beam current is completed.
Figure 4.4: Scattered spectrum of helium at 3.45 MeV

Figure 4.5: The ratio of SSD count to FC3 count at each charge state (q=1~5) at 3.45 MeV. It was performed 6 times. For each charge state, the ratio is stable with 5% error.

4.1.4 Measurement and error estimation

The measurements of CSD were carried out at Kyushu University Tandem Laboratory. Energetic oxygen beams at 7.2, 4.5, and 3.45 MeV (E_{cm}=2.4, 1.5, 1.15 MeV) were injected into windowless helium gas target. Current of the selected charge state ion was measured by
FC3 and total beam current was monitored by the Target SSD. The experimental procedures are as follows:

1. Extracting beam and setting RMS parameters
   RMS parameters were set so that the only selected \(^{16}\text{O}^{q+}\) could completely pass through RMS and come to measured terminal F1.

2. ED adjustment
   Setting slit width as \(\pm 10\) mm at first, and then we adjusted ED until count in FC3 reached the maximum.

3. D1 adjustment
   Adjusting D1 finely and so that the beam appeared at the center of focal plane 1 (F1).
   After finishing above procedures, selected \(^{16}\text{O}^{q+}\) can pass through center of the slit and come to center of F1.

4. Slit adjustment
   Right slit and left slit were set individually. First, fixing right (left) slit and widening left (right) slit gradually, until the selected ion current became constant. Finally, the slit widths were determined in the middle of plateau. (See 4.1 section: slit adjustment)

5. Measurements made
   (1) Measure FC2/FC1 transmission rate without gas and with gas
   (2) With helium gas in the target, helium counts in the target SSD and FC2 beam charge were measured simultaneously.
   (3) After (2), helium counts in target SSD and FC3 charge were measured simultaneously.
   (4) Measure the ratio FC2/FC1 again and check the transmission rate.
   After above procedures, measurement for one-charge state was finished. For other charge state measurements, we repeated procedures 1 to 3 after adjusting RMS parameter again. After that we repeated procedures 4 and 5 to measure specific charge state fraction. Experimental parameters are shown in table 4.2 and 4.3. At the present work, \(\text{O}^{1+}\) measurements at 7.2 and 4.5 MeV were difficult because of the limitation of ED field.
### Table 4.2. Experimental parameter: Slit widths

<table>
<thead>
<tr>
<th>Slit Widths</th>
<th>3.45 (Ecm=1.15)</th>
<th>4.5 MeV (Ecm=1.5 MeV)</th>
<th>7.2 MeV (Ecm=2.4 MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right slit</td>
<td>Left slit</td>
<td>Right slit</td>
<td>Left slit</td>
</tr>
<tr>
<td>1+</td>
<td>Open fully</td>
<td>Open fully</td>
<td></td>
</tr>
<tr>
<td>2+</td>
<td>25</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>3+</td>
<td>25</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>4+</td>
<td>25</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>5+</td>
<td>25</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>6+</td>
<td>--</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>7+</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>8+</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.3. Experimental parameters: beam, target, RMS setting

<table>
<thead>
<tr>
<th>Parameters</th>
<th>3.45 MeV</th>
<th>4.5 MeV</th>
<th>7.2 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident beam</td>
<td>$^{16}\text{O}^{1+}$</td>
<td>$^{16}\text{O}^{2+}$</td>
<td>$^{16}\text{O}^{2+}$</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>10nA</td>
<td>40nA</td>
<td>60nA</td>
</tr>
<tr>
<td>He gas pressure</td>
<td>3Torr</td>
<td>6Torr</td>
<td>6Torr</td>
</tr>
<tr>
<td>Effective target length</td>
<td>4.5 cm</td>
<td>4.5 cm</td>
<td>4.5 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main RMS parameters:</th>
<th>3.45MeV</th>
<th>4.5MeV</th>
<th>7.2MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED (kV) (Pos./Neg.)</td>
<td>D1 (A)</td>
<td>ED (kV) (Pos./Neg.)</td>
<td>D1 (A)</td>
</tr>
<tr>
<td>Charge state</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>1+</td>
<td>168/-168</td>
<td>281.65</td>
<td>------</td>
</tr>
<tr>
<td>2+</td>
<td>84.0/-84.0</td>
<td>139.83</td>
<td>110.1/-110.1</td>
</tr>
<tr>
<td>3+</td>
<td>56.1/-56.1</td>
<td>93.63</td>
<td>74.7/-74.7</td>
</tr>
<tr>
<td>4+</td>
<td>42.0/-42.0</td>
<td>70.26</td>
<td>54.9/-54.9</td>
</tr>
<tr>
<td>5+</td>
<td>33.6/-33.6</td>
<td>56.53</td>
<td>43.6/-43.6</td>
</tr>
<tr>
<td>6+</td>
<td>------</td>
<td>------</td>
<td>36.3/-36.3</td>
</tr>
<tr>
<td>7+</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>8+</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
</tbody>
</table>

ED: electric deflector, Pos.: positive voltage, Neg.: negative voltage
D1: magnetic deflector 1
Current of the selected charge state ion was measured by FC3. However, total beam current cannot be measured by FC1 simultaneously with FC3. Since helium counts in the target SSD is proportional to the total beam current, we could estimate the total beam current from the counting rate of the target monitor SSD.

Thus, the charge state fraction, $F(q)$, is expressed as follows:

$$F(q) = \frac{N_{FC3}(q)}{N_{beam}} \times \frac{N_{FC3}(q)}{Count_{SSD} / P_{He}} \times A,$$

where, $N_{FC3}(q)$ is the number of ion with $q^+$ in FC3, $N_{beam}$ is total number of beam particle, and $Count_{SSD}$ is the count of target monitor SSD. $A$ is a constant, and $P_{He}$ is the pressure of helium gas. According to normalization condition

$$\sum_q F(q) = 1,$$

constant $A$ can be written as:

$$A = \sum_q \frac{Count_{SSD}}{N_{FC3}(q) \times P_{He}}.$$

In errors, the statistical error in CSD measurement, which came mainly from the counts in the Target-SSD, was small. Beam charge count measured by current integrator had only error 1 in $10^4 \sim 10^5$ counts. Therefore, systematic error was the largest. The monitor counts slightly depend on beam position. Although up and down shift of beam position influenced the SSD count, the beam was usually shifted horizontally and scarcely shifted up and down. Furthermore, vacuum in RMS also was influenced by leakage of helium gas from the target. Bad vacuum in RMS could lead to charge exchange of ions passing through RMS. The distance from ED entrance to F1 is about 2.95 m. Table 4.4 shows the vacuum change in ED and F1 before and after injecting helium gas. Finally, systematic error is estimated as 3%.

<table>
<thead>
<tr>
<th>$P_1$(Torr)</th>
<th>$P_{ED}$(Torr)</th>
<th>$P_{F1}$(Torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>$1.6 \times 10^{-6}$</td>
<td>$3.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>6.0</td>
<td>$4.6 \times 10^{-6}$</td>
<td>$3.4 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

*P1 denotes the pressure of target cell, $P_{ED}$ is the pressure of ED, and $P_{F1}$ is the pressure of F1.
4.2 Experimental results: Equilibrium charge state distribution

We present experimental results of equilibrium distribution. Table 4.5 shows the experimental data in the present work. It represents equilibrium charge state fraction of oxygen ion through helium gas. TRIUMF data [7] are also presented in table 4.5.

Table 4.5. Experimental results of charge state fraction (%) of oxygen through helium gas, where * data are from TRIUMF laboratory system [7]. The projectile energies are shown in laboratory coordinate. (E_{cm}: energy in center of mass system)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>1+</th>
<th>2+</th>
<th>3+</th>
<th>4+</th>
<th>5+</th>
<th>6+</th>
<th>7+</th>
<th>8+</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.45 (E_{cm}=1.15)</td>
<td>5.8±0.2</td>
<td>23.2±0.7</td>
<td>43.9±1.3</td>
<td>24.0±0.7</td>
<td>3.1±0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.5 (E_{cm}=1.5)</td>
<td>11.8±0.3</td>
<td>38.4±1.1</td>
<td>38.7±1.1</td>
<td>10.3±0.3</td>
<td>0.8±0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2 (E_{cm}=2.4)</td>
<td>0.7±0.02</td>
<td>10.2±0.3</td>
<td>39.2±1.1</td>
<td>39.8±1.2</td>
<td>10.1±0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.208*</td>
<td>20.78±0.79</td>
<td>44.96±1.18</td>
<td>27.69±0.97</td>
<td>6.31±0.35</td>
<td>0.26±0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2*</td>
<td>0.02±0.003</td>
<td>33.04±1.1</td>
<td>46.31±1.22</td>
<td>18.64±0.74</td>
<td>1.92±0.15</td>
<td>0.07±0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.2*</td>
<td>7.9±0.43</td>
<td>34.48±1.1</td>
<td>42.28±1.17</td>
<td>14.61±0.59</td>
<td>0.73±0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.94*</td>
<td>4.82±0.27</td>
<td>25.56±0.93</td>
<td>47.21±1.47</td>
<td>20.31±0.78</td>
<td>2.10±0.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.4*</td>
<td>3.9±0.22</td>
<td>24.45±0.9</td>
<td>47.52±1.19</td>
<td>23.31±0.87</td>
<td>0.82±0.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12*</td>
<td>9.0±0.59</td>
<td>37.38±1.19</td>
<td>48.11±1.25</td>
<td>5.51±0.31</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14*</td>
<td>29.88±1.11</td>
<td>59.44±1.22</td>
<td>10.68±0.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.3 Discussion

4.3.1 Energy loss

Energy loss is known to be important energy transfer mechanism in interaction of projectile with medium. In our measurement, energy loss of $^{16}$O ion through helium gas could be negligible. The Stopping and Range of Ions in Matter (SRIM) program by Ziegler [8] suggests that oxygen of 1-10 MeV has an energy loss range of approximately 8-18 keV for helium gas target at the thickness of 6Torr×4.5 cm. Obviously, the energy loss of few MeV projectiles through a gas target is small, within 1% of incident energy. Through semi-empirical formula, we will find that the change in charge fractions caused by energy difference ($E - \triangle E$) is negligible. Energy loss effect does not affect the charge state distribution.

4.3.2 Gaussian distribution

Equilibrium charge state distributions we observed show a remarkable symmetry and that can be well described by a Gaussian distribution as typically shown in figure 4.6. The mean equilibrium charge state ($\bar{q}$) and distribution width ($d$) calculated from experimental data and fitted from Gaussian distribution are tabulated in table 4.6. Charge state distributions are not always symmetrical. As a measure of the degree of asymmetry, skewness is used. The “s” listed in table 4.6 is skewness as defined by following equation (4.4) [7]:

$$s = \sum_{q} (q - \bar{q})^3 F_q / d^3,$$

where, $\bar{q}$ is mean charge state and $d$ is distribution width. $F_q$ is the measured charge state fraction and $q$ is charge state. The equation is sum of all charge state. When the value of skewness is very small, it thus indicates a good symmetry of the distribution. For a Gaussian distribution, the skewness is ideally equally to zero.

As seen in table 4.6, the skewness values are very small at 4.5 MeV and 3.45 MeV. On the
other hand, there is a large skewness value at 7.2MeV. However, they still presented good symmetry of the distribution.

![Figure 4.6: Gaussian fits for experimental data at 7.2, 4.5, 3.45 MeV (E_{cm}=2.4, 1.5, 1.15 MeV). Symbols represent the experimental data and curves are fitted distribution.](image)

**Table 4.6.** Mean charge state $\bar{q}$, and distribution width $d$, from experiment and Gaussian fits.

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\bar{q}$ (Exp.)</th>
<th>$d$ (Exp.)</th>
<th>$s$</th>
<th>$\bar{q}$ (Gaussian)</th>
<th>$d$ (Gaussian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2 MeV</td>
<td>4.4±0.1</td>
<td>0.83±0.1</td>
<td>0.23</td>
<td>4.51±0.01</td>
<td>0.867±0.007</td>
</tr>
<tr>
<td>4.5 MeV</td>
<td>3.5±0.1</td>
<td>0.85±0.1</td>
<td>0.087</td>
<td>3.52±0.01</td>
<td>0.877±0.008</td>
</tr>
<tr>
<td>3.45 MeV</td>
<td>2.9±0.1</td>
<td>0.90±0.1</td>
<td>0.081</td>
<td>2.94±0.01</td>
<td>0.84±0.008</td>
</tr>
</tbody>
</table>

Therefore, the excellent agreement between experimental data and Gaussian distribution encouraged us to use semi-empirical formulas of mean equilibrium charge state $\bar{q}$ and distribution width ($d$). With the knowledge of mean change state and distribution width, we will be able to estimate the equilibrium charge state distribution by Gaussian distribution at energy range: 1~20 MeV.

A variety of semi-empirical models have been developed to predict experimental mean charge state. Several models have been introduced in chapter 2. Here, two models are used to estimate and predict the mean charge state because they were found to fit the low energy
range (<20 MeV) covered in this work. The details of these models were introduced in chapter 2.

The formula created by Schiwietz is a least-square fit with multi-parameters built from an array of over 800 data points in various ions and targets. The Schiwietz formula introduced in chapter 2 is applied to a solid target. For a gas target, mean charge state is written as [9]:

$$
\bar{q} = Z_p \times \frac{376x + x^6}{1428 - 1206x^{0.5} + 690x + x^6},
$$

4.5

$$
x = (v_p / v_0)Z_p^{0.32} Z_t^{0.03-0.017Z_p^{0.32}v_p / v_0}1+0.4/Z_p^{0.42},
$$

4.6

where, $Z_p$ and $Z_t$ are the nuclear number of projectile and target, respectively. $v_p$ and $v_0$ are the velocity of projectile and Bohr, respectively, and $x$ is a reformulated reduced velocity. In formula 4.5, there are no free parameters.

With parameterized formula, Betz model discussed in chapter 2 is applied, as follows [10]:

$$
\bar{q} = Z_p \times [1 - \exp(-\frac{A}{Z_p^{\gamma(\frac{E}{E'})}})]
$$

4.7

where, A, B, γ, $E'$ are free parameters. The best fit for helium gas target were obtained as A=1.058, B=0.304, γ=0.432, $E'$=1.082.

The fitting results are plotted in figure 4.7, with calculations in Betz model and Schiwietz model. We found the Betz model can reproduce the experimental data well. Schiwietz fitting is generally larger than experimental data. It indicates that the expression 4.5 cannot be extrapolated to very low energy region. Therefore, mean charge state with Betz formula will be applied to Gaussian charge state fraction formula.
The ability to predict the distribution width is important when the charge state fractions show Gaussian distribution. The distribution width is a very sensitive parameter and no reliable theoretical prediction is available yet. Empirical models for charge distribution width have been introduced in the chapter 2. We, hence, use Nikolaev model (equation 2.21) \[11\], to fit experimental data, although it is better to be applied to solid targets. The free parameters $d_2$ and $k$ for the combination of oxygen and helium were found to be 0.646 and 0.876, respectively. The fitting result in this model is shown in figure 4.8. Since the model was developed for experimental data in a limited energy range and with high Z ions. Therefore, at low energy, experimental data scattered about fitting curves.
Figure 4.8 Distribution widths against projectile energy. The curve is the result of Nikolaev fitting [11]. Solid circles are from our present results and open circles are obtained from TRIUMF data [7].

Charge state distributions are often approximated by a Gaussian (symmetric) distribution, which has been discussed in chapter 2. The expression for a Gaussian distribution can be described as follows (equation 2.13):

\[
F_q = \frac{1}{\sqrt{2\pi d^2}} \exp\left(-\frac{(q - \bar{q})^2}{2d^2}\right),
\]

where, \(F_q\) is the charge state fraction, \(d\) is the charge state distribution width, \(q\) is the charge state and \(\bar{q}\) is the mean charge state. In previous section, skewness has been used to check the symmetry of the charge state distribution. Because of the relatively small skewness, Gaussian distribution can be used to describe CSD of oxygen through helium gas.

The energy dependences of mean charge state and distribution width have been calculated by empirical formula 4.7 and 2.21, respectively. Thus, the evolution of charge fraction with projectile energy can be simulated according to the equation 4.8. Figure 4.9 displays the charge state fractions as a function of the projectile energy for oxygen through helium gas. In figure 4.9, experimental data are obtained from our measured work and TRIUMF Laboratory. Calculation results using equation 4.8 are shown in curves for different charge state. One color corresponds to one charge state in figure 4.9. Curves represent fairly well the data for
various charge states. As seen in figure 4.9, at high energy, the charge state fractions are dominated by highly charge states.

In general, there is reasonable agreement between the data and Gaussian fitting. In Gaussian distribution formula, there are two important parameters: mean charge state ($\bar{q}$) and distribution width ($\sigma$). Mean charge state can be described well by the semi-empirical formula. Thus, the deviation in figure 4.9 is mainly caused by the fitting of distribution width.

Charge changing process is a complicated many body collision process, and no theory can be available yet to predict the distribution accurately. In such situation, semi-empirical formulas have been developed and are useful fairly, but are limited to a certain range. On the other hand, semi-empirical formulas developed by a great number of experimental data cannot explain physical process of ion-atom collision. Furthermore, almost all the formulas are applied to equilibrium distribution of charge state. Obviously, non-equilibrium distribution cannot be predicted by semi-empirical formula, since non-equilibrium distribution strongly depends on the initial charge state of projectile and target thickness.

Therefore, charge-changing cross sections of electron capture and electron loss, based on quantum theory are desirable for a complete description of the charge state distribution resulting from ion-atom encounters. It helps to understand completely the charge changing processes of low energy heavy ions passing though gas target. In the next chapter, we will use quantum theory to calculate charge change cross section and simulate evolution of charge state fraction against the target thickness.
Figure 4.9: Charge state fractions as a function of incident energy for oxygen ions through helium gas. Solid circles represent the present work at 7.2 MeV, 4.5 MeV, and 3.45 MeV, and open ones are data taken at TRIUMF [7]. Curves are calculation result using Gaussian distribution formula (Equa. 4.8) for different charge state. In this figure, one color including dots and curves matches one charge state.
Reference

Chapter 5 Theoretical calculation

In chapter two, we have discussed the evolution equation of charge state fraction. Once the cross sections are known, the charge state evolution for ions having any initial charge state can be obtained from the solution of rate equations. In this chapter, we estimate the cross section of charge exchange using plane wave born approximation and continuum distorted wave approximation. The evolutions of charge state fractions thus are simulated. It is first work to simulate evolution of CDS with target thickness by theory at astrophysical nuclear reaction energy range. Density effect is taken into account to correct theory further. For equilibrium distribution, we discuss corrected results (with density effect) and original results (without density effect). A comparison between theoretical calculations and experimental data are discussed. For non-equilibrium distribution, a model is applied to simulate charge state fraction in case of $^4\text{He}^{12}\text{C}, ^{16}\text{O}$ reaction. The charge state of recoil particle at the moment of fusion reaction is assumed in this chapter. Finally, we estimate charge fraction of recoil oxygen in fusion reaction of $^4\text{He}^{12}\text{C}, ^{16}\text{O}$ at measured energy ($E_{\text{cm}}=2.4$, 1.5, and 1.15 MeV). With these results, the cross section of $^4\text{He}^{12}\text{C}, ^{16}\text{O}$ can be measured precisely.

5.1 Numerical calculation of cross section

5.1.1 Ionization cross section

Many theoretical works have been done by Bohr and Lindhard in ionization process [1,2]. Bohr thought that projectile electrons are stripped off during the penetration of matter if their orbital velocity is smaller than the projectile velocity. This criterion is proven to be in good agreement with experimental findings and can be applied successfully even at relativistic velocities. However, it does not incorporate any target dependence.

For asymmetric collision systems ($Z_T<Z_p$), the ionization of projectile ions can be reasonably well described within first order perturbation theory, such as the semi-classical
approximation [3] or plane wave Born approximation (PWBA) [4]. PWBA is obtained under the following assumptions [5]:

1. The projectile is represented in its initial and final states by plane waves. All distortions are neglected, whether they originate in any inelastic process or in the elastic deflection of the charged particle by the nucleus.

2. The perturbation of the atomic orbits, between which the projectile induces transitions, is neglected.

We present a brief illustration of the theory and consider multi-electron projectile’s collision target with two electrons. In a projectile, the ionization electron is considered active electron, the rest electron surrounding nuclear leads to a screening effect. Atom unit is applied. The Hamiltonian for a system with two target electrons with coordinates \( \mathbf{r}_1, \mathbf{r}_2 \) and one projectile electron with coordinate \( \mathbf{r}_p \) is [6]:

\[
H = -\frac{\nabla_{\mathbf{r}_1}^2}{2M} - \frac{\nabla_{\mathbf{r}_2}^2}{2} + Z_T \frac{\nabla_{\mathbf{r}_1}^2}{2} + \frac{1}{|\mathbf{r}_1 - \mathbf{r}_2|} - \frac{\nabla_{\mathbf{r}_2}^2}{2} + Z_P + V,
\]

where, \( Z_T \) is charge of target nuclear, and \( Z_P \) is the effective charge of the projectile. \( M \) is reduced mass of system. \( V \) is interaction potential between nucleus and electrons, which is defined as follows,

\[
V = \frac{Z_T Z_P}{R} - \frac{Z_P}{|\mathbf{R} + \mathbf{r}_1|} - \frac{Z_T}{|\mathbf{R} + \mathbf{r}_2|} + \frac{1}{|\mathbf{R} - \mathbf{r}_2|} + \frac{1}{|\mathbf{R} - \mathbf{r}_1|}
\]

where, \( R \) is distance of between projectile nuclear and target nuclear.

According to transition possibility, cross section is written as:

\[
d\sigma_{nn'} = \frac{M^2}{4\pi^2 \hbar^4} \left| \int \exp(i\mathbf{qR}) \psi_n^*(\mathbf{r})V(\mathbf{R},\mathbf{r})\psi_{n'}(\mathbf{r}) d\mathbf{r} d\mathbf{R} \right|^2 \ d\Omega
\]

where,

- Electron initial wave function: \( \Psi_n \), Electron final wave function: \( \Psi_{n'} \)
- Initial plane wave: \( \exp(i\mathbf{kR}) \), Final plane wave: \( \exp(i\mathbf{k'}R) \)
Transfer momentum: $\bar{q} = \bar{k} - k'$

Using following formula:

$$
\int \frac{e^{i\bar{q}\bar{r}}}{|\bar{R} \cdot \bar{r}|} d\bar{R} = 4\pi q^2 \exp(i\bar{q}\bar{r}),
$$

and without considering nuclear interaction, we can get:

$$
d\sigma_{nn}(\Omega) = 4Z_T^2 \left(\frac{Me}{\hbar^2}\right)^2 \frac{v'}{v} \frac{1}{q^2} \int \left|\psi_n^*(\bar{r})e^{i\bar{q}\bar{r}}\psi_n(\bar{r})d\bar{r}\right|^2 d\Omega
$$

Substituting for $d\Omega$:

$$
d\Omega = 2\pi \sin \theta d\theta
$$

$$
q^2 = k^2 + k'^2 - 2kk' \cos \theta
$$

$$
2q dq = 2kk' \sin \theta d\theta
$$

$$
d\Omega = 2\pi \sin \theta d\theta = \frac{2\pi q dq}{kk'}
$$

$$
\frac{v'}{v} = \frac{1}{kk'} = \frac{\hbar^2}{M^2 vv'} = \frac{\hbar^2}{M^2} \frac{1}{v^2}
$$

where, $v$ and $v'$ is initial and final projectile velocity, respectively. $k$ and $k'$ are initial and final projectile momentum, respectively. $M$ is reduced mass of system. $\Omega$ is scattered solid angle.

Finally, the projectile ionization cross section with account of the target atomic structure has the form:

$$
d\sigma_{nn}(q) = 8\pi Z_T^2 \left(\frac{e^2}{h\nu}\right)^2 \frac{dq}{q^2} \int \left|\psi_n^*(\bar{r})e^{i\bar{q}\bar{r}}\psi_n(\bar{r})d\bar{r}\right|^2
$$

After energy integral, the equation is rewritten as follows [7,8]:

$$
\sigma_{nn}(q) = 8\pi Z_T^2 \left(\frac{e^2}{h\nu}\right)^2 \int_0^\infty d\varepsilon \int_0^{q_{min}} dq \int \left|\psi_n^*(\bar{r})e^{i\bar{q}\bar{r}}\psi_n(\bar{r})d\bar{r}\right|^2
$$

$\varepsilon$ is the ejected electron energy, $q_{min}$ is the minimum momentum transfer, which is defined:

$$
q_{min} = (\varepsilon + \Delta E_T)/v
$$

where, $\Delta E_T$ is the target electron ionized energy.
Screening effect

In the PWBA, for target carrying N electrons, the PWBA cross section is proportional to \( Z_T^2 \). For projectile ionization by neutral target atoms, one must account for the screening of the perturbing nucleus by the target electrons, which is dependent on momentum transfer, \( Z_T^2(q) \). Specifically, for small \( q \) (corresponding to large impact parameters), \( Z_T^2(q) \) goes to \((Z_T - N)^2\) corresponding to screening of the target charge \( Z_T \) by electrons. At large \( q \) (corresponding to small impact parameters), \( Z_T^2(q) \) goes to \( Z_T^2 + N \) corresponding to scattering incoherently by the target nucleus and \( N \) electrons of target [9,10].

To account for electronic screening on projectile ionization, Eq. 5.7 has to be modified as follows [9]:

\[
\sigma_{\text{nn}}(q) = 8\pi\left(\frac{e^2}{\hbar v}\right)^2 \int d\varepsilon \int \frac{dq}{q^3} \left| \int \psi^*_n(\mathbf{r}) e^{iq\cdot\mathbf{r}} \psi_n(\mathbf{r}) d\mathbf{r} \right|^2 |Z_T(q)|^2
\]

Here, the effective charge of the target, \( Z_T(q) \) as a function of momentum transfer, substitutes for \( Z_T \). In collision, ionization and excitation of electron of target atom also occur. For a projectile ionization contribution, any final states of the target atom are considered in process of \( Z_T(q) \) evaluation. \( Z_T(q) \) is expressed as follows [11]:

\[
|Z_T(q)|^2 = \left[ Z - \sum_{j=1}^{N} F_{jj}(q) \right]^2 + \left[ N - \sum_{j=1}^{N} |F_{jj}(q)|^2 \right],
\]

\[
F_{jj}(q) = \langle j| \exp(iq\cdot\mathbf{r})|j \rangle,
\]

In equation 5.10, the first term (screening) includes the electron-electron interaction. The second term (antiscreening) describes the mechanism where target electrons act as an electron cloud in which every electron can ionize the projectile by changing its own state. The net effect of these terms is as follows; for small \( q \), corresponding to excitation at large impact parameters where the projectile would see a neutral target atom, the perturbing charge is nearly zero, while for large \( q \), cross section varies as \( Z_T^2 + Z_T \), where \( Z_T^2 \) comes from the electron-target nucleus Coulomb potential and \( Z_T \) comes from \( Z_T \) separate electron-electron interactions.
Therefore, for neutral targets, $Z_T$ is written as:

\[
|Z_T(q)|^2 = Z^2 + Z, \quad q \to \infty
\]

\[
|Z_T(q)|^2 = 0, \quad q \to 0
\]

The effective charge of target, equation 5.10 is expressed using Hartree-Fock wave functions for screening term and analytic approximation for the antiscreening term. V.P. Shevelko et al. gave formula for simple target such as H, He$^+$, He. For the helium neutral target and He$^+$, approximation expressions of the effective charge as a function of momentum transfer are written [11]:

\[
|Z_{He}(q)|^2 = \left[2 - \frac{2}{(1 + q^2 / 10.89)^2}\right]^2 + \left[2 - \frac{2}{(1 + q^2 / 10.89)^2}\right]
\]

\[
|Z_{He^+}(q)|^2 = \left[2 - \frac{2}{(1 + q^2 / 64)^2}\right]^2 + \left[2 - \frac{2}{(1 + q^2 / 64)^2}\right]
\]

The dependencies of the $Z_T^2(q)$ on the momentum transfer for He$^+$, He are plotted in figure 5.1. For the bare target He$^{2+}$, the value of $Z_T^2(q)$ is equal to 4 due to without electrons. Therefore, in our calculation for the ionization of cross section, effective charge term of equation 5.10 is expressed by equation 5.14.

Considering above effect, the ionization cross section of oxygen in He are calculated. Hydrogenic wave functions are used for the electronic states. Figure 5.2 shows ionization cross section in the process of O$^{3+} + \text{He} \rightarrow \text{O}^{3+} + \text{He} + \text{e}$. Different shell electrons, including 1s, 2s, and 2p, are taken into account, and summed to total ionization cross section. In figure 5.2, the dashed lines are the result using equation 5.7. and $Z_T$ is calculated by Slater screening formula: $Z_T \sim 0.3$. The solid lines are calculated by equation 5.9. Obviously, considering screening effect as a function of momentum transfer, calculated results can agree with the experimental data.

Figure 5.3 shows the various charge state O$^{Z+}$ ionization cross section in He, which are calculated by equation 5.9. The curves represent total cross section, and dots are from experimental data corresponding to different O$^{Z+}$. Almost, theoretical calculation can fit the
experimental data well. Therefore, equation 5.9 will be applied to calculate the ionization cross sections in oxygen-helium collision, which are going to be used to simulate the evolution of charge state fractions.

![Figure 5.1: The square of the effective charge for He and He\(^+\), for He\(^{++}\) target, Z\(^2\)\(_{He^{++}}\)=4](image1.png)

Figure 5.1: The square of the effective charge for He and He\(^+\), for He\(^{++}\) target, Z\(^2\)\(_{He^{++}}\)=4

![Figure 5.2: O\(^{3+}\) ionization cross section in He. It shows various shell cross section and total cross section. Solid lines are the results of Z\(_T\)(q), and dashed lines are the result of Z\(_T\)=0.3. The dots are from the experimental data[12,13].](image2.png)

Figure 5.2: O\(^{3+}\) ionization cross section in He. It shows various shell cross section and total cross section. Solid lines are the results of Z\(_T\)(q), and dashed lines are the result of Z\(_T\)=0.3. The dots are from the experimental data[12,13].
Figure 5.3: The process of $O^{Z+} + He \rightarrow O^{(Z-1)+} + He + e$, ionization cross section ($Z=0,1,\ldots,7$). The curves are total cross section for $O^{Z+}$, and the dots are experimental data from [12,13], corresponding to various $Z^+$. The charge states are (■) 7+, (▲)6+, (▼) 5+, (◇) 4+, (★) 3+, and (☆) 2+.

5.1.2 Capture cross section

Various theories have been developed to calculate ion capture cross section, and each theory has their own limitation of applicable energy range. Continuum distorted wave (CDW) approximation [14], is developed to calculate one electron capture cross section at high projectile energies around $> 100$ keV. Adiabatic approximation is applied for the calculation of one electron capture and ionization cross section at low energy ($<1$ MeV) [15,16]. The CAPTURE code based on Brinkman-Kramers (BK) approximation is developed to calculate the cross section for one electron capture in ion atom/ion collisions at intermediate and high energies [17].

At present, CDW approximation has been applied to estimate capture cross section widely and give a good agreement with experimental data. Thus, we introduce CDW approximation and calculate oxygen capture cross section in helium.

The continuum distorted wave approximation has been introduced by Cheshire who
considered resonant capture in the symmetric $\text{H}^+ + \text{H} (1s)$ collision [18]. The main feature of this theory is a single electron approximation. During the collision this active electron is transferred from target to projectile while all other electrons are spectators. Impact parameter treatment was used to calculate cross section. The initial and final orbitals of this active electron can be conveniently described in terms of a combination of Slater orbitals or hydrogenic orbitals. In CDW approximation, distorting potential is used to express bound perturbation of target and projectile.

The cross section is written as:

$$\sigma_{if} = 2 \int_{0}^{\infty} b |a_{if}|^2 \, db,$$

where, $b$ is impact parameter, $a_{if}$ is transition amplitude. The derivation of transition amplitude is shown in appendix 2.

Generally, all excited states should be considered in calculation of capture cross section, i.e. total capture cross sections are obtained by summing over all contributions from ground state to $n=\infty$. In fact, for large $n$, there is an assumption that $\sigma_n$ is proportional to $n^{-3}$ [19]. Figure 5.4 shows the quantum number $n$-distribution of the capture cross section $\sigma_n$ in the reaction $\text{O}^{8+} + \text{He} \rightarrow \text{O}^{7+} + \text{He}^+$ at 0.6 MeV, 6 MeV, and 60MeV. The distribution of the $\sigma_n$ value has a maximum at a certain principal quantum number $n$ which depends on the projectile velocity and the atomic structure of the collision particles. With the ion energy increasing, the distribution maximum is shift towards low $n$ value. Therefore, in our calculation, we consider excited state up to $n=20$, which bring a sufficient precision in the calculation of cross section.

We calculated the capture cross section for $\text{He}^{2+}$, $\text{Li}^{3+}$, $\text{C}^{6+}$ and $\text{O}^{8+}$ with helium. Hydrogenic wave functions are used in electron final wave function since projectiles are bare nucleus. For the initial wave function, it is expressed by a linear combination of Slater type orbitals[20]. The calculated results are displayed in figure 5.5-1 to 5.5-4.

Almost, theoretical results agree with experimental data well. Furthermore, for $\text{O}^{8+}$ in helium, CDW result shows an agreement with CAPTURE result [17]. However, at low energy region (<1MeV), CDW results are larger than the experimental data in $\text{He}^{2+}$ and $\text{Li}^{3+}$. It reveals the limitation of CDW. However, at present work, projectile energy is larger than 1 MeV. Thus, the CDW can be suitable for this energy range.
Figure 5.4: The $n$ distribution of the capture cross section in the process of $O^{8+} + He \rightarrow O^{7+} + He^+$ at 0.6 MeV, 6 MeV, and 60MeV.

Figure 5.5-1: Total cross section as a function of the incident energy for $He^{2+} + He \rightarrow He^+ + He^+$. Curve is theoretical calculation result. Dots are experimental result from [20].
Figure 5.5-2: Total cross section as a function of the incident energy for Li$^{3+}$ + He $\rightarrow$ Li$^{2+}$ + He$^+$. Curve is theoretical calculation result. Dots are experimental result from [20].

Figure 5.5-3: Total cross section as a function of the incident energy for C$^{6+}$ + He $\rightarrow$ C$^{5+}$ + He$^+$. Curve is theoretical calculation result. Dots are experimental result from [20].
Figure 5.5-4: Total cross section as a function of the incident energy for $O^{8+} + He \rightarrow O^{7+} + He^+$. Dashed curve is CAPTURE code from Russia Group,[17] and solid curve is CDW theoretical calculation result. Dots are experimental results from [20].

5.1.3 Evolution of CSD with target thickness

In chapter 2, we discussed evolution of CSD with target thickness. Calculation of charge state distributions is usually performed by solving a set of differential equations, which can be written, with normalization condition [10, 21]:

$$\frac{dF_q}{dx} = \sum_{q', q \neq q} \left( F_{q'} \sigma_{q',q} - F_q \sigma_{q,q'} \right), \quad 5.17$$

$$\sum_q F_q(x) = 1.$$

Here, $F_q$ is a fraction of ions in a specific charge state $q$, $x$ is the penetration target thickness (expressed in atoms/cm$^2$), and $\sigma_{q,q'}$ is the collision cross section (ionization cross section or capture cross section) for a from projectile state $q$ to state $q'$. At equilibrium ($x \rightarrow \infty$), equation 5.17 becomes:

$$0 = \sum_{q', q \neq q} \left( F_{q'} \sigma_{q',q} - F_q \sigma_{q,q'} \right), \quad 5.18$$
Under the assumption of single electron capture and loss (see chapter 2), equation 5.17 can be written as follows:

\[
\frac{dF_q}{dx} = F_{q+1} \sigma_{q+1,q} + F_{q-1} \sigma_{q-1,q} - F_q (\sigma_{q,q+1} + \sigma_{q,q-1})
\]  

5.19

All the corresponding charge fractions can then be directly calculated when a complete set of cross section \(\sigma(q \rightarrow q')\) are known.

There are some limitations on the application of equation 5.17, 5.18 and 5.19:

1. All ions must be in the ground state prior to a charge-changing collision. It means that only ionization and capture cross section are taken into account. Ionization cross sections through excited state in projectile ions are neglected.

2. Energy loss of the ion can be neglected during projectile ion through gas target.

Therefore, for the charge exchange processes of oxygen through helium gas, the electron ionization and electron capture cross sections are calculated by PWBA and CDW, respectively. The evolutions of charge state fraction with target thickness are simulated according to equation 5.17-5.19. (Charge exchange cross sections \(\sigma(q \rightarrow q')\) data, see appendix 3).

Using charge exchange cross section, equation 5.19 is computed. Figure 5.6-1 and 5.6-2 show the charge state evolution for the ions \(\text{O}^{3+}\) and \(\text{O}^{1+}\) at 7.2 MeV (\(E_{\text{cm}}=2.4\) MeV) in helium gas. Clearly, once entering a target, the ions change their charge states significantly from their initial charge state. With the increase of the target thickness, some charge fractions grow to their maximum intensities, such as charge state 4+ in \(\text{O}^{3+}\) incidence (figure 5.6-1) and charge state 2+ in \(\text{O}^{1+}\) incidence (figure 5.6-2), then their charge distribution change gradually when they traverse target further. As shown in these figures, charge state fractions change with the target thickness at very onset of charge exchange. When the target reaches a critical thickness, charge state distribution does not change anymore. The critical thickness of figure 5.6-1 and figure 5.6-2 are around \(1000\times10^{14}/\text{cm}^2\) and \(2000\times10^{14}/\text{cm}^2\), respectively. We compared figure 5.6-1 with figure 5.6-2. For the process of \(\text{O}^{3+}\) in helium, at non-equilibrium distribution region, charge state fractions are different from the process of \(\text{O}^{1+}\) in He. However, at equilibrium distribution region, charge state fractions are almost the
same. The evolution of CSD with target thickness makes clear that equilibrium distributions are independent on initial charge state of projectile and non-equilibrium distributions are dependent on initial charge state of projectile. Therefore, according to the evolution of charge state fraction, the charge state fractions at equilibrium distribution are acquired to compare with experimental data.

Figure 5.6-1: Charge fraction evolution of 7.2 MeV $^{16}$O$^{3+}$ impinging on Helium gas. The curves represent various charge states $Z^+$. The critical thickness is around $1.0 \times 10^{17}/$cm$^2$.

Figure 5.6-2: Charge state evolution of 7.2 MeV $^{16}$O$^{1+}$ impinging on Helium gas. The curves represent various charge states $Z^+$. The critical thickness is around $2.0 \times 10^{17}/$cm$^2$. 

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5.2 Comparison with experimental data

In the following sections, we compare the theoretical results with experimental data. Both experimental data and calculated result in equilibrium charge state distributions for O^{1+} in helium gas are displayed in figure 5.7, 5.8 and 5.9 corresponding to 7.2, 4.5, 3.45 MeV ($E_{cm}$=2.4, 1.5, 1.15 MeV) respectively. As can be seen from these figures, to some extent the theoretical calculation can reproduce the experimental data. At 7.2 MeV, it gives a better agreement with the experimental data. However, the calculated results clearly show a disagreement with experimental data. Theoretical CSD results shift toward low charge state and such disagreement becomes serious at 4.5 and 3.45 MeV.

Experimental data from TRIUMF laboratory are used to verify theoretical calculation. Figure 5.10-5.16 show CSD at 2.2, 3.2, 5.2, 5.94, 9.4, 12, 14 MeV for oxygen through helium gas. Both experimental and theoretical data are shown in these figures. Similarly, the theoretical calculations at 14, 12, and 9 MeV show good agreement with the observed experimental data. However, at low energies, the discrepancies between the experimental data and calculated data become serious and there are general tendencies that the equilibrium charge fractions at lower charges in theory are overestimated, showing that mean charge state becomes lower than those observed. The discrepancies are probably induced by the target density effect. This effect is more likely to influence the charge exchange cross sections.

![Figure 5.7: Charge state distribution of 7.2MeV O^{1+} through helium gas target. The red dash line is theoretical calculated result. The black solid line is experimental data.](image-url)
Figure 5.8: Charge state distribution of 4.5 MeV O$^{1+}$ through helium gas target. The red dashed line is theoretical calculated result. The black solid line is experimental data.

Figure 5.9: Charge state distribution of 3.45 MeV O$^{1+}$ through helium gas target. The red dashed line is theoretical calculated result. The black solid line is experimental data.
Figure 5.10

Figure 5.11

Figure 5.12

Figure 5.13
Figure 5.10-5.16: Charge state distribution of oxygen ion through helium gas target. Incident energies of projectile are 2.2, 3.2, 5.2, 5.94, 9.4, 12, and 14 MeV. The red dashed lines are theoretical calculation, and the black solid lines are experimental data from TRIUMF lab.
5.3 Modification with density effect

Density effect of charge state distribution experiments was observed early in fission fragment [22,23]. Experimental results showed a large difference between gas target and solid target [24-26]. Bohr and Lindhard first explained this effect was caused by excited projectile state. In the dense target excited ion collides with subsequent target atom before de-excited occurs, resulting in further ionization. It results in ionization cross section enhancement and charge state distribution shift to higher charge state.

In gas target, the change of electron capture cross section is more obvious. Theoretically, V P Shevelko et al. explained the target density in electron capture processes by theory [17]. Figure 5.17 shows their calculated result. The target density dependence of the total capture cross section in the process of $O^{7+} + He \rightarrow O^{6+} + He^+$ was plotted as a function of helium density. As is seen, at relatively low density, cross section is nearly constant and shows an independence of the target density. But, with increasing of density, the cross section decreases approximately as $\sigma_{tot} \sim (N_{He})^{-0.7}$. With the helium density increasing from $10^{19}$ to $10^{21}$ cm$^{-3}$, the total cross section value drops off almost one order of magnitude[17]. Density effect of capture cross section was also observed in experiment [27].

![Figure 5.17 Capture cross section as a function of target density in the $O^{7+} + He \rightarrow O^{6+} + He^+$ reaction at 100 keV u$^{-1}$ [17].](image)

Ionization cross sections also are influence by target density. [28]. In general, the influence of density effect in solid target is obvious. Figure 5.18 shows ionization cross section in the process of $O^{7+} + C \rightarrow O^{8+} + C + e^-$ [28]. Compared to cross section in a dilute gas ($N_e=0$)
target, ionization cross sections in solid target \((N_c=10^{23}/\text{cm}^3)\) are enhanced by a factor of 2. Therefore, we can infer that the influence of the density effects in gas target \((N_g\sim10^{18}/\text{cm}^3)\) is slight.

\[ \text{Figure 5.18 Ionization cross section in process of } O^{7+} + C \rightarrow O^{8+} + C + e^{-} \text{, density is 0, } 10^{21} \text{ and } 10^{23} \text{ atom/cm}^{-3}. \text{ The cross sections increase with the target density increasing [28].} \]

We conclude that in gas target density effects would lead to a significant reduction in the capture cross sections and a slight increase in the projectile ionization cross sections, which is negligible in process of charge exchange. Thus, we correct capture cross section by density effect and compute the evolution of charge state distribution further.

In the following section, we introduce V P Shevelko’s method [17,28] to account for the density effect in capture cross section. It is found that the present model taking into account the density effects can reproduce the observed equilibrium charge distributions.

The density effect in electron capture can be attributed to following processes:

P1: be captured to excited state of projectile:
\[ X^{q+} + A \rightarrow X^{(q-1)^{++}(n)} + A^+ \]

P2: be ionized through collision with target atom:
\[ X^{(q-1)^{++}(n)} + A \rightarrow X^{q+} + e^- + A \]

P3: decay to ground state of projectile
\[ X^{(q-1)^{++}(n)} \rightarrow X^{(q-1)^+} \]
Highly excited projectile $X^{(q-1)++}$ are created via electron capture (process p1). Generally, the excited projectile $X^{(q-1)++}$ decay to lower states. The total capture cross section is sum of the all excited state cross section $\sigma_n$:

$$\sigma_{tot} = \sum_{n}^{\infty} \sigma_n$$  \hspace{1cm}  5.20

In dense target, the population of highly excited $n$ states can be destroyed by the ionization collisions with target particles. In such case, there are two behaviors, see figure 5.19: (1) $n > n_{cut}$ (process p2) ($n_{cut}$ highest possible principal quantum number), all the excited $X^{(q-1)++}$ ($n$) are ionized through the successive collisions with the target particles and then, the ions return to the previous ions $X^{q+}$. (2) $n < n_{cut}$ (process p3), all the excited $X^{(q-1)++}$ ions return to ground state via de-excitation and create $X^{(q-1)+}$. Due to behavior (1), electron capture cross section will reduce to sum of $n_{cut}$ excited state cross section, from ground state to $n_{cut}$ excited state:

$$\sigma_{tot} = \sum_{n}^{n_{cut}} \sigma_n$$  \hspace{1cm}  5.21

The $n_{cut}$ depends on target density, which can be estimated from ionization rate and radiative decay rate. Employing the classical Krames formula the total radiative decay rate and Thomson formula [29] for ionization cross section, one obtains the following approximated expression for $n_{cut}$ [17]:

$$n_{cut} = n_0 + \Delta n$$

$$\Delta n \approx q \left( \frac{10^{18}}{Z_T^2 N_T (cm^{-3})} \right)^{1/7} \left( \frac{v^2}{10q^2} \right)^{1/14}$$

$$\approx q \left( \frac{10^{18}}{Z_T^2 N_T (cm^{-3})} \right)^{1/7} \left( \frac{E(KeVu^{-1})}{250q^2} \right)^{1/14}$$  \hspace{1cm}  5.22

where, $n_0$ is the largest principal quantum number of the ground state of projectile ion, the target density $N_T$ is given in $cm^{-3}$, the relative velocity $v$ is in atomic units, the projectile energy $E$ is in $KeVu^{-1}$ and $q$ is charge state of projectile. Equation 5.22 gives a rough estimation of $n_{cut}$. The $n_{cut}$ increases with incident energy $E$, and decreases with target nuclear charge $Z_T$ and target density $N_T$. When $N_T$ is very large, then $\Delta n$ is nearly 0, namely $n_{cut} \approx n_0$. 

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resulting in only the electron captured into the ground state can survive. Thus, the total cross section reaches its minimum value. In a very dilute gas target ($N_T \to 0$), $n_{cut} \to \infty$, electron can be captured into any excited state and survive via de-excitation to ground state. In such case, the value of total cross section comes to maximum.

\[ \text{Process:p1 capture:} \quad X^{q+} + e^{-} \to X^{(q-1)+} + X \]

\[ \text{Process:p2, ionization:} \quad X^{(q-1)+} \to X^{q+} \]

\[ \text{Process:p3, de-excitation:} \quad X^{(q-1)+} \to X^{(q-1)+} \]

\[ n_{cut} \]

\[ n_{0} \]

\[ n_{0} \]

Figure 5.19: Schematic drawing of the density effect of electron capture. Three processes (p1, p2, p3) are shown. (p2: above $n_{cut}$, high excited projectiles are ionize.),( p3: below $n_{cut}$, excited projectiles are de-excited to ground state)

Using equation 5.22, the values of $n_{cut}$ are estimated and displayed in the table 5.1 in process of O$^{4+} + \text{He} \to \text{O}^{3+} + \text{He}^{+}$ with different energies of oxygen projectiles. In the table 5.1, the number of n-states will contribute to the total capture cross sections in formula 5.21. Obviously, $n_{cut}$ decreases with increasing target density and incident energy.
The capture cross sections of oxygen ion in helium gas are estimated with taking density effect into account. We recalculated the equilibrium charge state distribution for oxygen ion through helium gas using equation 5.19. The results are shown in figure 5.20-5.29. In these figures, theoretical calculations are corrected by density effect. Compared with original calculation without density effect, calculated results with density effect can reproduce experimental data. The reduction of capture cross section leads to charge state distribution shifts toward high charge state value and provide good agreement with experimental data. At 9.4, 12, and 14 MeV, capture cross sections are dominated by the low electron orbitals (small n). The corrected of density effect is slight, and calculated results are almost the same with original calculation of without density effect.

However, there are discrepancies between the theory and experiment at low energies. At 2.2 MeV, the fraction of 2+ are overestimated, and the theoretical calculation still shifts toward low charge state at 3.2 MeV, and 3.45 MeV. In theory calculation at 4.5 MeV, charge state at the highest fraction is 3+, rather than 4+. The discrepancies probably originate from the charge exchange cross section calculation. In the calculation of ionization cross section, PWBA works well at high energies range. At low energies, the coulomb effect between nuclear interaction, resulting in the non-linearly trajectory will influence the calculation [30,31]. Furthermore, the polarization and binding corrections were proposed by Basbas et al. in PWBA [32]. In calculation of capture cross section, the continuum distorted wave approximation also overestimates the electron capture possibilities at low energies. In future, the charge exchange in the collision of ion-atom needs to be studied in detail.
Figure 5.26

Figure 5.27

Figure 5.28

Figure 5.29

Figure 5.20-5.29: Theoretical calculation of equilibrium charge state distribution. The blue solid line is calculated result with density effect. The red dash line is the original calculated result without density effect. The black solid line is experimental result.
5.4 CSD of recoil oxygen in fusion reaction

In fusion reaction, recoil $^{16}$O ions are produced at the different geometric location of the gas target. Those recoil $^{16}$O produced near the inlet of the target cell reaches an equilibrium charge state distribution when it exits the cell, while those $^{16}$O produced near outlet of the target takes non-equilibrium one. This non-equilibrium contribution possibly influences the uncertainty in the fusion cross section measurement.

In previous section, it was found that non-equilibrium distribution of charge state depends on the initial charge state of projectile and target thickness. In experiment, it is difficult to measure the non-equilibrium distribution because the initial charge state of recoil oxygen is unknown at fusion moment. Some researchers tried to find it out. Schurmann et al. [33] investigated the CSD of recoils from the $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction. They assumed that in the fusion reaction, the charge state of recoil oxygen was the same as the charge state of projectile. However, the calculation result based on this assumption deviated from their data seriously. It suggested that above assumption may not be approximate. The new model and theory calculation are desirable for understand the CSD of recoil particle in fusion reaction.

In this work, we present a model to simulate the CSD of recoil oxygen in $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction. This model is a modification to previous works [33,34]. Charge exchange cross sections of both carbon helium collision and oxygen helium collision are used. In this model, we have to consider following processes:

1. CSD of carbon beam through helium gas.
2. Recoil oxygen creation
3. Recoil oxygen’s charge state at the moment of fusion reaction
4. CSD of recoil oxygen through helium gas after fusion reaction

Figure 5.30 illustrates the model. The gas target is considered as layer structure. C-beam moves through the helium gas and collides with helium atoms. In each target layer, most of C ions would pass through this helium layer and lose or capture electrons due to change exchange with helium atoms. However, a few C particles capture with helium nucleus, and fusion reaction occurs to create recoil oxygen. The recoil oxygen created at relevant helium layer will traverse the remaining helium gas target and take CSD due to change exchange.
with helium atoms. At each layer of the gas target cell, we calculate the CSD of incoming carbon beam as well as the CSD of recoil oxygen over the remaining gas target length. The simulation includes all the contributions from different geometrical locations of recoil oxygen. Therefore, the final charge state fraction of recoil oxygen can be written as follows:

$$F(q) = \frac{\sum F_{i}(q)N_{i}}{\sum N_{i}}$$  \hspace{1cm}  \text{5.23}$$

where, $F(q)$ is the final total fraction of $O^{q+}$, $F_{i}(q)$ is the recoil oxygen fraction with charge state of $q$, which are created at the $i^{th}$ layer and traverse over the remaining gas, $N_{i}$ is the number of recoil oxygen created at the $i^{th}$ layer, $I_{B}$ is the particle number of carbon beam, $N_{T}$ is the particle number of each target layer, and $\sigma_{F}$ is cross section of fusion reaction.

In formula 5.23, the numerator term is sum of specific charge state fraction of recoil oxygen at each layer and the denominator term is sum of total recoil oxygen throughout fusion reaction. Here, the cross section of fusion reaction is taken into account. At high energy, the term of cross section can be considered as constant neglecting the energy loss effect. At low energy, in order to increase the reaction events, thick target is desirable. In such case, energy loss becomes obvious, the cross section as a function of energy changes with target depth.

At non-equilibrium, CSD depends on the initial charge state of incident ion. Thus, the initial charge state of oxygen at the moment of creation is necessary to be known. However, the charge transfer mechanisms at the moment of fusion reaction are unknown. In this model
several assumptions on the electron capture process are suggested to simulate the charge transfer at the moment of fusion reaction. There are following several cases

Case 1 (0e): $^{12}\text{C}^{q+}$ ions do not capture electron from helium atom. In such case, the charge state of recoil oxygen is $q+2$, i.e. $^{16}\text{O}^{q+2}$.

Case 2 (1e): $^{12}\text{C}^{q+}$ ions capture one electron from helium atom. That means that at the moment of fusion reaction, the charge state of recoil oxygen is $q+1$, i.e. $^{16}\text{O}^{q+1}$.

Case 3(2e): $^{12}\text{C}^{q+}$ ions capture two electrons from helium atom. That means that at the moment of fusion reaction, the charge state of recoil oxygen is the same with the carbon ion, i.e. $^{16}\text{O}^{q+}$.

Case 4 (L1e): $^{12}\text{C}^{q+}$ ions do not only capture electron from helium atom, but also lose one electron. In such case, the charge state of recoil oxygen is $q-1$, i.e. $^{16}\text{O}^{q+3}$.

Case 5 (Mix.): the mixture of case 1 and case 3 with certain probability.

Five assumptions are drawn in figure 5.31. We use $^{12}\text{C}^{3+}$ as the projectile beam to illustrate the charge state of recoil oxygen at the fusion moment. Since the case 5 is the mixture of case 1 and case 3, creation possibility of case 1 is used in this assumption.

![Figure 5.31: Five assumptions of the charge state of recoil oxygen created at the moment of fusion reaction. Here, $^{12}\text{C}^{3+}$ as a projectile collides with helium atom. For the case 5, $P$ is the creation possibility of case 1.](image)
In the model, the CSD of incoming carbon beam as well as CSD of recoil oxygen through the gas target length are simulated using evolution equations of charge state on the target thickness at previous section.

At present, only set experimental data at $E_{lab}=12.8$ MeV is available to compare these simulation results. Thus, for $^4\text{He}(^{12}\text{C},^{16}\text{O})\gamma$ reaction, the CSD simulation of recoil oxygen is performed. Firstly, we have to simulate the CSD of incoming carbon beam, using the charge exchange cross section (electron loss and electron capture). For $^{12}\text{C}^{3+}$ beam through helium gas target, simulation result is plotted in figure 5.32. It presents the evolution of charge state fraction against the target thickness. Primary charge states are shown. Charge exchange cross sections of carbon with helium are from cross section obtained through fitting experimental data [34]. The dots shown in the figure 5.32 are experimental results from [34]. Simulated result of CSD of carbon beam agrees well with the experimental data.

Similarly, the CSD of oxygen ion at 9.6 MeV through helium gas target is simulated, which is shown in figure 5.33. Charge exchange cross sections are calculated, using PWBA and CDW. The experimental dots are from [33].

As seen in figure 5.32 and 5.33, the CSD simulation can reproduce the experimental data. From non-equilibrium distribution to equilibrium distribution, simulated results agree with experimental result well.
Figure 5.32 Evolution of charge state fraction of 12.8 MeV ($E_{lab}$) $^{12}$C$^{3+}$ through helium gas target. Fusion reaction is not taken into account in this process. Curves represent specific charge state of carbon ion. The dots are experimental data from [34].

Figure 5.33 Evolution of charge state fraction of 9.6 MeV ($E_{lab}$) oxygen ions through helium gas target. Curves corresponding to specific charge state of oxygen ion are simulation results. The dots are experimental data from [33]. Charge exchange cross sections are calculated using PWBA and CDW.
In fusion reaction $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ at $E_{\text{lab}}=12.8$ MeV, the CSD of recoil oxygen were simulated. At observed experiment, only data of recoil $^{\text{O}}^{6+}$ and $^{\text{O}}^{6+}/^{\text{O}}^{5+}$ are available. We thus, give the simulated results shown in figure 5.34 and 5.35. For the case 5 (mixture behavior), creation possibility of case 1(0e) is assumed 90%, 80% and 50%. Figure 5.34 shows the recoil $^{\text{O}}^{6+}$ fraction with various capture assumptions, along with experimental data [33]. Figure 5.35 shows the ratio of the fraction $^{\text{O}}^{6+}$ (F6) and $^{\text{O}}^{5+}$ (F5), along with experimental data [34]. These figures display the CSD of recoil oxygen dependence on target thickness. It is found from figure 5.34 and 5.35 that all the curves tend toward unified value when the target is sufficiently thick. In such case, evolution of CSD is dominated by equilibrium distribution, which is independent on the initial charge state of ion.

In figure 5.34, the assumption of without electron capture fits experimental data better than other assumptions. When the assumption 0e contains more assumption 2e, simulated results become worse. Assumption 2e is worst to fit the experimental data. Assumption L1e as well as assumption 1e also deviates experimental result. These results suggests in the $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction, the recoils do not contain the electrons of the target particle just after fusion reaction.

Similarly, in figure 5.35, the agreement between the simulation and experimental data is quite good for the assumption of without electron capture. It become worse as the assumption includes one or more electron capture. Assumption 1e and 2e show disagreement with the experimental data. It is noted that the ratio of F6 to F5 is larger than 1 at L1e assumption. In simulation, $^{12}\text{C}$ ion with charge state 3+ collide with helium atom. In L1e assumption, $^{12}\text{C}^{3+}$ ions create $^{16}\text{O}^{6+}$ directly at the moment of fusion reaction. When the target is very thin, the fraction $^{16}\text{O}^{6+}$ is larger than $^{16}\text{O}^{5+}$. With increasing the target thickness, the ratio of F6 to F5 decreases gradually and reaches to constant. Assumption L1e involves the ability of carbon loss electron directly. It indicates clearly that carbon nucleus do not lose one electron fully.

Above simulated results suggest in the $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ reaction, the recoils oxygen do not contain the electrons of the target particle just after fusion reaction. However, the assumption of without electron capture still presents deviation from the experimental data. The simulated result of recoil $^{\text{O}}^{6+}$ underestimates experimental data.
Assumptions are modified further. Because of underestimation of fraction of recoil $^{16}\text{O}^{6+}$, we try to increase fraction of recoil $^{16}\text{O}^{6+}$ under the assumption of without electron capture. In the assumption of without electron capture, $^{16}\text{O}^{5+}$ ions are created by $^{12}\text{C}^{3+}$ capturing helium bare nuclear at the fusion moment. Here, we assume $^{12}\text{C}^{3+}$ ion form a mixture of $^{16}\text{O}^{5+}$ and $^{16}\text{O}^{6+}$ under a certain possibility by capturing helium nuclear. For instance, $^{12}\text{C}^{3+}$ ions form 80% $^{16}\text{O}^{5+}$ and 20% $^{16}\text{O}^{6+}$. That means electron is possible to lose at the fusion moment. Therefore, several mixture possibilities are suggested, as shown in the figure 5.36 and 5.37. The possibilities between $^{16}\text{O}^{5+}$ and $^{16}\text{O}^{6+}$ are assumed as 100%:0%, 90%:10%, 80%:20%, 70%:30%, and 50%:50%. As seen in two figures, possibility assumptions at 50:50, 70:30, and 80:20 overestimate the experimental data occurred at small thickness, although they are in good agreement with experimental data at large thickness. Compared to other assumptions, the assumption of 90:10 presents good agreement with experimental data.

From the above simulated results, it is found that electrons of recoil particle created at the fusion moment are different from the charge state fraction evolution experienced by ions which pass completely through a gas target. At the moment of fusion reaction, electron capture involves special conditions such as small impact parameters and violent deceleration of the incident beam nucleus. However, the mechanism is still unclear. Furthermore, another question of electron capture at the fusion moment is whether this assumption is specific to this beam energy or is a general feature of capture reactions.

Generally, in order to determine the CSD of recoil oxygen precisely, some approaches such as, to add a post-stripper gas cell or enhance the target thickness are used. Post-stripper could produce new background. Enhancement of target thickness could lead to large energy loss. Despite the good agreement between experimental data and simulation results, certain limitations of the applied such models must be stressed. Various factors are possible to influence the CSD of recoils particles, including combination of projectile with target, and incident energy of projectile. Furthermore, more experimental data are desirable to measure the recoil CSD, because simplifying assumptions are not necessarily accurate.

It is noted that simulated result in [34] also showed similar result that recoil oxygen do not contain the electrons of the target particle at the moment of fusion reaction. Compared with the result in [34], our simulation result suggested L1e behavior further, which involves the
ability of carbon loss electron directly. The results show clearly that carbon nucleus do not lose one electron fully. Furthermore, in [34] the charge exchange cross section was obtained through fitting the experimental data. In our work, charge exchange cross sections are calculated by PWBA and CDW. It is first work to study the CSD of recoil by theoretical change exchange cross section. Thus, our simulated results are more valuable to investigate the CSD of recoil particle, and the fraction of recoil particle can be simulated at any energy while being independent on experimental data.
Figure 5.34 The fraction of recoil $^{16}O^{6+}$ in $^4He(^{12}C, ^{16}O)\gamma$ reaction. The curves are simulated results with various assumptions. The dashed curves are the mixture behavior of 0e and 2e, which represent different mixture possibilities (90:10, 80:20, 50:50). Dots are from [33].

Figure 5.35 the fraction ratio of recoil $^{16}O^{6+}$ and $O^{5+}$ in $^4He(^{12}C, ^{16}O)\gamma$ reaction. The curves are simulated results with various assumptions. Dots are experimental data from [34]. The mixture assumption (case 5) is shown as 90:10, 80:10, and 50:50.
Figure 5.36 the fraction of $^{16}O^{6+}$ in $^4$He($^{12}$C, $^{16}$O)$\gamma$ reaction. In the assumption, $^{12}$C$^{3+}$ ions produce $^{16}O^{5+}$ and $^{16}O^{6+}$ ions in various possibilities. Curves are the simulated results with different possibility assumptions. For instance, 90:10 represents 90% $^{16}O^{5+}$ and 10% $^{16}O^{6+}$.

Figure 5.37 the fraction ratio of $^{16}O^{6+}$ to $^{16}O^{5+}$ in $^4$He($^{12}$C, $^{16}$O)$\gamma$ reaction. In the assumption, $^{12}$C$^{3+}$ ions produce $^{16}O^{5+}$ and $^{16}O^{6+}$ ions in various possibilities. Curves are the simulated results with different possibility assumptions. For instance, 90:10 represents 90% $^{16}O^{5+}$ and 10% $^{16}O^{6+}$. 
In previous simulation of recoil oxygen CSD, theoretical calculation under 0e assumption agrees well with experimental data. These results reveal that in fusion reaction carbon ions mainly capture helium nucleus. In fusion reaction, charge state of recoil oxygen ions created near outlet of target take a non-equilibrium distribution, which depends on initial charge state of projectile and target thickness. Thus, we employ assumption 0e to estimate charge fractions of recoil oxygen in non-equilibrium distribution at our measured energies (E_{cm}=2.4, 1.5, and 1.15 MeV). After that we estimate charge fraction of recoil oxygen at 15 Torr under various assumptions. All simulated parameters are based on our experiment of ^4He(^12C, ^16O)_\gamma fusion reaction, including gas pressure, effective target length, incident carbon beam, measured energies and calculated charge state of recoil oxygen.

Firstly, we simulate charge state distribution of recoil oxygen created at relevant target location. The energy at center of mass system is 2.4 MeV. Gas pressure is 15 Torr. Charge state distribution of recoil oxygen depends on location within target, where fusion reaction occurs. In order to explain the simulation result clearly, target structure is shown in the upper of figure 5.38. Whole target length is 4.5 cm. Figure 5.38 shows $^{16}\text{O}^{5+}$ fraction changes with target position. At region 1, the value of $^{16}\text{O}^{5+}$ fraction remains constant, which indicates that recoil oxygen ions created at region 1 take an equilibrium distribution after coming out of target. At region 2, the value of $^{16}\text{O}^{5+}$ fraction varies with target position. Thus, recoil oxygen ions created at region 2 take a non-equilibrium distribution after coming out of target. From figure 5.38, the length of region 2 is around 0.59 cm, taking up 13% of whole target length. Simulated results are obtained under 0e assumption. Regarding other assumptions, the length of non-equilibrium distribution may charge a few. At 1.5 MeV, and 1.15 MeV, non-equilibrium distribution length are also estimated. The results are shown in table 5.2. At 1.15 MeV, the ratio of non-equilibrium distribution length is smallest.

Next, we try to determine upper limit and lower limit of charge fraction of recoil oxygen. Employed assumptions of electron capture just after the moment of fusion reaction are 0e, 1e, 2e, L1e, $^{16}\text{O}^{6+}$, and $^{16}\text{O}^{8+}$, where $^{16}\text{O}^{6+}$ and $^{16}\text{O}^{8+}$ represent that bear carbon nucleus captures helium atom, and bear helium nucleus, respectively. Figure 5.39 shows $^{16}\text{O}^{5+}$ fraction varies with gas pressure results under various assumptions. Curves represent different assumptions. At low pressure, the differences of fraction due to assumptions are obvious. At high pressure
(thick target), the differences become small and no noticeable changes caused by assumptions are observed. All of simulated results tend to equilibrium distribution with increasing of gas pressure.

At 1.5 MeV, and 1.15 MeV, charge fractions of recoil oxygen are also simulated, where, recoil $^{16}\text{O}^{3+}$ ions are calculated. (Simulated figures are shown in appendix 5)

Thus, we derive the values of charge fraction of recoil $^{16}\text{O}^{q+}$ at 15 Torr. The results are tabulated in table 5.3. In thick target charge state of recoil oxygen just after the moment of fusion reaction has small influence on charge fraction of recoil oxygen. Thus, upper limit and lower limit of fraction range are determined according to charge fractions obtained under different assumptions. Charge fraction at 2.4 MeV, 1.5 MeV, and 1.15 MeV are $38.5 \pm 0.5\%$, $37.3 \pm 0.3\%$, and $39.1 \pm 0.1\%$, respectively. The results are reliable and valuable to obtained total number of recoil oxygen precisely since the non-equilibrium distribution is taken into account.

As shown in table 5.3, charge fraction in thick target is sensitive to equilibrium distribution. In equilibrium distribution calculation, charge exchange cross sections play an important role, which influence calculated results obviously. In previous calculation of equilibrium distribution, we found that the discrepancies between theoretical data and experimental data still exist at low energies, which has been discussed in section 5.3 (density effect). Such discrepancies in equilibrium distribution may lead to large deviation in charge fraction of recoil particles relative to actual value and result in inaccurate estimation of total recoil particle. Thus, experimental measurements in equilibrium distribution are still necessary at low energies ($E_{\text{cm}}=1.0~0.7$ MeV). These experimental results contribute to correct the theory further. Theoretical calculation needs to be corrected further and more effects will be taken into account at low energies. However, charge exchange cross sections are reliable at present measured energy ($E_{\text{cm}}=2.4$, 1.5, and 1.15 MeV).
Figure 5.38: $^{16}$O$^{5+}$ fraction simulation result ($E_{cm}=2.4$ MeV). Incident energy of $^{12}$C$^{2+}$ beam is 9.6 MeV, and recoil oxygen energy is 7.2 MeV. At region 1, the length of equilibrium distribution is around 3.91 cm (87% of total target length), and at region 2, the length of non-equilibrium distribution is around 0.59 cm (13% of total target length).

Figure 5.39: $^{16}$O$^{5+}$ fraction changes with gas pressure at $E_{cm}=2.4$ MeV. Curves represent different assumption. All of simulation results tend to equilibrium distribution with increasing of gas pressure.
Table 5.2. Non-equilibrium distribution length at 15 Torr under 0e assumption.
The energies shown in the table are in center of mass system.

<table>
<thead>
<tr>
<th>Calculated ion</th>
<th>2.4MeV</th>
<th>1.5 MeV</th>
<th>1.15MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{O}^{5+}$</td>
<td>3.91 cm (87%)</td>
<td>4.15 cm (92%)</td>
<td>4.32 cm (94%)</td>
</tr>
<tr>
<td>$^{16}\text{O}^{3+}$</td>
<td>0.59 cm (13%)</td>
<td>0.35 cm (8%)</td>
<td>0.27 cm (6%)</td>
</tr>
</tbody>
</table>

Table 5.3. Recoil oxygen charge state fraction at 15 Torr under different assumptions, from which fraction range is derived.
The energies shown in the table are in center of mass system.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>2.4MeV</th>
<th>1.5 MeV</th>
<th>1.15MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated recoil ion</td>
<td>$^{16}\text{O}^{5+}$</td>
<td>$^{16}\text{O}^{3+}$</td>
<td>$^{16}\text{O}^{3+}$</td>
</tr>
<tr>
<td>0e</td>
<td>38.6%</td>
<td>37.2%</td>
<td>39.1%</td>
</tr>
<tr>
<td>1e</td>
<td>39.0%</td>
<td>37.1%</td>
<td>39.2%</td>
</tr>
<tr>
<td>2e</td>
<td>38.9%</td>
<td>37.6%</td>
<td>39.2%</td>
</tr>
<tr>
<td>L1e</td>
<td>38.3%</td>
<td>37.1%</td>
<td>39.0%</td>
</tr>
<tr>
<td>$^{16}\text{O}^{6+}$</td>
<td>38.9%</td>
<td>37.2%</td>
<td>39.0%</td>
</tr>
<tr>
<td>$^{16}\text{O}^{8+}$</td>
<td>38.0%</td>
<td>37.0%</td>
<td>39.0%</td>
</tr>
<tr>
<td>Charge fraction</td>
<td>38.5 ± 0.5%</td>
<td>37.3 ± 0.3%</td>
<td>39.1 ± 0.1%</td>
</tr>
</tbody>
</table>
Reference


Chapter 6 Conclusions

The reaction $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$ ($Q=7.16$ MeV) takes place during helium burning in Red Giants. The reaction rate at the relevant thermonuclear fusion energy ($E_0=0.3$ MeV) determines the abundances of carbon and oxygen at the end of helium burning. Most promising experimental system was suggested. For recoil oxygen measurement in $^{12}\text{C}^+^4\text{He}$ reaction, only one charge state of the recoil oxygen can be transmitted for a given separator setting. In order to determine the yield from a reaction accurately, the charge state distribution of the recoils must be understood. Thus, the present work investigated ion-atom collision that is involved with charge state distributions of astrophysical interest.

Windowless gas target was used to confine the gas in vacuum. In the target cell, gas pressure can reach up to $\sim 3.16 \times 10^3$ Pa (24 Torr), which can provide sufficient target atoms in fusion reaction. Equilibrium charge state distributions of oxygen ions through helium gas target have been measured at 7.2 MeV, 4.5 MeV and 3.45 MeV. The charge distributions at the measured energies can be modeled with a Gaussian formula. Thus, mean charge state and distribution width are fitted using semi-empirical models. These fitting results are used to predict the equilibrium charge state distributions with the energy range from 1 MeV to 20 MeV. However, the current use of empirical fits is devoid of any physics and provides little scientific value to the charge exchange processes. Furthermore, it fails to explain the evolution of charge state distribution with the target thickness.

The quantum mechanical theory for charge exchange is applied to calculate collision cross section. In our calculation, plane wave born approximation with screening effect is employed to calculate the ionization cross sections. Capture cross sections are estimated by continuum distorted wave approximation. Calculation has been done for oxygen-helium collision over the energy range: 0.5 keV~20 MeV. Despite of discrepancies at low energies, agreements with the existing experimental data indicate that present theoretical approximations are proper for the estimation of charge exchange cross section at our measured energy range: 1 MeV~15 MeV. The evolution of charge state fractions with target thickness are firstly simulated using theoretical charge exchange cross sections at astrophysical nuclear reaction
energy range. The results show that charge state fractions varied with target thickness from non-equilibrium distribution to equilibrium distribution. For the equilibrium distribution, we compared theoretical result and experimental data. At high energies (>9.0MeV), they show a good agreement. However, at low energies (<9.0MeV), theoretical result deviated from the experimental data and shift toward low charge state. Theoretical calculation overestimated the fraction of low charge state. After taking density effect into account, we recalculated capture cross sections that provides a better agreement with experimental data. Experimental data thus almost could be reproduced. It reveals that target density influences charge exchange to some extent, especially in dense medium. These good agreements clearly indicate that our theoretical calculation is proper to simulate the evolution of charge state distribution.

Furthermore, we analyzed the charge state distribution of recoil oxygen in $^4\text{He}(^{12}\text{C}, ^{16}\text{O})\gamma$. A model is used to simulate the CSD of recoil oxygen. Both CSD of carbon beam and recoil oxygen are included into this model. Several assumptions are suggested to simulate the charge state of recoil oxygen just after the moment of fusion reaction. Simulation results can provide good agreement with available experimental data. The best agreement with experiment comes from the 0e assumption: without electron capture from target. Furthermore, the modified results of 0e assumption imply that additional electrons may be lost during the fusion reaction. Whole simulated results reveal that CSD of recoil particles differ from CSD of ions completely through a gas target. Those efforts may provide information to understand electron capture at moment of fusion reaction. However, the CSD of recoil particles is a complicate process and involve many special conditions, such as, combination of projectile and target, reaction energy of fusion reaction, projectile energy, and binding energy of recoil oxygen.

Under the assumption of without electron capture (0e), the region of non-equilibrium distribution within target is simulated. At $E_{\text{cm}}=1.15$ MeV, region length is smallest amounting to 6% of total target length. Furthermore, at 15 Torr, we obtained the value of charge fraction under various assumptions and estimated charge fraction of recoil oxygen. We realized the estimation of charge state distribution of recoil oxygen using charge exchange theoretical cross section for first time. The results are useful to obtain cross section in fusion reaction
precisely since non-equilibrium charge state distribution of recoil oxygen is taken into account. At present calculation, there are still discrepancies at low energies. We expect more experimental measurements including non-equilibrium and equilibrium charge state distribution and theoretical correction at low energy.
Acknowledgements

Back to first visit to Japan, I was picked up by my supervisor and his wife. Now, three years go by. During this period, I learned a lot, not only in knowledge, life, culture, still in affection.

Thus, there are so many people I would like to thank and not enough space to make it happen, so if you do not see your name here I am sorry. You will be in my heart, I promise.

At Kobe University, my deepest gratitude goes first and foremost to thank my supervisor, associate Professor Sakurai, a modest and kindly scientist, for his constant encouragement and guidance. He has walked me through all the stages of the writing of thesis. Without his consistent and illuminating instruction, I could not complete my study at Kobe University.

I would like to thank Associate professor Komoto and Associate professor Okamura for their help and instruction when I came to quantum dynamics group. I certainly want to thank all other members of quantum dynamics group: Mr. Moriya, Mr. Asakurai, Mr. Iida, Mr. Sakai, Ms. Liang, Mr. Takahara, Mr. Yamazaki, et al. I will remember ours happy time: studying, playing and, eating.

I am also greatly indebted to the professors and staffs at the department of physics, who have instructed and help me a lot in the past three years.

At Kyushu University, I would like to give my deep thanks to Professor Sagara at Kyushu University, a humorous and knowledgeable scientist. I am appreciated him for allowing me to join astrophysics nuclear experiment. During my study at Kyushu University, I got a lot of advice and guidance from him, including experiment, theory, writing of this thesis, even the life at Fukuoka.

Special thank goes to Associate professor Teranishi and Assistant professor Fujita. I got a lot of helpful discussion and guidance from them. Also, I would like to thank KUTL. It is just like a big family, full of friendship.
Of course, I won’t forget other members of astrophysical nuclear group: Mr. Yamakuchi, Ms. Matsuda, Mr. Mitsudumi, Mr. Makoto, Mr. Kotama, Ms. Maria T. Rosary, et al. In each experiment, we stayed up all night together. Without their hard work, experiment could not go smoothly. I also enjoyed the fruitful discussion in every astrophysics meeting.

I would like to thank Dr. I. Yu. Tolstikhina and Dr. Kato, for their help on theoretical calculation.

I would like to thank a kind Japanese friend, Ms. Iida, who gave me instruction in my Japanese study.

In addition, my thanks would go to my beloved family for their loving considerations and great confidence in me all through these years.

I owe my sincere gratitude to Lanzhou University Professor Wang, who gave me supports and encouragements for my study. I thank him for visiting me twice in Japan.

Finally, I thank the China CSC scholarship program for supporting my study in Japan so that I could finish the doctor study smoothly.
Appendix

Appendix 1 (chapter 1):

The height of the Coulomb barrier between two nuclei is written as:

$$E_{\text{coul}} = \frac{e^2 Z_i Z_j}{4\pi\varepsilon_0 r_0}$$

$r_0$ is nuclear interaction radius at short distances. At $E < E_{\text{coul}}$, penetrability $P$ is approximated by the relation:

$$P \propto \exp\left(-\frac{2\pi Z_i Z_j e^2}{h\nu}\right) = \exp(-2\pi\eta)$$

where $Z_i$ is the atomic number of nucleus $i$ and $\eta$ is the Sommerfeld parameter given by

$$\eta = \frac{Z_i Z_j e^2}{h\nu}$$

The probability for the tunnel effect is given:

$$P \propto \sigma(E) \propto \exp(-2\pi\eta)$$

Moreover, cross section scales with the square of De Broglie wavelength: $\pi\lambda^2$ ($\lambda$ is the De Broglie wave length),

$$\sigma \propto \pi\lambda^2 \propto \frac{1}{E}$$

Thus, we have non-nuclear energy dependence $\sigma(E) \sim 1/E$. The cross section is obtained from above relations:

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

The $S(E)$ in the equation reflects the pure nuclear physics energy dependence, called nuclear or astrophysical S-factor.
Appendix 2 (chapter 5):

Capture cross section (CDW approximation)

Figure app.2 projectile, target and active electron vector position

$R$: the position vector of projectile (nuclear charge: $Z_P$) relative to target (nuclear charge: $Z_T$)
$s$: position vector of electron relative to projectile
$x$: position vector of electron relative to target
$r$: position vector of electron relative to the mid-point of projectile-target.
$v$: speed of projectile
$t$: time
$b$: impact parameter

$R = b + vt$

In the impact parameter formulation it is assumed that the position of target remains fixed while projectile moves in a straight line with a constant speed $v$.

The time dependent Schrödinger equation:

$$\left(\frac{1}{2} \nabla^2_r + \frac{Z_T}{x} + \frac{Z_P}{s} + i \frac{\partial}{\partial t} + \frac{Z_T Z_P}{R}\right)\Psi = 0$$

A.1

The asymptotic condition on the wave function $\Psi$ may be written as:

$$\Psi_i(t) \xrightarrow{t \to -\infty} \Phi_i(r,t) \exp(i\zeta_i) = \Phi_i(r,t) \exp\left\{i\frac{Z_1(Z_1-1)}{v} \ln(vR - v^2t)\right\}$$

A.2

$$\Psi_f(t) \xrightarrow{t \to +\infty} \Phi_f(r,t) \exp(-i\zeta_f) = \Phi_f(r,t) \exp\left\{-i\frac{Z_1(Z_1-1)}{v} \ln(vR + v^2t)\right\}$$

A.3

The unperturbed initial and final states $\Phi_i$ and $\Phi_f$ satisfy the equations:

$$\left(\frac{1}{2} \nabla^2_r + \frac{Z_T}{x} + i \frac{\partial}{\partial t}\right)\Phi_i = 0$$

A.4
The solutions of above equations are given:

\[
\Phi_i = \phi_i(x) \exp(-\tau_\alpha) \quad \Phi_f = \phi_f(s) \exp(-\tau_\beta)
\]

\[
\tau_\alpha = \frac{1}{2} v \cdot r + \frac{1}{8} v^2 t + \varepsilon_\alpha t \quad \tau_\beta = -\frac{1}{2} v \cdot r + \frac{1}{8} v^2 t + \varepsilon_\beta t
\]

where \( \exp \left( i \left( \frac{1}{2} v \cdot r - \frac{1}{8} v^2 t \right) \right) \) or \( \exp \left( -i \left( \frac{1}{2} v \cdot r + \frac{1}{8} v^2 t \right) \right) \) is denoted as electron translation factor. It takes into account momentum and energy of electron orbital moving with the projectile. Thus, for the moving projectile, the electron translation factor is included into \( \Phi_i \) and \( \Phi_f \).

\( \phi_i \) and \( \phi_f \) are electronic eigenfunctions with the corresponding eigenenergies \( \varepsilon_i \) and \( \varepsilon_f \) in their own coordinate systems.

To introduce distorted wave:

\[
\frac{1}{2} \nabla_r^2 + \frac{Z_p}{s} + i \frac{\partial}{\partial t} + U_i ) \chi_i(r,t) = 0 \tag{A.8}
\]

\[
\frac{1}{2} \nabla_r^2 + \frac{Z_p}{s} + i \frac{\partial}{\partial t} + U_f ) \chi_f(r,t) = 0 \tag{A.9}
\]

with boundary condition:

\[
\chi_i(r,t) \xrightarrow{t \to \infty} \Phi_i \exp(i\zeta_\alpha) \tag{A.10}
\]

\[
\chi_f(r,t) \xrightarrow{t \to \infty} \Phi_f \exp(i\zeta_\beta) \tag{A.11}
\]

\( U_i \) and \( U_f \) are some distorting potentials that have to be chosen in accordance with the boundary condition on \( \chi_i \) and \( \chi_f \).

Here, we use post form. The transition amplitude for the charge exchange:

\[
a_{if} = i \lim_{t \to +\infty} \int dr \Phi_f^* \Psi_i = \lim_{t \to +\infty} \int dr \chi_f^* \Psi_i = \int dr \int dt (\frac{\partial \chi_f^*}{\partial t} \Psi_i + \chi_f^* \frac{\partial \Psi_i}{\partial t})
\]

\[
= i \int_{-\infty}^{+\infty} dr \int \left( \frac{Z_i - Z_p}{s} - U_f \right) \chi_f^* \Psi_i \tag{A.12}
\]

Suppose we factorize \( \Psi \) as:
Using A.4, and A.13, we have:

\[
\Psi(r,t) = \Phi_i F_i
\]  

A.13

\[
\left(\frac{1}{2} \nabla_i^2 + \frac{Z_p}{s} + i \frac{\partial}{\partial t} - \frac{Z_f Z_p}{R} - \frac{1}{2} iv \cdot \nabla\right) F_i = \exp(\tau_\alpha) \nabla \Phi_i \cdot \nabla F_i
\]  

A.14

Neglect the right-hand side of A.14 to obtain a zero order approximation \( F_i^0 \) to \( F_i \)

\[
\left(\frac{1}{2} \nabla_i^2 + \frac{Z_p}{s} + i \frac{\partial}{\partial t} - \frac{Z_f Z_p}{R} - \frac{1}{2} iv \cdot \nabla\right) F_i^0 = 0, \quad F_i^0(\infty) = 1
\]  

A.15

which has the regular solution,

\[
F_i^0(s,t) = N(v_p) \exp\left\{ iv \ln(vR - v^2 t)\right\} \exp\left(1 + ivs + iv \cdot s\right)
\]  

A.16

Similarly, we have the \( F_f^0 \):

\[
F_f^0(x,t) = N^*(v_T) \exp\left\{-iv \ln(vR + v^2 t)\right\} \exp\left(1 - ivx - iv \cdot x\right)
\]  

A.17

\[
N(v_i) = \exp(\pi v_i / 2) \Gamma(1 - iv_i); \quad v_i = \frac{Z_l v}{v} (l = P, T), v = \frac{Z_f Z_p}{v}
\]  

A.18

The distorted wave functions are defined by:

\[
\chi_i = \Phi_i F_i^0
\]  

A.19

\[
\chi_f = \Phi_f F_f^0
\]  

A.20

The corresponding distorting potentials are

\[
U_i = \frac{1}{s} - \frac{1}{R} + A_i
\]  

A.21

\[
U_f = \frac{1}{x} - \frac{1}{R} + A_f
\]  

A.22

We then have:

\[
A_i \chi_i = \exp(-\tau_\alpha) \nabla \phi_i \cdot \nabla F_i^0
\]  

and

\[
A_f \chi_f = \exp(-\tau_\beta) \nabla \phi_f \cdot \nabla F_f^0
\]  

A.23

Finally, the transition amplitude A.12 can be written by substituting A.23 and \( \chi_i \) for \( \Psi_i \),

\[
a_{if} = i N(v_p) N(v_T) (bv)^2 \int_{-\infty}^{+\infty} dt \int dr \exp\left\{-i(v \cdot r + \Delta ct)\right\} \Re_{if}
\]  

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\begin{align}
\mathcal{R}_{if} &= \phi_i(x) F_1(i\nu_p, l, i\nu_s + iv \cdot s) \nabla \phi_j^*(s) \cdot \nabla F_1(i\nu_T, l, i\nu_x + iv \cdot x) \\
\Delta \epsilon &= \epsilon_i - \epsilon_f
\end{align}

The cross section for electron capture is then obtained by integrating over all possible impact parameters $b$:

$$\sigma_{if} = 2 \int_0^\infty b |a_{if}|^2 \, db$$

Reference:

Appendix 3 (chapter 5)
Charge exchange cross section (unit: cm²)

**Ionization (PWBA):** \(^{16}\text{O}^{q+} + \text{He} \rightarrow ^{16}\text{O}^{(q+1)+} + \text{He} + e\)

**Capture (CDW):** \(^{16}\text{O}^{q+} + \text{He} \rightarrow ^{16}\text{O}^{(q-1)+} + \text{He}^{1+}\)

### Oxygen at 2.2 MeV

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<td>$6.25 \times 10^{-19}$</td>
<td>$7^+ \rightarrow 6^+$</td>
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<td>$2.01 \times 10^{-19}$</td>
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### Oxygen at 12 MeV

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<td>$8.94 \times 10^{-19}$</td>
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<td>$8.74 \times 10^{-18}$</td>
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### Oxygen at 14 MeV

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Appendix 4:

O^{q+} ionization energy:

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<th>2p(eV)</th>
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<tr>
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<td>6+</td>
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<td>7+</td>
<td>871</td>
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</tbody>
</table>

Reference:
Appendix 5 (chapter 5)

Upper figure: O^{3+} fraction simulation result ($E_{cm}=1.5$ MeV). Incident energy of $^{12}C^{2+}$ beam is 6.0 MeV, and recoil oxygen energy is 4.5 MeV. 0e assumption is used. The length of non-equilibrium distribution is around 0.35 cm (8% of total target length).

Lower figure: O^{3+} fraction simulation result ($E_{cm}=1.15$ MeV). Incident energy of $^{12}C^{2+}$ beam is 4.6 MeV, and recoil oxygen energy is 3.45 MeV. 0e assumption is used. The length of non-equilibrium distribution is around 0.27 cm (6% of total target length).
At 15 Torr, recoil oxygen fraction in different assumptions. Curves represent various assumption of charge state of recoil oxygen just after moment of fusion reaction. All of simulated results tend to equilibrium distribution.

Upper figure: $E_{cm}=1.5$ MeV

Lower figure: $E_{cm}=1.15$ MeV

At 15 Torr, recoil oxygen fraction in different assumptions. Curves represent various assumption of charge state of recoil oxygen just after moment of fusion reaction. All of simulated results tend to equilibrium distribution.

Upper figure: $E_{cm}=1.5$ MeV

Lower figure: $E_{cm}=1.15$ MeV
Appendix 6:

Abbreviation

CNO: carbon nitrogen and oxygen
CSD: charge state distribution
CDW: continuum distorted wave
DP: diffusion pump
ED: electric deflector
$E_{\text{cm}}$: the energy at the coordinate of center of mass
$E_{\text{lab}}$: the energy at the coordinate of laboratory
FC: Faraday cup
KUTL: Kyushu University tandem laboratory
NRC: Non-radiative electron capture
PWBA: plane wave born approximation
RMS: recoil mass separator
REC: radiative electron capture
SNICS: sputtering negative ion cesium source
SRIM: Stopping and Range of Ions in Matter
Target-SSD: target silicon solid state detector
TOF: time of flight
TMP: turbo molecular pump