Atomic charge exchange between semi-relativistic ($v/c = 0.49$) helium ions and targets from carbon to lead.

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Abstract

Ratios of equilibrium charge-state yields for singly to doubly ionized ^{3}He ions at an energy of 420 MeV were measured using the Grand Raiden magnetic spectrometer at RCNP. Targets with atomic numbers of 6, 12, 28, 40, 50 and 82 were used. It is found that theoretical calculations for atomic electron capture and stripping cross sections, which have been successful in describing the data up to beam energies of 200 MeV, are also applicable at this higher energy. However, where at the lower energies the stripping cross sections were calculated with a combination of models by Bohr and Gillespie, the best description of the data at E(^{3}He)=420 MeV is obtained when using only the model by Gillespie. The experimental results are also

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compared with calculations using the code CHARGE, originally developed for fast, heavy ($Z > 29$) projectiles, to test the extrapolation to low-Z projectiles. It is found that the code underestimates the production of singly-charged ^{3}He ions, in particular for heavier target nuclei.

Key words: Atomic charge-exchange, Ionization (stripping), Capture
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1 Introduction

The (^{3}He,t) nuclear charge-exchange reaction has been employed widely to study the spin-isospin response of nuclei. In recent years, most of such experiments have been performed at the Research Center for Nuclear Physics (RCNP), using ^{3}He^{++} beams with bombarding energies of 420 and 450 MeV. When the scattered tritons are measured in the focal plane of the magnetic spectrometer Grand Raiden [1], a strong peak due to ^{3}He$^+$ ions is observed. This peak originates from atomic capture of electrons from target atoms by incoming ^{3}He^{++} ions. The ^{3}He$^+$ charge-state contaminants are useful for calibration purposes. Compared to the nuclear charge-exchange reactions, the atomic charge-exchange process does not involve significant energy and momentum transfer. Therefore, the ^{3}He$^+$ charge-state measured in the focal plane of the spectrometer provides information about properties such as angular spread of the incoming ^{3}He^{++} beam and it designates the central beam axis. In addition, if the atomic charge-exchange process can be well described, the yield of ^{3}He$^+$ ions in the focal plane can be used as a tool to check normalization procedures for obtaining absolute nuclear charge-exchange cross sections.

The present work is mostly motivated by the prospect of using the atomic charge-exchange data in normalization procedures for (^{3}He,t) nuclear charge-exchange experiments at E(^{3}He)=420 MeV. However, a proper description of the atomic charge-exchange process is also important for other purposes. In particular, reasonable estimates of atomic electron-capture and stripping are important for the design of future facilities and detection systems employing radioactive ion beams [2]. In addition, the atomic charge-exchange process is of interest for astrophysical applications [3].

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There is no comprehensive theory that describes the atomic charge-exchange process consistently over wide energy and mass ranges. Therefore, a semi-phenomenological approach is often used, which takes into account the balance between stripping and capture contributions. This approach - based on the works of Allison [4], Betz [5], Bohr [6], Gillespie [7] and Nikolaev [8] and tested experimentally by Katayama *et al.* [9–12], Dennis *et al.* [13] and Gójska *et al.* [14,15] - is described in more detail below. In spite of the many approximations made, the results of the calculations are in good agreement with data obtained over a wide range of beam energies (E(^{3}He)=67.9 MeV, 99.2 MeV, 130.2 MeV [9–12], and 200 MeV [13]).

We studied the atomic charge-exchange between ^{3}He ions at 420 MeV ($\beta = 0.49$) and a variety of targets with different atomic number. The experimental results are compared with the theoretical calculations mentioned above and are an extension to higher beam energies of the work by Dennis *et al.* [13]. At present, efforts to improve the theoretical description based on data taken at 450 MeV are also in progress [14,15]. The data presented here can provide additional input for such studies.

To calculate atomic charge-exchange cross sections of relevance in experiments with fast radioactive beams, computer programs such as CHARGE [2] (implemented in the code LISE++ [16]) are used. The program CHARGE was developed for projectiles with $Z > 29$ and beam energies exceeding 80 MeV/u. It is not well known whether extensions to lower energies and projectile atomic number will produce reasonable estimates of charge-state distributions, despite a strong interest in such predictions. Therefore, we compare the present results with the predictions of the code CHARGE as well.

2 Experiment

A beam of ^{3}He^{++} particles with a kinetic energy E=420 MeV generated at the Ring Cyclotron Facility at RCNP was used to bombard a variety of isotopically-enriched targets at beam intensities varying between 4 and 10 enA. The targets and their thicknesses were: ^{12}C (4.1 mg/cm^2), ^{26}Mg (3.6 mg/cm^2), ^{60}Ni (4.0 mg/cm^2), ^{90}Zr (7.3 mg/cm^2), ^{120}Sn (2.6 mg/cm^2), and ^{208}Pb (5.2 mg/cm^2). These target thicknesses far exceed those used in earlier experiments of about 50 μg/cm^2 for ^{12}C [9] to about 200μg/cm^2 for ^{197}Au [14] for which equilibrium between electron stripping and capture is reached and the charge-state distribution thus becomes independent of the target thicknesses.

The ^{3}He$^+$ ions were detected in the focal plane of the Grand Raiden spectrometer [1] set at 0° relative to the incoming beam axis. The details of the

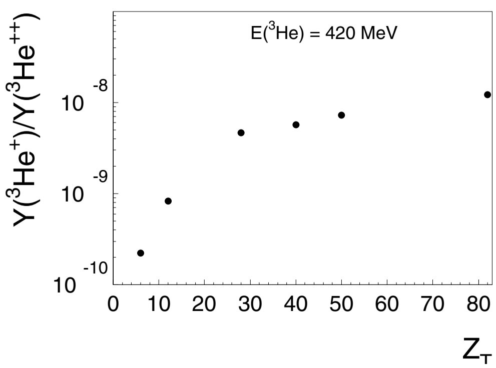

Fig. 1. Ratio of measured yields (Y) for ^{3}He$^+$ and ^{3}He^{++} ions for targets with Z_T= 6, 12, 28, 40, 50, and 82 at E(^{3}He)=420 MeV.

experimental setup are the same as given in Refs. [17,18]. The tritons produced in the (^{3}He,t) nuclear charge-exchange reactions were easily separated from the ^{3}He$^+$ ions by measuring the energy losses in a stack of focal-plane scintillators. For each target, the number of ^{3}He$^+$ charge-state events was summed and the total yield was corrected for data-acquisition dead time ($\sim$ 1%). The ^{3}He^{++} ions were collected in a Faraday cup placed in the first dipole magnet of the spectrometer. The systematic error in the current integration was estimated by comparing the differential cross sections for the ^{13}C(^{3}He,t)^{13}N(1/2$^-$, g.s.) and ^{208}Pb(^{3}He,t)^{208}Bi(0$^+$,15.16 MeV) nuclear charge-exchange reactions measured in this experiment, to those previously reported (see Refs. [19] and [17], respectively). The difference between the present and previous results was less than 10% [20]. This deviation provides a reasonable estimate for the error in the beam integration. However, it should be noted that this systematic error is the same for all targets used in this experiment and would only lead to an overall scaling factor. Therefore, this systematic error is not indicated in the figures.

Fig. 1 shows the ratio of measured yields (Y) for ^{3}He$^+$ and ^{3}He^{++} particles as a function of atomic number of the target Z_T. Statistical errors are negligibly small. The rising trend as a function of Z_T is very similar to those seen at lower beam energies [9–13].

3 Theoretical Cross-Section Estimates

The charge-state distribution following atomic charge-exchange reactions depends strongly upon the velocity of the incoming particles and the atomic number of the target atoms. These factors are included in the descriptions of capture and stripping cross sections. The charge-state distribution can be calculated using the following differential equations [4,5]:

$$\frac{dY(^3He^+)}{dx} = N\{\sigma_{cap}Y(^3He^{++}) - \sigma_{strip}Y(^3He^+)\}, \tag{1}$$

$$\frac{dY(^3He^{++})}{dx} = N\{\sigma_{strip}Y(^3He^+) - \sigma_{cap}Y(^3He^{++})\}. \tag{2}$$

In the case of equilibrium charge-state distribution, this reduces to:

$$\frac{Y(^3He^+)}{Y(^3He^{++})} = \frac{\sigma_{cap}}{\sigma_{strip}}. \tag{3}$$

By measuring the charge-state distributions, the ratio of theoretical estimates for the capture and stripping cross sections can thus be tested.

3.1 Calculation of Capture Cross Section

Nikolaev calculated atomic capture cross sections for protons colliding with multi-electron atoms using hydrogen-like wave functions in the one-electron variant of the Brinkmann-Kramers' approximation [8]. The cross section for the capture of an electron into a projectile state with principal quantum number n_a from a target with a fully-filled electron shell of principal quantum number n is determined by:

$$\sigma_{cap}(n_a|n) = \pi a_0^2 \frac{2^8}{5} N_a n^2 (\frac{v_0}{v})^2 \gamma^5 \eta_n^5 (1+\beta)^{\frac{5}{2}} (1+\beta\gamma)^{-3} \Phi_4(\beta\gamma), \tag{4}$$

where $a_0 \simeq 5.292 \times 10^{-9}$ cm and $v_0 \simeq 2.188 \times 10^8$ cm/s are the atomic units of length (Bohr radius) and velocity, respectively and N_a is the number of electrons in the shell with principal quantum number n_a. The other parameters in Eq. 4 are defined as:

$$\gamma = 4V^{-2}[1 + 2(1+\eta_n^2)V^{-2} + (1-\eta_n^2)^2 V^{-4}]^{-1}, \tag{5}$$

$$V = v/u; u = (2\epsilon_a/\mu)^{1/2}, \tag{6}$$

$$\eta_n = Zv_0/nu, \tag{7}$$

and [3]

$$\beta = \mu v_0^2 b_a^2/(2\epsilon_a c^2) - 1. \tag{8}$$

[3] The expression for β differs from that given in Ref. [8], because of a misprint in the latter.

In these equations, v is the speed of the projectile (in cm/s), and ϵ_a is the weighted average of the binding energies of electrons [21] in keV. μ is the mass of the electron (keV), Z is the charge of the projectile ($Z = 2$ for ^{3}He), and b_a describes the screening effect due to other electrons in the target atom. To calculate b_a, the effective charge of the nucleus is divided by the principal quantum number n_a of the electron shell from which capture occurs. The effective charge Z_T^* equals $Z_T - s$, where s is calculated using the Slater rules [22].

Finally, Φ_4 was approximated as

$$\Phi_4 = 1 - 0.25\beta\gamma, \tag{9}$$

because $\beta\gamma$ is smaller than 1 for all the targets considered here (Z_T=1-82). The full expression for Φ_4, as well as further justification for the aforementioned approximation, is given in Ref. [8].

In Ref. [8] Eq. (4) was renormalized to ensure agreement with experimental capture cross sections for protons at low energies. This phenomenological renormalization was introduced as:

$$R_0(t) = \frac{0.3}{(t^{-8} + t)^{0.2}}, \tag{10}$$

with

$$t = \frac{7}{9}\frac{v}{v_0\sqrt{b_a}}. \tag{11}$$

Further discussion of this correction is given in Ref. [13]. The calculated values of σ_{cap} for target nuclei with $Z_T = 1 - 82$ are plotted in Fig. 2a.

3.2 Calculation of Stripping Cross Section

Classical approximations for the stripping cross section of low, medium, and high-Z targets were derived by Bohr [6]. For the medium-Z_T case the stripping cross section is given by:

$$\sigma_{strip} = \pi a_0^2 \frac{Z_T^{2/3}}{Z}(\frac{v_0}{v}). \tag{12}$$

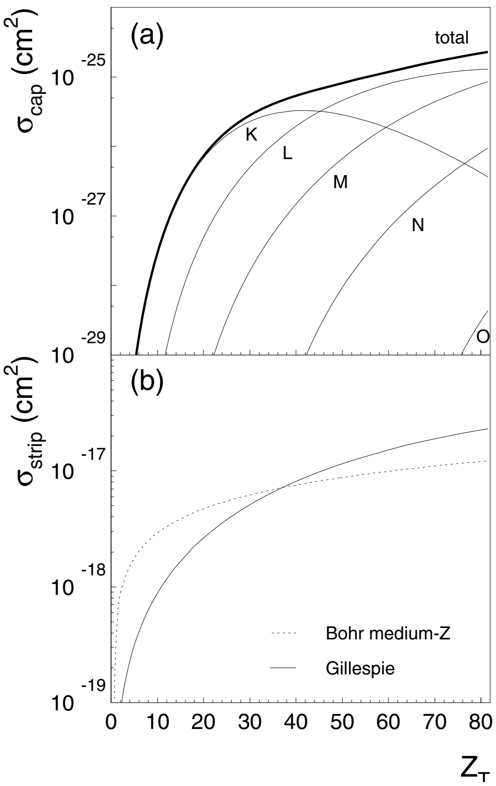

Fig. 2. Calculated cross sections at E(^{3}He)=420 MeV as a function of atomic number of the target. (a) Capture cross sections for the transition $^3He^{++} \rightarrow {}^3He^{+}$. The contributions from individual electron shells (K-O) are shown. (b) Stripping cross sections for the transition $^3He^{+} \rightarrow {}^3He^{++}$ following the descriptions by Bohr for medium Z_T-nuclei [6] (dashed line) and by Gillespie [7] (solid line) are shown.

An independent description, was given by Gillespie [7] on the basis of the asymptotic (high-energy) Born approximation:

$$\sigma_{strip} = 8\pi a_0^2 I_g (\frac{v_0}{v})^2, \tag{13}$$

where I_g is a purely phenomenological expression for the ionization collision strength (for details, see Ref. [13]):

$$I_g = \frac{1.24}{Z^2} Z_T (1 + .105 Z_T - 5.4 \times 10^{-4} Z_T^2). \tag{14}$$

The stripping cross sections for each of these descriptions are shown in Fig. 2b. It was previously found that at energies up to 200 MeV [9–13] a combination of the descriptions by Bohr for medium-Z targets and Gillespie reproduced the data if the latter approach was used for low-Z nuclei.

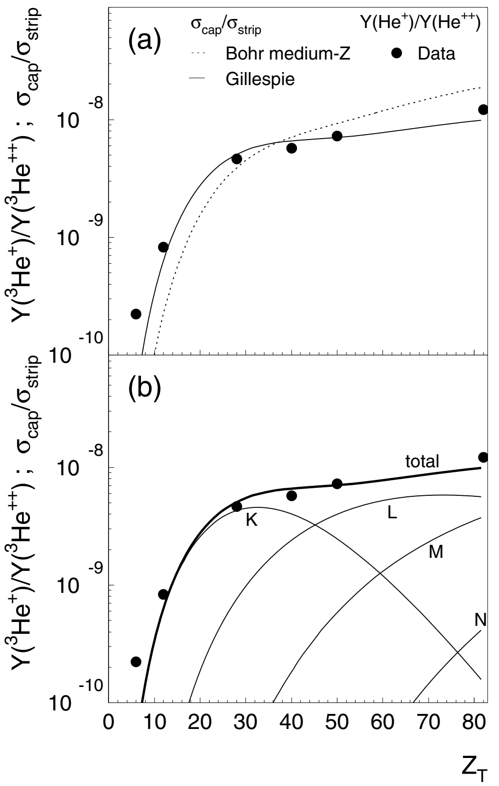

Fig. 3. Measured Y(^{3}He$^+$)/Y(^{3}He^{++}) yield ratios obtained at E(^{3}He)=420 MeV and comparison to ratios $\sigma_{cap}/\sigma_{strip}$. (a) Calculated ratios are shown for both the Bohr medium-Z_T and Gillespie approximations of σ_{strip}. The ratio calculated using the latter stripping cross section provides a better fit to the data. (b) Same as a) but using the Gillespie approximation for stripping only, and showing the capture contributions from individual shells.

4 Comparison Between Experimental Results and Theory

In Fig. 3a, the experimental charge-state yield ratios are compared with the theoretical capture-to-stripping cross-section ratios as a function of atomic number of the target. In contrast to the studies performed at lower beam energies, we find that using only the stripping cross-section calculation by Gillespie [7] in the calculation of the ratio, gives the best description of the data. For the high-energy Born approximation to be valid, the passage time of the projectile through the target atom should be sufficiently short so as to reduce the contribution from multi-step processes. Apparently, at the beam energy of 420 MeV this condition is satisfied over the full range of target sizes.

Fig. 3b displays the measured yield ratios and the calculated cross-section ratios for target nuclei with $Z = 1-82$. Eq. (4) was employed in the calculation of the capture cross section, and Eq. (13) was used in the stripping cross-section calculations. For clarity, the results obtained for the individual targets in the present work are shown in Table 1. Overall, the theory describes the

Table 1
Calculated cross sections and measured yield ratios at E(^{3}He)=420 MeV. The common systematic error in the experimental ratios is less than 10% (see Section 2).

Z_T	σ_{cap} (cm^2) Nikolaev [8]	σ_{strip} (cm^2) Gillespie [7]	$\sigma_{cap}/\sigma_{strip}$	Y(^{3}He$^+$)/Y(^{3}He^{++}) Measured
6	2.9×10^{-29}	4.6×10^{-19}	6.3×10^{-11}	2.2×10^{-10}
12	9.1×10^{-28}	1.3×10^{-18}	7.3×10^{-10}	8.3×10^{-10}
28	2.4×10^{-26}	4.7×10^{-18}	5.2×10^{-9}	4.6×10^{-9}
40	5.5×10^{-26}	8.3×10^{-18}	6.6×10^{-9}	5.7×10^{-9}
50	8.3×10^{-26}	1.2×10^{-17}	7.1×10^{-9}	7.2×10^{-9}
82	2.3×10^{-25}	2.3×10^{-17}	1.0×10^{-8}	1.2×10^{-8}

data within 20%, except for the case of the ^{12}C target, where the theory underestimates the data by a factor of 3. For this particular target a more detailed study was presented in Ref. [15], in which the stripping and capture cross sections were determined separately from thin-target measurements producing non-equilibrium charge-state distributions. For both stripping and capture contributions, a deviation between data and theory was found, indicating the need to further develop the theory for low Z targets at high beam energies.

To visualize the dependence of the yield ratios on beam energy, the previously measured [9–13] results are combined in Fig. 4 with those from the present work. Since the atomic numbers of the targets used in the present work slightly differed from those in the previous studies, we included our results for $Z_T = 12, 50$ and 82 in the plots for $Z_T = 13, 47$ and 79, respectively. The Y(^{3}He$^+$)/Y(^{3}He^{++}) yield ratio decreases as a function of beam energy for all targets. The theoretical calculations described above (solid lines in Fig. 4) agree well with the data.

Yield ratios calculated using the CHARGE program of LISE++ are also included in Fig. 4 (dashed line). As this program was initially designed for high-energy (80-1000 MeV/u), high-Z (>29) projectiles [2], it is perhaps not surprising that it fails to reproduce the data taken with a low-Z projectile. It does quite well in qualitatively describing the trend as a function of beam energy, but increasingly underestimates the production of singly ionized ^{3}He particles as the target atomic mass number increases. For the highest atomic mass number (Z_T=79) the experimental trend is no longer reproduced. Clearly, caution should be taken when using the code CHARGE to calculate charge-state distributions for low-Z projectiles, especially as Z_T increases.

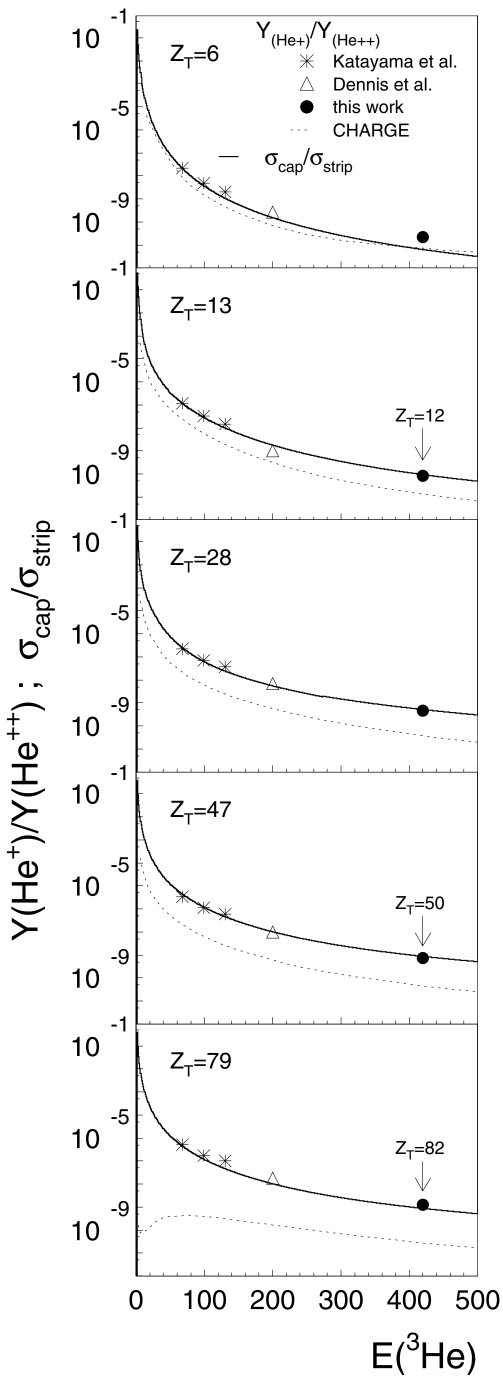

Fig. 4. Measured yield ratios and calculated $\sigma_{cap}/\sigma_{strip}$, plotted as a function of energy for specific targets. Yield ratios calculated by the CHARGE program of LISE++ are also included.

5 Conclusion

The $^3He^+$ to $^3He^{++}$ equilibrium charge-state yield ratios were measured at $E(^3He^{++})$ = 420 MeV for a variety of targets. The data were compared to the theoretical ratios of electron-capture to stripping cross sections. Except for the case of the ^{12}C target. they were found to be in good agreement if the high-energy Born approximation was used in the calculation of stripping cross sections and the capture cross sections were calculated using the description by Nikolaev. Although these calculations were originally developed for low beam energies, it is found that they work well even beyond the range previously covered (up to 200 MeV). However, in contrast to the measurements performed at lower energies, there is no need at E(^{3}He^{++}) = 420 MeV to apply Bohr's medium-Z_T description for stripping cross sections for targets of higher atomic number. Instead, the description by Gillespie works well over the whole Z_T range studied here. The applicability of the code CHARGE was tested for beams of light ions. The CHARGE calculations underestimate the experimental yield ratios of ^{3}He$^+$ to ^{3}He^{++}. The acquired data can provide additional testing ground for the development of more rigorous theoretical approaches [14,23] than applied here.

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