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Atomic charge exchange between semi-relativistic helium ions and targets from carbon to lead.

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In (^{3}He,*t*) nuclear charge-exchange reactions, ^{3}He$^+$ charge states are produced as a result of atomic charge-exchange between ^{3}He^{++} ions and atoms in the target. In equilibrium, the atomic charge-exchange process consists of both electron ionization (stripping), and electron capture, which can proceed through Radiative Electron Capture (REC) or Non-Radiative Electron Capture (NREC). Unfortunately, a complete description of the atomic charge-exchange process is lacking. As a result, a largely phenomenological approach has been used, which has not been tested for high beam energies. In this work, ratios of equilibrium charge-state yields for singly to doubly ionized ^{3}He ions were measured using the Grand Raiden Spectrometer at the Research Center for Nuclear Physics (RCNP). A semi-phenomenological approach used when calculating atomic electron capture and stripping cross sections is successful in describing the data for beam energies of E(^{3}He) = 420 MeV.

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1. Introduction

The (^{3}He,*t*) nuclear charge-exchange reaction has been widely used to study the spin-isospin response of nuclei, in particular Gamow-Teller transitions which are important to extract weak transition strengths in excitation-energy regions inaccessible to β-decay [1]. Recently, these experiments have been performed at RCNP with ^{3}He^{++} beams of E(^{3}He) $=$ 420 and 450 MeV. Along with the scattered tritons, ^{3}He$^+$ ions originating from atomic charge-exchange reactions produce a strong peak in the focal plane of the spectrometer Grand Raiden [2]. These ^{3}He$^+$ charge-state contaminants are useful for calibration purposes, as they provide information about the angular spread of the incoming beam and designate the central beam axis.

The present work is motivated by the potential for the use of ^{3}He$^+$ atomic charge-exchange events to be used in normalization procedures for (^{3}He,*t*) nuclear charge-exchange experiments. Other applications include using REC photons as an observable for ^{3}He^{++} ions in extragalactic space [3] and estimating charge-state production for the design of future radioactive ion beam facilities.

No comprehensive theory exists describing the atomic charge-exchange process over a wide energy and mass range. A semi-phenomenological approach is often used, based on the works of Allison [4], Betz [5], Bohr [6], Gillespie [7] and Nikolaev [8] and tested experimentally by Katayama *et al.* [9], Dennis *et al.* [10] and Gójska *et al.* [11]. This approach takes into account the balance between electron stripping and capture contributions, and the results of the calculations are in good agreement with data obtained over the energy range tested thus far (E(^{3}He) $=$ 67.9 MeV, 99.2 MeV, 130.2 MeV [9], and 200 MeV [10]).

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.* [10]. We also compare results with the predictions of the codes CHARGE and GLOBAL [12] (implemented in the code LISE++ [13]), to demonstrate the need for improved estimates of charge-exchange cross sections for fast radioactive ion beam experiments.

2. Experiment

The details of the experimental setup are the same as given in Ref. [1]. An incident beam of ^{3}He^{++} particles with a kinetic energy E $=$ 420 MeV was generated at the Ring Cyclotron Facility at RCNP with beam intensities between 4 and 10 enA. This beam was used to bombard isotopically-enriched targets of ^{12}C, ^{26}Mg, ^{60}Ni, ^{90}Zr, ^{120}Sn, and ^{208}Pb. All targets were sufficiently thick to reach equilibrium between electron stripping and capture and thus the charge-state distribution was independent of target thickness.

The ^{3}He$^+$ ions were detected at the focal plane of the spectrometer, along with the tritons produced in the nuclear charge-exchange reaction. The two products were easily separated using energy-loss measurements through 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%). ^{3}He^{++} ions were collected in a Faraday cup placed in the first dipole magnet of the spectrometer. The systematic error in current integration was estimated to be less than 10%, and is the same for all targets used. Since this would only lead to an overall scaling factor, the systematic error is not indicated in the included figure.

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. In the case of equilibrium charge-state distribution, there is a simple relationship connecting the charge-state yield ratios to the capture and stripping cross-sections [4, 5]:

$$\frac{Y(^3He^+)}{Y(^3He^{++})} = \frac{\sigma_{cap}}{\sigma_{strip}}. \tag{3.1}$$

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

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:

$$\sigma_{cap}(n_a|n) = \pi a_0^2 \frac{2^8}{5} N_a n^2 (\frac{v_0}{v})^2 \gamma^5 \eta_n^5 (1+\beta)^{\frac{5}{2}} (1+\beta\gamma)^{-3} \Phi_4(\beta\gamma), \tag{3.2}$$

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. 3.2 are defined as: $\gamma = 4V^{-2}[1+2(1+\eta_n^2)V^{-2}+(1-\eta_n^2)^2V^{-4}]^{-1}$, $V = v/u$ with $u = (2\varepsilon_a/\mu)^{1/2}$, $\eta_n = Zv_0/nu$ and $\beta = \mu v_0^2 b_a^2/(2\varepsilon_a c^2) - 1$. 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 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 [14]. Finally, Φ_4 was approximated as $\Phi_4 = 1 - 0.25\beta\gamma$, which is valid for $\beta\gamma < 1$ [8], as is the case here .

In Ref. [8] Eq. (3.2) was renormalized to ensure agreement with experimental capture cross sections for protons at low energies. This phenomenological renormalization was introduced as:

$$R_0(t) = \frac{0.3}{(t^{-8}+t)^{0.2}},\ t = \frac{7}{9}\frac{v}{v_0\sqrt{b_a}}. \tag{3.3}$$

Further discussion of this correction is given in Ref. [10].

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

$$\sigma_{strip} = \pi a_0^2 \frac{Z_T^{2/3}}{Z}(\frac{v_0}{v}). \tag{3.4}$$

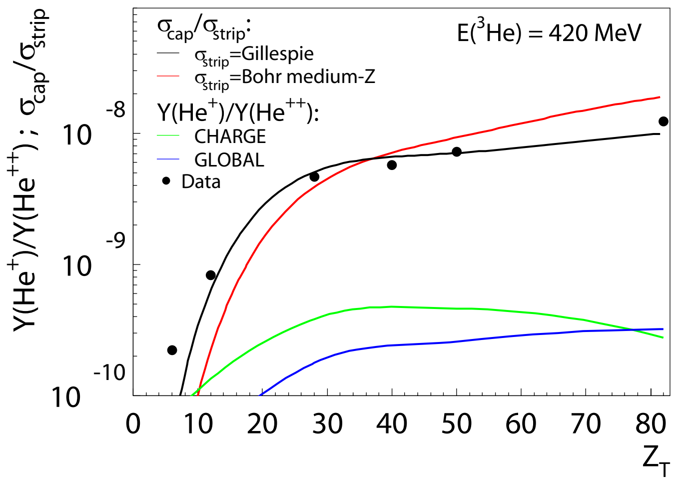

Figure 1: $Y(^3He^+)/Y(^3He^{++})$ yield ratios obtained at $E(^3He) = 420$ MeV and comparison to calculated ratios $\sigma_{cap}/\sigma_{strip}$. The black points correspond to our measured values. Statistical errors are negligibly small. The black and red lines correspond to calculated cross-section ratios using the Gillespie and Bohr stripping cross sections respectively. The green and blue lines correspond to the yield ratios given by the CHARGE and GLOBAL codes, respectively.

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

$$\sigma_{strip} = 8\pi a_0^2 I_g (\frac{v_0}{v})^2, \tag{3.5}$$

where I_g is a purely phenomenological expression for the ionization collision strength (for details, see Ref. [10]):

$$I_g = \frac{1.24}{Z^2} Z_T (1 + .105 Z_T - 5.4 \times 10^{-4} Z_T^2). \tag{3.6}$$

It was previously found that at energies up to 200 MeV [9, 10] 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. We have found that at 420 MeV, the Gillespie approximation represents the data over the full target range.

4. Comparison Between Experimental Results and Theory

In Fig. 1, the measured charge-state yield ratios are compared with the calculated capture-to-stripping cross-section ratios as a function of atomic number of the target. Eq. (3.2) was employed in the calculation of the capture cross section, and Eqs. (3.4-3.6) were used in the stripping cross-section calculations. 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. This is likely due to the high beam energy resulting in a short passage time of the projectile through the target atom and reducing the contribution from multi-step processes.

Yield ratios calculated using the CHARGE and GLOBAL programs of LISE++ are also included in Fig. 1. As these programs were initially designed for high-energy (80-1000 MeV/u), high-Z (>29) projectiles [12], it is perhaps not surprising that they fail to reproduce the data taken with a low-Z projectile. Clearly, caution should be taken when using these codes to calculate charge-state distributions for low-Z projectiles, especially as Z_T increases.

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. 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 $E(^3He^{++}) =$ 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 $^3He^+$ to $^3He^{++}$. The acquired data can provide additional testing ground for the development of more rigorous theoretical approaches [11] than applied here.

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