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Charge exchange processes for semi-relativistic helium ions ($\beta = 0.51$) in solid gold

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Abstract

Interactions of 150 MeV/amu $^3He^{++}$ projectiles with solid gold targets have been studied at the isochronous cyclotron of the RCNP in Osaka. The $^3He^+$ ions resulting from capture of the target electrons to the projectile were observed with the use of large magnetic spectrograph, Grand Raiden, set at $\theta = 0°$ with respect to the beam. The yield ratio of singly to doubly ionized helium ions emerging from thin gold foils, He^+/He^{++}, has been measured as a function of the foil thickness. Extrapolating the results to zero Au target thickness permits to determine the cross section values for electron stripping from $^3He^+$ ions, $\sigma_{STRIP} = 1.05 \times 10^{-17}$ cm^2, and for electron capture to $^3He^{++}$ ions, $\sigma_{CAP} = 1.12 \times 10^{-25}$ cm^2. The results obtained extend significantly the existing systematics for both processes to high (semi-relativistic) velocities. The collision strength deduced from the stripping cross sections deviates strongly from the theoretical predictions of Gillespie in absolute values as well as in the velocity dependence. It can, however, be well approximated by the simple Bohr formula for mid Z atoms. Also the capture data indicate the need to improve the theoretical approximations. A more detailed treatment of electrons captured from different shells in a high Z target is presumably needed. The astrophysical interest in the data of this kind for very light ions (hydrogen, helium) is indicated.

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Keywords: Charge exchange; Ionization (stripping); Capture

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1. Introduction

The dominant processes occurring to a fast ion traversing a solid are the capture of electrons from the target atoms to the vacant states in the ion and the stripping of the bound electrons from the ions. These charge exchange processes are of primary interest for understanding the passage of ions through matter. Though known and studied since the early days of atomic and sub-atomic physics, they are still only crudely described theoretically. The experimental information is also limited, particularly for light projectiles at intermediate and high (relativistic) energies. Because of huge differences in cross-sections between the capture and the stripping processes the experiments require very special techniques of advanced nuclear physics.

The capture of electrons by an ion colliding with an atom proceeds via two processes: the Radiative Recombination, RR, and the Non-Radiative Electron Capture, NREC. To the extent that the captured electron can be considered as free and at rest, the RR process corresponds to the Radiative Electron Capture, REC, which is the time reversed photo-electric effect on the partly ionized projectile atom. The NREC process cannot occur for free electrons. The momentum and energy conservation conditions require the presence of a third body, in this case the atomic nucleus of the target atom. The cross section, σ_{NREC}, depends sharply on the energy of the ion, E_{P}, and on the atomic number of the target, Z_{T}, as well as of the ion, Z_{P}. It has a maximum close to the velocity matching condition, $v_{\mathrm{p}} \approx v_{\mathrm{e}}$, where v_{p} and v_{e} are the velocities of the ion and the captured electron, respectively. For $v_{\mathrm{p}} \gg v_{\mathrm{e}}$

$$\sigma_{\mathrm{NREC}} \sim Z_{\mathrm{P}}^5 Z_{\mathrm{T}}^5 E_{\mathrm{P}}^{-6}. \tag{1}$$

Due to sharp Z_{T} dependence the NREC process dominates for high Z targets and the total capture cross section, $\sigma_{\mathrm{CAP}} \approx \sigma_{\mathrm{NREC}}$.

In contrast, the ionization cross section, σ_{STRIP}, depends smoothly on E_{P} and Z. Crudely,

$$\sigma_{\mathrm{STRIP}} \sim \frac{Z_{\mathrm{T}}^2}{Z_{\mathrm{P}}^2} E_{\mathrm{P}}^{-1}. \tag{2}$$

A review of the various processes occurring in the relativistic ion – atom collisions is given in [1] (see also [2] are Refs. therein).

Recent experimental information on interaction of fast helium ions with various gaseous and solid targets can be found in the work of Katayama et al. [3–5]. These authors have measured the stripping and the capture cross section for ^{3}He ions with energies up to 43.4 MeV/amu. The present work extends this information to much higher ^{3}He energy, 150 MeV/amu, for $Z = 79$. The results are compared with basic theories.

Interaction of relativistic helium ions with atoms as well as with free electrons is of primary astrophysical interest [2]. Likewise, information on the charge exchange process involving fast ions is much needed in hot plasma diagnostics.

2. Theoretical predictions

Collisions between fast ions and target atoms lead to electron capture to the vacant states in the ions. The impinging ions may also lose electrons in the ionization process, i.e. in the stripping of the bound electrons from the ion to the continuum. The ionization (stripping) process is described by Bohr [6] and Gillespie [7,8]. The electron capture cross section is given by the approximate calculations according to Oppenheimer–Brinkmann–Kramer [9–11] OBK, and Nikolaev [12,13] calculations. More realistic expressions in the relativistic eikonal approximation are given by Eichler [1,14].

The first description of electron ionization process was given by Bohr [6]. Three approximate expressions for the electron stripping were given for high, low and medium Z of target, correspondingly. The expression for high Z takes the particularly simple form

$$\sigma_{\mathrm{STRIP}}(\mathrm{high}\, Z) \approx \pi a_0^2. \tag{3}$$

The Bohr predictions for mid Z targets include the screening effects due to tightly bound inner electrons

$$\sigma_{\mathrm{STRIP}}(\mathrm{mid}\, Z) = \pi a_0^2 \frac{Z_{\mathrm{T}}^{2/3}}{Z_{\mathrm{P}}} \left(\frac{v_0}{v}\right), \tag{3a}$$