Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research B 258 (2007) 340–344
NIM B
Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Double-to-single ionization ratios of helium bombarded by low-to-intermediate velocity C^{q+}, O^{q+} ($q = 1 \sim 3$) ions

J.X. Shao, X.M. Chen *, B.W. Ding, H.B. Fu, Z.M. Gao, Y.W. Liu, J. Du, Y.X. Lu, Y. Cui

Department of Modern Physics, Lanzhou University, Lanzhou 730000, China

Received 19 July 2006; received in revised form 16 October 2006
Available online 26 March 2007

Abstract

We measured the double-to-single ionization ratios R of Helium bombarded by C^{q+} and O^{q+} ions ($q = 1 \sim 3$). The velocity of the projectile varies from v_{Bohr} to 4 v_{Bohr}, the energy varies from 25 keV/amu to 500 keV/amu. The value of R increases rapidly with the collision velocity and reaches the maximum when the velocity is about 2 or 3 v_{Bohr}, then it decreases slowly for the higher velocity. A simple model is presented to estimate the value R varying with the collision velocity. The results calculated by the model are in agreement with the experimental data basically.

Keywords: Double ionization; Helium; Carbon ions; Oxygen ions

1. Introduction

Ionization is one of the basic processes mediated by Coulomb forces during ion–atom collisions, and this process has been studied both theoretically and experimentally from the beginning of atomic and quantum physics. In high energy range ($v_{\text{ion}} > 10\, v_{\text{Bohr}}$), the removal of a single-electron by the projectile is well described in the framework of the first Born approximation [1]. In the framework of first Born approximation, McGuire proposed that double ionization by ions at intermediate to high velocities ($v_{\text{ion}} \geqslant 10\, v_{\text{Bohr}}$) can be understood in terms of two mechanisms [2,3]: (1) a two-step process (TS), $v_{\text{ion}} \sim 10\, v_{\text{Bohr}}$, in which both target electrons are removed in separate direct interactions with the projectile, the value of R increases with the projectile charge q and decreases with collision velocity v as $q^2/(v^2 \ln v)$; (2) a shake-off process (SO), $v_{\text{ion}} \gg 10\, v_{\text{Bohr}}$, in which the first electron is removed in a direct interaction with the projectile while the second electron is ejected when the resulting ion "relaxes" to a continuum state and the ratio R is expected to be a constant.

In the low energy range ($v_{\text{ion}} < v_{\text{Bohr}}$), single removal is understood well in the framework of Bohr's Classical-Over-Barrier-Model (COBM). COBM [4] indicates: that electron capture is the dominant process, direct ionization is neglected in this model. The cross section of capture is independent of the collision velocity v, as a result, the double-to-single ionization ratio R is also expected to be a constant.

In the low-to-intermediate velocity range ($v_{\text{ion}} \geqslant v_{\text{Bohr}}$), many experiments had been made focusing on the ratios R [5–10]. No matter whether the projectile is bare ions or partially bare, the trends of R varying with the collision velocity have a similar character. That is, the value of R increases rapidly with the collision velocity and reaches the maximum when the velocity is about 2 or 3 v_{Bohr} then it decreases slowly for the higher velocity [1].

In the present work, C^{q+} and O^{q+} ions ($q = 1 \sim 3$) with the velocity varying from v_{Bohr} to 4 v_{Bohr} collide with He, the double-to-single ionization ratios R of Helium are measured using the time-to-flight and coincidence technique, the details of the experimental method are discussed

* Corresponding author. Tel.: +86 931 8913541.
E-mail addresses: chenxm@lzu.edu.cn (X.M. Chen), shaojx02@st.lzu.edu.cn (J.X. Shao).

0168-583X/$ - see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.nimb.2006.10.072

elsewhere [11]. When the velocity is about 2 or 3 v_{Bohr}, the value of R reaches the maximum, not only in the direct ionization process but also in the charge exchange process.

The experimental data and the details of the model will be discussed in Sections 2 and 3.

2. A simple theoretical estimate

The model we used to estimate the double-to-single ionization ratios R, is based on Bohr–Lindhard's COBM [4]. They introduce two important ion–atom interaction distances in COBM.

First, they introduced the release distance R_r, where the electron can be released from the target nucleus. The release distance R_r satisfies:

$$\frac{q}{(R_r - a)^2} = \frac{Z}{a^2}, \tag{1}$$

where a is the orbital radius of the electron, q is the charge state of the projectile and Z is the atomic number of the target.

Eq. (1) indicates that the electron can be released when the forces on the electron extracted by the projectile and the target atom are in balance.

Second, the capture distance R_C is introduced. R_C is the ion–atom distance where the electron can be captured by the projectile. R_C satisfies the following equation:

$$\frac{q}{R_C} = \frac{1}{2} V_P^2, \tag{2}$$

where V_P is the velocity of the ion.

Eqs. (1) and (2) means: it is only that the process of release occurred within the distance of capture the electron can be captured, otherwise, the release is temporary.

In the low energy range, $R_C \geqslant R_r$, the released electrons are all captured, the capture cross section is given by

$$\sigma_C = \pi R_r^2. \tag{3}$$

For higher energy, $R_C < R_r$. Only the electrons released within the distance of R_C can be captured, as a result, the capture cross section

$$\sigma_C = \pi R_C^2 \cdot f. \tag{4}$$

f is the probability of release process occurring within the distance of R_C.

Where $f = \left(\frac{v_e}{a} \cdot \frac{R_C}{V_P}\right)$, means the ratio of the duration of collision to the orbital period of the bound electron. v_e is the orbital velocity of this electron.

In Bohr's theory of COBM [4], the electrons which are released but not captured will go back to the target atom after collision.

The energy level of the released electron had already been estimated by Bohr et al. [4] and Niehaus [12], it is $I_n + \frac{q}{R_r}$, the ionization energy of the target electron added by the stark-energy by the ion.

We consider that the released but not captured electrons will be accelerated by the approaching ion. At some distance R_I, the electrons will get enough kinetic energy from the ion to escape from the target atom, meanwhile, these electrons will not be captured, they will be ionized.

The ionization distance R_I satisfies:

$$\frac{q}{R_I} \geqslant I_n + \frac{q}{R_r}. \tag{5}$$

It means when the stark-energy transferred to the kinetic energy of the electron is larger than the ionization energy of the quasi-molecular states, the electron will escape from the target atom. If the released electron has enough energy to escape from the target atom and can not form the stable bound states of the ion, ionization occurs.

According to Bohr's theory, electrons have not been released during the collision are in the perturbative bound states of the target atom all the time, the kinetic energy of these electrons are almost the initial value, are not large enough to escape, thus, the ionization of these electrons is neglected in our model.

That is, in our model, the electrons released within the distance R_C will be captured, those released between R_r and R_C will not be ionized until the ion entered the distance R_I.

Before we calculate the cross sections about two-electron system, it is necessary to get the ionization or capture cross section of the single-electron system. Then, those cross sections about the two electrons will be calculated by the independent electron model (IED) easily.

Several approximations are made:

(1) These projectiles move along the linear trajectories with the collision parameter b and the velocity V_P.
(2) The orbital period of the electron is $T = \frac{2\pi \cdot a}{v}$, neglecting the influence of the ions.

For the given collision parameter b and velocity V_P, the probability that electron will be released is $P_r(b) = \frac{2\sqrt{R_r^2 - b^2}}{V_P} \cdot \frac{1}{T}$, the ratio of the duration of collision (duration of the release process) to the period of the bound electron, for $b \leqslant R_r$.

The capture probability is $P_C(b) = \frac{2\sqrt{R_C^2 - b^2}}{V_P} \cdot \frac{1}{T}$, the ratio of the duration of the capture process to the period of the bound electron, for $b \leqslant R_C$.

Then the ionization probability is $P_I(b) = P_r(b) - P_C(b)$, for $b \leqslant R_I$. When we construct the cross sections of two-electron system with these single-electron probabilities, the only thing is to distinguish these two electrons with subscript 1 and 2, e.g. R_{r1}, R_{C1}, R_{I1}, the distances for the first electron; R_{r2}, R_{C2}, R_{I2}, the distances for the second electron.

They satisfy the following equations:

$$\begin{aligned} &\frac{q_i}{(R_{ri} - a)^2} = \frac{Z_i}{a^2}, \\ &\frac{q_i}{R_{Ci}} = \frac{1}{2} V_P^2, \\ &\frac{q_i}{R_{Ii}} = I_i + \frac{q_i}{R_{ri}} \quad (i = 1, 2), \end{aligned} \tag{6}$$