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Doubly differential cross sections for ejection of electrons from atomic and molecular hydrogen by 30–120 keV He^+ ion impact

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The University of Nebraska - Lincoln, 1993

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DOUBLY DIFFERENTIAL CROSS SECTIONS FOR EJECTION OF ELECTRONS FROM ATOMIC AND MOLECULAR HYDROGEN BY 30-120 KEV He^{+} ION IMPACT

BY

Ying-Yuan Hsu

A DISSERTATION

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DISSERTATION TITLE

Doubly Differential Cross Sections for Ejection of Electrons from Atomic and Molecular Hydrogen by 30-120 keV He^+ Ion Impact

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Ying-Yuan Hsu

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GRADUATE COLLEGE
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DOUBLY DIFFERENTIAL CROSS SECTIONS

FOR EJECTION OF ELECTRONS

FROM ATOMIC AND MOLECULAR HYDROGEN

BY 30-120 KEV He^+ ION IMPACT

Ying-Yuan Hsu, Ph.D.

University of Nebraska, 1993

Advisor: M. Eugene Rudd

Electrons ejected from atomic and molecular hydrogen in He^+ ion impacts were observed with projectile energies ranging from 30 to 120 keV. The ejection angles observed were 15°, 30°, 50°, 70°, 90°, 110°, 130° and 160° with electron energies ranging from 1.5 to 130 eV. Ejected electrons were energy analyzed by an electrostatic analyzer with 5% resolution and were detected by a channel electron multiplier.

A Slevin-type RF hydrogen atom source was used to generate a mixed target of atomic and molecular hydrogen. The dissociation fraction of the target was determined from the measurement of 9-eV H^+ ions coming from the break-up of the $2p\sigma_u$ state of the H_2^+ molecular ion. Methods were devised to extract the electron ejection cross section ratio between hydrogen atoms and molecules. Cross sections for the hydrogen atom were then calculated from additional measurements on pure H_2.

The results are compared to plane-wave-Born approximation (PWBA) calculations, classical-trajectory-Monte-Carlo (CTMC) calculations, and continuum-distorted-wave-eikonal-initial-state (CDW-EIS) calculations for proton impact. Electron loss cross sections are calculated with PWBA and used as a correction to the above calculations.

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I. INTRODUCTION

Though the experimental study of ionization processes in ion-atom collisions has continued for several decades, due to the lack of reliable atomic hydrogen sources, most of the studies have been limited to multi-electron targets. The lack of experimental data on simple targets has made the comparison between theories inconclusive, since calculations involving multi-electron targets usually require approximations. Measurements on atomic hydrogen are hence of fundamental importance.

Most of the experiments involving atomic hydrogen targets have used bare particles as projectiles. Work that has been reported include electron scattering [Zhou 1993, Shyn 1989], positron scattering [Zhou 1993], electron impact ionization [Shyn 1992] and proton impact ionization [Schultz 1991, Shah 1987, 1981, Ireland 1964]. Though theoretical calculations for these processes have been made using various approximations, Dodd's [1966, see also Faddeev 1961] method provides a theoretically sound solution for both electron and proton impact processes. The application of this method to proton impact ionization with the impact-parameter approach has been reviewed by Fainstein et al.[1991].

In this project, ionization of atomic and molecular hydrogen by He^+ ion impact was investigated. The processes are:

a) $He^+ + H \rightarrow e^- + \ldots$

b) $He^{+} + H_2 \rightarrow e^- + \ldots$

Despite their simplicity, data on these processes provide valuable and fundamental information in understanding the collision process.

Process a) involves the collision of two one-electron subsystems, both of which have precisely determined initial states. In spite of the simplicity of this system, mechanisms such as electron loss, auto-ionization and charge transfer to the continuum are possible and provide an interesting system to study. By comparing this process with that of H on H, the effects of the nuclear charge can also be studied. These systems with more than three particles were classified as multi-particle systems and have been studied by S. Weinberg [1964] in the framework of formal scattering theory. However, no calculations invoking such a theory are known to the author.

Even though process b) is an easy system to study, measurements have not been carried out in doubly differential form. The only results available are the total cross sections measured by Solov'ev [1964] and Keene [1949].

To study these processes, an electrostatic analyzer was used to energy analyze the secondary particles and a channel-electron multiplier (CEM) was employed as the detector. To study the process b), a static molecular hydrogen target gas was used and measurements were made at angles ranging from 15° to 160° with He^{+} projectiles ranging from 30 to 120 keV.

In studying process a), due to difficulties in producing a pure static atomic-hydrogen target, a method was devised to extract the cross section ratio between process a) and b) from crossed beam measurements. An RF-powered Slevin source was used to dissociate the H_2 molecules and provide the H-atom target. However, since the source does not produce a pure H-atom target, additional measurements were made to determine the dissociation fraction. The dissociation fraction was determined by observing the change in the number of recoil ions coming mainly from the process: $H^+ + H_2$. Protons at 70 keV energy were used for this purpose. Knowing the dissociation fraction, the cross section ratio between processes a) and b) can then be obtained by making measurements on the electron signals with the source being on and off.

Doubly differential cross sections for ionization are presented in tabular form along with the integrated results for singly differential and total cross sections.

Along with the ionization cross sections for He^+ ion impact on H and H_2, recoil ion cross sections for 70 keV proton impact on hydrogen molecules were also obtained which supplement the measurements of J.B. Crooks [1974].

II. THEORY

The current project studies the collision processes

$He^+ + H \dashrightarrow e- + \ldots$

$He^+ + H_2 \dashrightarrow e- + \ldots$

with projectile velocities ranging from 0.55 a.u. to about 1.1 a.u. Theoretical treatments of these processes are rare. The only calculation was done by Boyd [1957] et al. in calculated the total cross section for He^+ ion impact on hydrogen atoms by using the Born approximation.

Since the electron of He^+ ion are tightly bound, approaches taken here are 1)treat the He^+ ion as a H^+ nucleus with same velocity, 2)improve the results of 1) with electron loss corrections and 3)try to treat the problem exactly. Because of the low velocities used in this project, a section is also included describing the perturbed-stationary-state (PSS) approach. In the following sections, we first describe the methods available for H^+ impact and then make comments on the possibility of extending those methods to the currently investigated problems.

Before describing the formal treatment of the problem, a few general features of the electron ionization spectra are described. These features include the binary-encounter peak, charge transfer to the continuum, autoionization peaks and the electron loss spectrum.

The binary encounter peak [Rudd 1966] is best described as a billiard-ball-like collision between the incoming projectile and the target electron. For this process the energy of the ejected electron is given by [Rudd 1980]:

$$E=4T\cos^2\theta-I \tag{1}$$

where I is the binding energy and T is the energy an electron would have at the same velocity as the projectile.

Charge transfer to the continuum can be described as an electron emitted at low velocity in the reference frame of the projectile. Therefore, it would have almost the same velocity as the projectile. The energy of this peak is given by [Rudd 1980]:

$$E=T\cos^2\theta \tag{2}$$

where T has the same definition as above.

The autoionization peaks in our spectrum come mainly from the doubly excited states of He [Schowengerdt 1973] formed when the He^+ ion picks up an electron from the target. Since He^{**} is moving in the laboratory frame, the resulting peak is Doppler shifted. The energy of the autoionization electron in the laboratory frame is given by:

$$E=E'+T\cos2\theta\pm2T\cos\theta\sqrt{\frac{E'}{T}-\sin^2\theta} \tag{3}$$