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Double electron capture by protons in collisions with H_2

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ABSTRACT

Double electron capture of protons in collisions with molecular hydrogen in the energy range 1.5–10 keV was studied by measuring the resulting H^- velocity distributions. In this paper, a technique that provides experimental evidence about double capture mechanisms is proposed. In addition, cross-sections for this process were measured in the energy range of 1–5 keV.

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1. Introduction

The fact that a proton can capture up to two electrons and become a negative ion during a collision with a simple molecule is a remarkable process of fundamental interest which details still remain as an open question in the field of atomic physics.

Even for the case of a simple atomic target, it has been pointed out that electronic correlation and interaction between the projectile and the target nuclei are important processes that are yet not well accounted for [1] by present quantum mechanical models.

The role of DEC in the diagnosis of low temperature edge fusion plasma [2], combined with its inherent simplicity to test theoretical models beyond the independent electron model [3] has renewed interest in its study [1,4].

The process of capturing the two available electrons from H_2 by a proton in the present collision system, is intrinsically selective because electronic excited states are not accessible neither in the initial nor in final states:

$$H^+ + H_2 \rightarrow H^- + 2H^+ \quad (1)$$

This system exhibits advantages that simplify the study of electron capture from molecules and collision induced molecular dissociation [5] because, in principle, the resulting H^- distributions completely determine the kinematics of the interaction. For instance, high resolution H^- energy distributions have been used to measure ionization potentials [6]. Another advantage over the case of simple atomic targets is that here, electron correlation is expected to be simpler because of the presence of two nuclei in the molecular target.

To the best of our knowledge, the dynamics of this system in the present energy range has not been experimentally tested. It is noted that this collision system was studied, for simple ionization, in a higher collision energy range. It was found that projectile-target nucleus interaction was an important contribution [7].

In this paper we study the dynamics of DEC by protons by deriving approximated ion-yield probability angular distributions from energy distributions. We propose a simple experimental technique that gives information about the dynamics of DEC.

In addition, cross-sections for the energy collision range of 1–5 keV measured with the grow-rate method are reported. In the present energy range, Fogel et al. [8] measured cross-sections with an ionization chamber technique and Williams [9] used the grow-rate method to measure above 2 keV.

2. Experiment

A general description of the apparatus used in this study is in Ref. [10]. Here, a short self-contained description is provided together with the additions and improvements necessary for the present study.

A proton beam was generated by injecting a mixture of hydrogen and argon gases into a incandescent filament-type ion source. Ions produced by electronic impact inside the filament chamber were repelled toward a set of focusing lenses.

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Protons were selected by a 60° section analyzing magnet. As shown in Fig. 1, a set of slits were located at the output of the analyzing magnet to trim the beam diameter to a maximum of about 0.5 mm.

The proton beam passed through a cell with input and output collimating circular orifices of 1 and 1.5 mm respectively. The maximum base pressure in the collision chamber was 1×10^{-7} Torr.

The proton beam intensity was measured by a Faraday cup (retractable Faraday cup in Fig. 1) located at the output of the gas-cell. To fine tune the alignment of the beam with the accelerator's central axis, two sets of steering plates were used to direct the beam through a 1 mm diameter collimator placed in front of a tuning Faraday cup.

The resulting H^- could be deflected to the detector or to the electrostatic analyzer by switching the polarity of the analyzing plates. To measure the cross-sections, the H^- ions were directed to a channel electron multiplier (CEM). The acceptance diameter of the CEM was 1.5 cm. To measure the spectra, the H^- ions were guided to a 3 mm diameter entrance of the electrostatic analyzer. The CEM and the electrostatic analyzer inputs were situated at an angle of 12.5° on each other side of the beam central axis.

When the ion-beam passes through the gas-cell, it can change its charge state. The amount of ions that undergo a change of charge, with respect to the incident ion-beam, can be described by the relative fragment equilibrium equation [11]:

$$\frac{dF_i}{d\pi} = F_j\sigma_{ji} + F_k\sigma_{ki} - F_i(\sigma_{ij} + \sigma_{ik}) \tag{2}$$

where, σ_{ji} is the total cross-section for the ion to change its charge state from i to j; $i = j = \{-1, 0, 1\}$; F_j is the fraction of the number of ions with j charge state to the number of ions with initial charge state i; and, π is the target thickness defined as the number of particles per unit area that the beam encounters during its passage through the gas-cell. π is derived from the ideal gas equation:

$$\pi = \frac{\ell P}{\kappa T} \tag{3}$$

where P is the gas-cell pressure, ℓ is the gas-cell effective length, T is the temperature and, κ is Boltzman's constant.

Since there are three possible states of charge, Eq. (2) is constrained to:

$$\sum_{i=-1}^{1} F_i = 1 \tag{4}$$

The general solution of Eq. (2) is of the form [12]:

$$F_i = \sum_{m=0}^{2} a_m^i e^{-r_m\pi}$$

where the constants a_m^i and r_m are functions of the six possible ij permutations for σ_{ij}. i and j can take -1, 0 and 1, charge state values; and $r_0 = 0$.

The grow-rate method used here to measure the cross-section, is based on the first order approximation to the solution of Eq. (2):

$$F_i = \sigma_{ij}\pi \tag{5}$$

It is remarkable that under adequate experimental conditions, Eq. (5) can be used to derive σ_{ij}. These conditions are known as single collision conditions and they can be checked by plotting F_i versus π. In the present case, a linear dependence of the H^- signal as a function of the gas-cell pressure was verified for every cross-section data point and, for the spectra. In addition, the gas-cell pressure was maintained below 10^{-4} Torr in accordance to Čović et al. [13].

To measure the spectra, the pressure in the gas-cell was set in the 10^{-5} Torr range. In order to find the H^- signal in the electrostatic analyzer, the proton beam was first deviated to the Faraday cup located behind the electrostatic analyzer by applying the proper voltage and polarity to the analyzer plates. After optimization of the analyzer plates voltage, their polarity was switched in order to exchange protons for the H^- signal. The voltage of the electrostatic analyzer was swept several times with a precision better than 0.01%. The H^- signal was recorded in time intervals of 10–20 s as a function of the applied voltage in steps of 5 V. The experiment was repeated with no H_2 in the gas-cell to measure the resulting H^- from the interaction with the residual gas with the ion-beam; although the background signal was small, it was subtracted from every signal spectra. An example of a resulting spectrum is shown in Figs. 2 and 4.

The highest pressure value in the detection chamber during the recording of the data was 2.5×10^{-7} Torr and the maximum base pressure before admitting H_2 gas in the cell was 1×10^{-7} Torr.

3. Analysis of the spectra

As a consequence of the double electron capture (DEC), most of the resulting H^- ions are scattered away from the ion-beam trajectory. Because of the collimator's limited diameter, the experimental setup happens to be very efficient in detecting

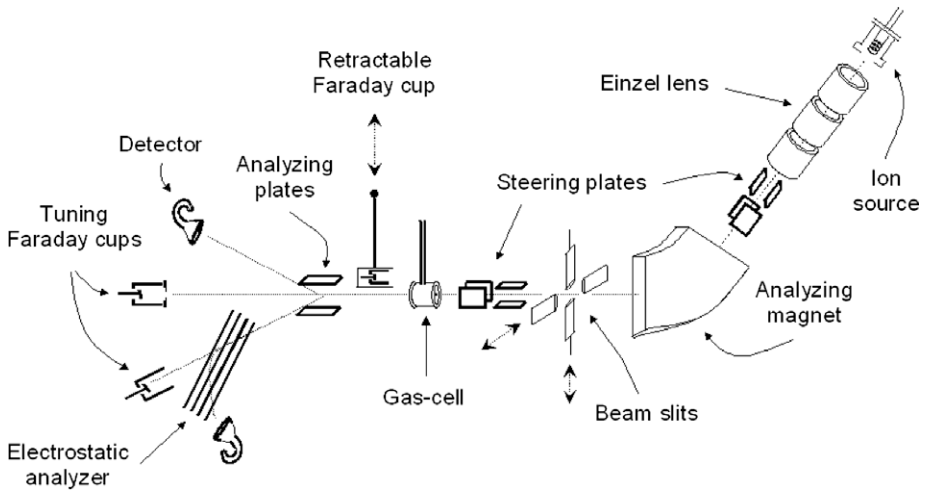

Fig. 1. Schematic of the apparatus. The ion-beam trajectory is indicated by a dotted line.

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