Journal of Electron Spectroscopy and Related Phenomena 228 (2018) 13–19

Contents lists available at ScienceDirect

Journal of Electron Spectroscopy and Related Phenomena

journal homepage: www.elsevier.com/locate/elspec

Measurement of electron-calcium ionization integral cross section using an ion trap with a low-energy, pulsed electron gun

Łukasz Kłosowski*, Mariusz Piwiński, Szymon Wójtewicz, Daniel Lisak

Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, Grudziądzka 5, 87-100 Toruń, Poland

A R T I C L E I N F O

Keywords:
Calcium
Ionization
Ion traps
Cross secion
Electron scattering

A B S T R A C T

An apparatus for production of various atomic and molecular ions inside a linear Paul trap has been set up. The system applies a custom-made, low energy, pulsed electron gun to produce ions in electron impact process. Such ionization method can find some interesting possible applications such as derivation of ions inaccessible other ways, which can be used in molecular ion experiments. The technique allows also for determination of cross sections for various collisional processes.

As a feasibility study, the apparatus was used for determination of ionization integral cross section of calcium in the 16-160 eV range of electron impact energy. The obtained cross section values are discussed and compared with existing data sets.

1. Introduction

Research involving trapped ions, at some stage of experimental procedure, requires loading the trap [1]. It can be achieved by injection of ions from outside, which is possible using an external source [2] or ablation of a solid with laser [3,4] or electron [5] pulse. An alternative way is creation of ions inside the trap by ionization of a neutral quantum object, such as atom or molecule [6–9]. There are experiments, where some species of ions are derived from other ones in a chemical reaction [10,11].

The ionization utilizes usually a photon [6–8] or electron interaction with a neutral atom. Contemporary apparatuses involve rather photoionization than impact process as the laser technology experiences continuous development, allowing for driving optical transitions of an atom with high efficiency and precision, leading to well controlled production of ions. The most important disadvantage of such technique is that the optical ionization system can be designed for one, selected species of ions only. It is also difficult to apply in molecular ion production [9], as the optical spectra of molecules are much more complex than atomic ones.

More universal method of electron bombardment of neutrals had been used in the past, however since the optical methods development it became much less common. As the electron impact ionization is not as selective as optical interactions, application of such technique can lead to ionization of a background gas, multiple ionization of atoms of interest, lack of isotope-selectivity of the process, etc. Additionally, most of the past applications of electron impact ionization inside trap involved relatively high energy of electron, of the order of several keV. The energies of such electrons are high above the ionization thresholds and typical electron impact ionization cross sections maxima of atoms and molecules. For example the maximum of cross section for calcium is noticed at around 25 eV [12], typical molecules like CO_2 have their ionization maxima at about 100 eV [13,14]. This way, the cross sections have usually low value at energies above 1 keV, making the electron impact inefficient for ion derivation.

In this paper we present a low energy (below 200 eV) electron gun system allowing for ionization of various neutral species at energies closer to ionization cross sections maxima. The selectivity of ion production can be achieved by application of proper trap settings [15]. To improve the precision of electron beam controlling, a pulsed system has been designed. It provides better control of the number of produced ions and helps to avoid some undesirable effects such as heat transfer or interaction of electrons with ions of interest.

2. Apparatus

The apparatus has been set up in the National Laboratory FAMO in Torun. It consists of a vacuum chamber ($10^{-10} \div 10^{-9}$ mbar) equipped with a Paul trap [16] and sources of necessary beams: electronic, atomic (calcium) and molecular (not used in the tests described in this paper). Additionally the system contains optical part used for cooling and detection of the trapped ions. Overall scheme of the apparatus is

* Corresponding author.
E-mail address: lklos@fizyka.umk.pl (Ł. Kłosowski).

https://doi.org/10.1016/j.elspec.2018.08.002
Received 11 May 2018; Received in revised form 3 August 2018; Accepted 14 August 2018
Available online 18 August 2018
0368-2048/

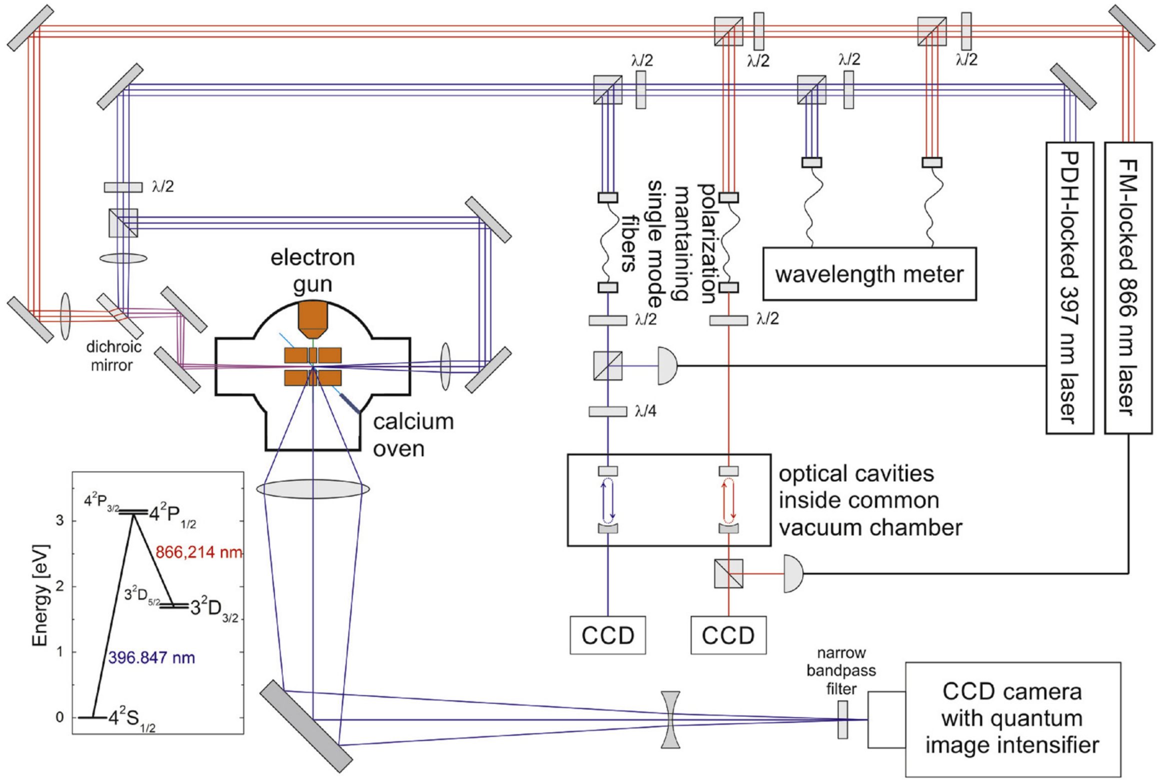

Fig. 1. Simplified scheme of the experimental setup. The laser beams are produced by Toptica DL pro (397 nm) and DL 100 (866 nm) diode lasers. The lasers are stabilized using high finesse optical cavities. Both beams are merged using dichroic mirror and introduced to the vacuum chamber and aligned to the trap's main axis. The beams are focused near the trap center. To balance the photon pressure, the 397 nm beam is splitted into two counter-propagating beams. The sources of atomic, molecular and electronic beams are aligned to cross the trap center. The trapped ions are detected using CCD camera equipped with two lenses, mirror, filter, and quantum image intensifier. The left bottom inset presents simplified scheme of the calcium ion energy levels with the optical transitions applied in the experiment.

presented in Fig. 1. The individual parts of the system are described in following sections of this paper.

2.1. Linear Paul trap

The trap used in the system is a standard, linear, segmented Paul trap with cylindrical electrodes [17]. Its geometry is presented in Fig. 2. The cylindrical electrodes have diameter of 8.0 mm and are placed in a quadrupole configuration with 4.0 mm distance between the electrode pairs. To provide confinement of ions' motion along the trap axis, the electrodes have been divided into three segments. The central one has length of 4 mm, while the outer ones are 10 mm long. The gap between segments is 0.1 mm.

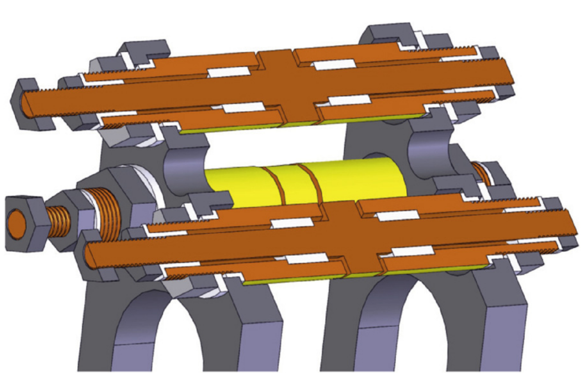

Fig. 2. Geometry of the trap used in the experiment (cross sections of 2 electrodes). The orange and yellow parts are the electrodes made of gold-coated copper. The gray parts are mechanical parts made of stainless, nonmagnetic steel. The white parts are insulators made of macor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The electrodes are held with conducting, grounded frame providing support for electric connections for the trap's voltage supplies and optical access for the laser cooling and imaging systems, as well as the atomic, molecular, and electronic beams.

The electrodes are made of copper cylinders (7.8 mm diameter) placed inside 0.1 mm thick gold tube (99.95% purity), providing 8.0 mm diameter of the entire electrode. Such technique of coating allows to avoid flaking off the gold in vacuum, which is typical issue for layers obtained by vapor deposition. The electric connectors are attached to the end part of the electrodes, outside the supporting frame. The central segment electrodes are connected coaxially with the outer segment parts.

As the intended way of ion production is electron impact, the trap's design requires that no dielectric surfaces are exposed to the stray electrons. Otherwise, there would be possible electric charge patches from electrons settling on such parts, disturbing the trapping potential, making proper operation of the trap impossible. To provide such condition, all the insulating parts, made of macor, are hidden inside the electrodes, as presented in Fig. 2.

The voltage supply system for the trap provides a radio-frequency voltage combined with DC voltages which are introduced to given electrodes via electrical feedthrough. The schematic of voltage system is presented in Fig. 3 together with notation of the voltages used.

The radio frequency (RF) AC voltage is generated using a waveform generator (Agilent 33220A) and amplified with high speed amplifier (Falco Systems WMA-300) providing maximum output amplitude of 150 V. As at higher frequencies, higher amplitudes are necessary, additional amplification by helical resonator [18] is introduced. Several, exchangeable resonators have been prepared to work with various