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High-energy electron impact study on autoionizing region in helium by detection of ejected electrons

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ABSTRACT

Ejected electron spectra from autoionizing region of He in the energy region of $N=2$ and $N=3$ Rydberg series have been measured at electron impact energies of 505, 1816 and 2018 eV and ejection angles of 40°, 90° and 130°. At high electron impact energies and large ejection angles this energy region is dominated by optically allowed transitions, while optically forbidden transitions are less pronounced. At the angle of 40° optically forbidden states almost vanish and resonances dominate the spectrum. A new resonance at 64.18 eV has been found at the angle of 40° and the electron impact energy of 505 eV. In energy region above 65 eV of excitation energy the first three levels of $N=3$ and the first level of $N=4$, Rydberg series have been measured. A good agreement in energy positions between these features and the corresponding ones reported by Domke et al.[2] was found.

1. Introduction

The autoionizing region in helium starts with the lowest $(2s^2)^1S_0$ level of the energy of 57.8 eV and it is followed by a series of Rydberg states described by two principal quantum numbers: N for the inner and n for the outer electron. The region ends with the double-ionization threshold at approximately 79 eV. The autoionizing region below the first $N=2$ threshold, lying between 57.8 and 65.4 eV of excitation energy, has been extensively studied in the past by different impact particles: electrons, ions and photons. To our knowledge, the first photon studies were reported in 1963 by Madden and Codling [1]. Since then, there has been a significant improvement of the energy resolution by using synchrotron radiation sources, allowing the discovery of new Rydberg series by Domke et al. [2]. The first experimental studies by ions which had a sufficient resolution to resolve and identify the autoionization states were performed by Rudd [3]. Although with an insufficient energy resolution in comparison with photo-electron spectroscopy studies to bring new spectral information, the latter studies by Barker and Berry [4] on collisions of He and Ne ions with He atom lead to the discovery of the post-collision interaction (PCI) effect.

Studies by electron impact can be divided into two categories: according to either low (below 500 eV) or high impact electron energies. The low-energy projectiles have been extensively used in the past. Using classical crossed beams experiments with detection of scattered electrons with very low energy, close to the threshold of excited states, the resonances have been found (see the review by Buckman and Clark [5]). On the other side, by detection of ejected electrons with energies below 10 eV above the threshold of the first double-excited sate, the PCI phenomenon was found by Hicks et al. [6]. This phenomenon is specifically connected with short-lived excited states of He and the electron impact energies close to the corresponding thresholds. As a result of Coulomb interaction between the scattered and the ejected electron, the later gains in energy because it leaves the interaction zone subsequently as explained by Read [7].[1] Therefore, the final result is an energy shift to higher ejected energy of the corresponding states. All of the low energy electron studies until 1975 (Spence [8] and references therein) have been focused on the first four excited states in He, i.e. the $(2s^2)^1S$, $(2s2p)^3P$, $(2p^2)^1D$ and $(2s2p)^1P$ as well as on the resonances in the energy region from 57 to 65 eV.

The second category includes studies utilizing the high impact electron energies (above 500 eV) and the high resolution of the electron energy analyzer. This was obtained in the experiment of deHarak et al. [9]. These authors studied ejected electron spectra of He below the He^+ $N=2$ threshold for the incident energies of 550, 150 and 75 eV and the ejection angles (the angle between the incident electron beam axis and the direction of the ejected electron, i.e. the fixed analyzer axis) of 60°, 90° and 120°. With the overall

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[1] Private communication from S. Cvejanovic.

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resolution of about 0.040 eV they observed up to $n = 7$ levels of the four main series, $^1S_0^e$, $^3P_1^o$, $^1D_2^e$ and $^1P_1^o$, and resolved levels up to $n = 5$. According to our knowledge, this study reports the best resolution obtained in the ejected electron spectra at high impact energies until now, however the authors have not studied the energy region of $N = 3$ Rydberg series.

Theoretical studies on the autoionization in He have been started in 1961 by Fano [10]. Since then, many theoretical papers have been published in order to explain phenomena connected to the behavior of double excited resonances in He, including resonance energies, Fano-q parameters, and quantum defects. More details are given by Domke et al. [2] and references therein.

Helium atom is a specific system concerning the autoionizing region in which a form of the measured feature strongly depends on both the electron impact energy and the ejection angle. Therefore, in order to perform a correct interpretation of the measured features, it is necessary to make measurements both at different electron impact energies and different ejection angles.

In the present measurements we use a classical crossed electron–atom beams experiment in order to measure ejected electrons produced in collisions between electrons with high impact energies from 505 to 2018 eV and He atoms. Due to a very high resolution in the analyzer part, as well as a short accumulation time needed to reach satisfactory statistics for each spectra, we were able to detect both optically allowed and optically forbidden transitions of Rydberg series of $N = 2$ up to $n = 5$. A strong angular dependence between incoming and ejected electrons has been studied at 40° and 130° with respect to the direction of the analyzer axis, for the whole autoionizing region and the impact electron energies of 505, 1816 and 2018 eV. At the angle of 40° and the electron impact energy of 505 eV, a new resonance was found at the energy of 64.18 eV (39.59 eV of the ejected electron energy).

Moreover, the first three levels of the $N = 3$ and the first level of the $N = 4$ Rydberg series are obtained for the first time in detection of ejected electrons at the high impact electron energy. Due to a very high background from the continuum and small cross-sections of helium in the energy region below 79 eV, we could not detect higher Rydberg series like in photoionization experiment [2], but we present spectra at electron energy of 1816 eV and ejection angles of 30°, 60°, 90° and 120°.

2. Experimental

The present study on autoionization in He has been performed using an apparatus that includes Omicron High Resolution Hemispherical Analyzer (OHRHA), high energy electron gun, hypodermic needle as a source of effusive beam of target gas and a Faraday cup as a collector for electron beam. Both the electron analyzer and the electron gun were designed by Omicron Vakuumphysik Gmbh and have been assembled in the high vacuum chamber, in order to perform a classical crossed electron-atom beams experiment for studies on autoionization in atoms and molecules. The schematic view of the experimental set-up is given in Fig. 1. A special attention was paid to avoid an influence of the Earth and other stray magnetic fields: (a) the vacuum chamber was shielded inside and outside by two μ-metal shields of 0.5 mm thickness, (b) the interaction region, the electron gun and the lens stack were shielded separately.

The gas beam was formed in a gold plated platinum–iridium tube 30 mm long, with an inside diameter of 0.5 mm, and was situated 3 mm away from the interaction axis. The background pressure in the vacuum chamber was 8×10^{-8} mbar, reached by three Pfeffier turbo molecular pumps, while the working pressure of helium was 2×10^{-6} mbar. The vacuum chamber was heated even during the measurements at 80 °C by two halogen lamps.

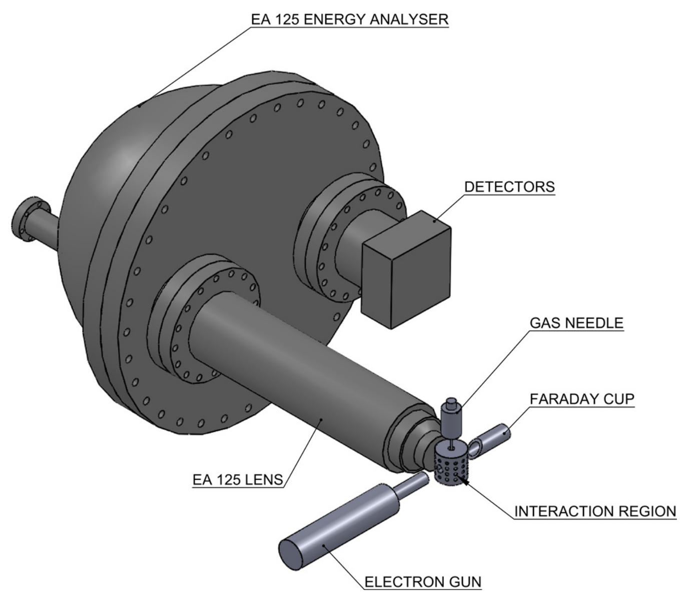

Fig. 1. Experimental set-up of Omicron High Resolution Hemispherical Analyzer (OHRHA) apparatus at The Institute of Physics University of Belgrade.

The electron gun has been designed to produce a well-collimated electron beam at energies from 10 eV to 2.5 keV and an electron current of 1–15 μA., Typical incident electron currents used in this experiment were in the range 8–12 μA. The gun can rotate around the analyzer axis in the angular region from 10° to 130°.

The hemispherical electron energy analyzer (EA 125 HR, Omicron) has a mean radius of 125 mm and variable entrance/exit slits. It is equipped with 7 channeltrons for electron detection. The analyzer has a fixed position with the entrance aperture of a diameter of $\Phi = 12$ mm, which has been reduced in the present experiment to 6 mm, in order to improve the angular analysis. The distance of the entrance aperture from the interaction region was 30 mm. Two operation modes of the analyser are predefined: The Constant Analyzer Energy mode (CAE mode) and the Constant Retard Ratio mode (CRR mode). The CAE mode scans the kinetic energy of ejected electrons by varying the retarding ratio whilst holding the analyser pass energy (E_p) constant. In the present measurements, the CRR mode has been used, meaning that the pass energy (E_p) was changed whilst holding the retarding ratio constant. Therefore, the ejected electrons are retarded by the lens stack by a constant proportion of their kinetic energy, so that the ratio of the electron kinetic energy to the E_p was kept constant during the acquisition of a spectrum. The good focus at the entrance of the analyzer was achieved by the lens stack having the three modes of magnification high, medium and low.

All components of the electron gun, the analyzer and the lens stack have been controlled by dedicated electronic components made by the Omicron company. A personal computer has been used to perform the control of all experimental parameters and data acquisition. The accumulation time of the spectra was typically between 30 and 60 min.

Generally, the overall energy resolution in the electron spectroscopy experiments depends on the energy resolution of both the electron source and the electron analyser, as well as on broadening effects such as Doppler broadening or broadening due to stray electrostatic fields as defined by Read [11] for different types of electron spectra. The energy resolution of the incident electron beam in the present experiment was verified according to the elastic peak