Near-Threshold Electron-Impact Ionization of Calcium Atoms

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INTRODUCTION

The electron-impact ionization of alkali-earth atoms has been extensively studied experimentally and theoretically for many years [1]. Both partial and total ionization cross sections were investigated (see, e.g., [2, 3]). However, experiments with these atoms meet certain difficulties, related, first of all, to high temperatures necessary for creating fairly dense atomic beams. In particular, in the case of calcium atoms, the temperature of the atomic source must be maintained above 600°C. Second, the chemical activity of these elements leads to a change in the surface properties of elements of electron-optical systems. At the same time, precision measurements require a fairly intense low-energy electron beam with a high monochromaticity.

The electronic configuration of the outer 4s² subshell of the calcium atom suggests a helium-like behavior. However, the calcium atom has a rather large number of electrons and, hence, a more complicated structure of subshells. The calcium atom is of interest because it is the lightest atom whose outer 4s subshell in the ground state is filled while its 3d subshell remains empty. The energetic proximity of these states leads to well-resolved electronic correlation effects upon excitation and ionization from the 3p subshell [2]. These effects were mainly observed when studying the photoionization of calcium atoms [4–6].

At present, there have been numerous experimental studies of the photoionization and photoabsorption of the calcium atom and only a few works on the measurement of electron-impact ionization cross sections. Since the 1970s, the main part of experiments in the latter direction has been performed using the method of intersecting beams. These investigations include the measurements of the energy dependences of the partial cross sections of k-order ionization of the calcium atom, for k = 1–4 [7] and k = 1–3 [8] in the range of incident electron energies of 12–1100 eV. The absolute total ionization cross sections were measured in the range from the ionization threshold to 200 eV [3, 9], 500 eV [10], and 1 keV [11]. Recently [2], the relative partial (for k = 1) and total ionization cross sections of the Ca atom in the energy range to 100.7 eV were measured by the method of intersecting atomic and electron beams with separation of Ca⁺ ions by the time-of-flight method. To obtain absolute cross sections, the authors normalized their curves to the results of work [3] for the incident electron energies of 40 eV.

Theoretical calculations of total ionization cross sections were performed in several studies [3, 12]. Work [3] contains calculations using both the Born and classical binary approximations. Both calculations well describe the general behavior of the ionization curve, but do not reproduce details of experimental curves. The authors of [12] calculated the total ionization cross section of the calcium atom using the symmetrical collision model [13]. Taking into account the electron exchange, they managed to achieve a better coincidence of calculations with the experimental results in the region of low (E < 20 eV) incident electron energies.

Analysis of the investigations performed to date shows that they are mainly devoted to measurements of the absolute ionization cross sections of the calcium atom in a wide range of ionizing electron energies (from the threshold to 1100 eV) with a rather large
The electron beam was directed to a collision zone, where it crossed with the atomic beam. Positive ions formed in the collision zone were extracted to plates, to which a potential of ~1.5 V was applied. The current of the ion collector was measured with a digital picoammeter. With the use of a voltage-to-frequency converter, an analog signal from the picoammeter output was accumulated in the form of pulses by a PC-based recording system. The signal accumulation time per one point was $\tau = 5$–20 s. This made it possible to reduce the statistical measurement error to $<1\%$.

**MEASUREMENT RESULTS AND DISCUSSION**

The measured energy dependence of the total ionization cross section of the calcium atom is shown in Fig. 1. The measurements were performed in the range of incident electron energies from 6.11 to 16 eV with a step of 0.05 eV. The energy scale was set by the maximum of the first derivative in the initial range of the current–voltage characteristic of the electron current to the primary beam collector and by the spectroscopic ionization threshold of the calcium atom. The position of the ionization threshold of the atom was refined by the method proposed by Lossing et al. [16]. The error of calibration of the energy scale was $\pm 0.05$ eV. The absolute cross section was determined by normalizing our data at an energy of 15.5 eV to the results obtained in [3], which agree well with our data in the shape of the curve (Fig. 1).

As is seen from Fig. 1, the calcium ionization cross section continuously increases in the entire energy range studied. Immediately after the ionization threshold, one observes a linear region in the range of $\sim 1$ eV, while, in the energy region of 13–14.2 eV, there is a feature that is more clearly seen on an enlarged scale in the inset.

In the calcium atom, similar to other alkali-earth atoms, the formation of the singly charged ion (A$^+$) from the ground atomic state (A) in the near-threshold energy region occurs due to the transition of one of the $s$ electrons to the continuum (so-called direct ionization),

$$A(ns^2) + e \rightarrow A^+(ns) + 2e. \quad (1)$$

The formation of ions can also occur via another channel, through low-lying AISs of the atom (A$^{**}$). These AISs are formed as a result of the simultaneous excitation of two outer electrons. The electronic decay of these AISs leads to the formation of an ion

$$A(ns^2) + e \rightarrow A^{**}(nl_1l_2) + e \rightarrow A^+(nl) + 2e, \quad (2)$$

where $n_1, 2, l_1, 2$, and $n, l$ are the principal and orbital quantum numbers of the electronic configuration of the atomic AISs and ionic states, respectively.

The interpretation of the data on the electron-impact ionization cross section of atoms is compli-