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On the Measurement of Electron Impact Ionisation Cross-sections for Highly Charged Ions Using an Electron Beam Ion Trap (EBIT)

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Abstract

Experiments in which the time evolution of the charge distribution of Argon ions in the Tokyo EBIT was measured have been carried out. These measurements involved extracting the ions from the trap after a controlled confinement time and determining the charge distribution of these ions. By repeating the procedure at various confinement times the onsets for ions of particular charge states were determined at a series of electron beam energies. This sort of data should permit electron impact ionisation cross-sections to be determined as well as providing interesting information relating to EBIT physics.

1. Introduction

Electron impact ionisation is an important process in the physics of highly charged ions and experimental determinations of the cross-sections for such processes are therefore useful for plasma applications. In addition, more fundamentally, they are important for testing the various theoretical calculations [1].

In the past electron impact ionisation cross-sections have been obtained from X-ray measurements determining the equilibrium charge balance within an EBIT [2]. However, it is also possible to obtain ionisation cross-sections by measuring the charge distribution of ions extracted from an EBIT as a function of their confinement time within the trap. This sort of data yields onsets for the appearance of ions of particular charge states. Generally, the time evolution of the charge distribution in the trap is described by a set of differential equations that include the important physical processes that occur [3,4]. At times shortly after the appearance of ions of a charge state q, the rate of increase of the number of ions of this charge state depends only on the number of ions of charge state $q-1$ and the rate of ionisation from this lower charge state. In this regime, if the number of ions of a charge state q is denoted N_q, the rate of ionisation ($R^I_{q-1\to q}$) for ions of the next lowest charge state is given by:

$$\frac{dN_q}{dt} = R^I_{q-1\to q} N_{q-1}. \tag{1}$$

These ionisation rates in turn are proportional to the ionisation cross-sections.

2. Experimental

The present, preliminary, experiments on Argon were performed using the Tokyo EBIT [5] with the arrangement that is shown schematically in Fig 1. In an EBIT, ions are confined in the axial direction by electrostatic potentials applied to three drift tube electrodes. The application of asymmetric potentials, lower than the effective radial potential, ensures that ions leaving the trap travel in the direction of the ion extraction line. This extraction line consists of two Einzel lens, which incorporate deflectors, an electrostatic bender and an analysing magnet [6]. At a given magnetic field, ions having the appropriate velocity and mass to charge (m/q) ratio pass around the analysing magnet and are detected using a commercial position sensitive detector (Quantar Technology Model 3390A). The whole trap region was held at a constant potential of approximately 3 kV with respect to the analysing magnet so that the m/q values of ions arriving at the detector could be determined from their arrival positions and the strength of the analysing magnet field.

In these measurements, the confinement time of ions within the EBIT was controlled by raising the potential of the central drift tube (DT2) so that positive ions were no longer confined in the axial direction, and travelled towards the ion extraction line. The potential of DT2 was ramped at a rate of ~20 V/ms in order to empty the trap. A variety of confinement times, ranging from ~10–1000 ms, were investigated using an arbitrary function generator to control the time after which the trap was emptied. The whole *dumping cycle*, consisting of 28 different confinement times, had a period of ~4 s. In addition to the positional and magnetic field information associated with each detected ion, its temporal position in the *dump cycle* was monitored using a multiparameter system [7]. This information was recorded for each detected ion as the magnetic field was slowly (~300 μHz) ramped in order to cover the Ar^{q+} charge states of interest.

Utilising this information from the multiparameter system, the charge distribution of Argon ions in the trap corresponding to each of the confinement times was determined. By finding the abundance of Ar^{16+}, Ar^{17+} and Ar^{18+} ions in each of these spectra, the onsets for the appearance of these species were obtained. A portion of one of these onsets, recorded at an electron impact energy of 30 keV, is shown in Fig. 2. Similar onsets have been obtained at impact energies ranging from 17–35 keV. The determination of cross-sections from these onsets would extend the existing experimental measurements in Argon which appear to have been limited to one energy [8].

During these experiments the ion signal was continuously monitored. Consequently information about ions that escape from the trap, as oppose to those that reach the detec-

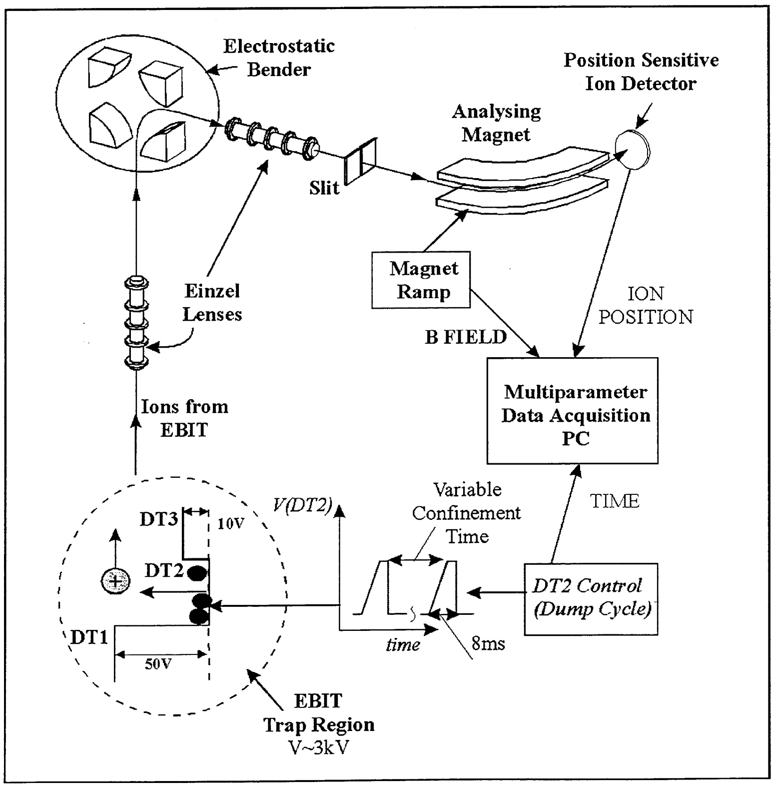

Fig. 1. Schematic diagram of the experimental arrangement.

tor as a result of removing the axial trapping potential, was also obtained. The rate of escape of ions of a specific charge state as a function of confinement time gives information relating to the temperature of these ions [3]. This quantity is important in the physics of EBITs. For example, the spatial overlap of a particular ion cloud with the electron beam depends on this ion temperature.

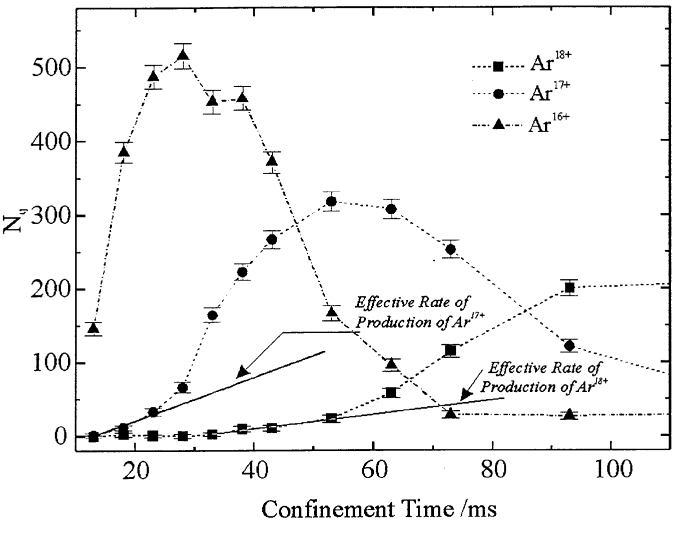

Fig. 2. Onsets for the appearance of Ar^{16+}, Ar^{17+} and Ar^{18+} obtained at an electron impact energy of ~30 keV. Each point represents the average of two measurements obtained at similar confinement times. The straight lines on the plot indicate the *effective production rates* for Ar^{17+} and Ar^{18+}, from which the associated ionisation rates were derived as described in the text.

3. Data Analysis

The equation yielding the ionisation rates (1) is only valid at times shortly after the appearance of ions of a particular charge state. In this time regime the ratio of the gradient of the onset curve for an ion of charge state q, which gives the *effective rate of production* of these ions, to the number of ions of charge state $q-1$ yields the ionisation rate, $R^I_{q-1\to q}$. In this treatment, the only additional assumption is that the detection efficiency for ions of charge state q and $q-1$ is the same. By fitting straight lines to the appropriate portions of the onset curves for Ar^{18+} and Ar^{17+}, as indicated in Fig. 2, the associated ionisation rates may be determined. This analysis yields values of $R^I_{16+\to 17+} = 7.6 \pm 1.8$/s and $R^I_{17+\to 18+} = 3.9 \pm 0.6$/s respectively at an electron impact energy of ~30 keV. These values, differing by a factor of ~2, appear to be reasonable on the grounds that there are two 1 s electrons in the Helium like species (16+) compared to a single one in the Hydrogen like ion. For an electron beam current I, these rates are related to the ionisation cross-sections ($\sigma^I_{q-1\to q}$) by the expression;

$$R^I_{q-1\to q} = \frac{I}{e\pi r_e^2}\sigma^I_{q-1\to q} f_{q-1}. \tag{2}$$

Consequently, if the electron beam radius (r_e) and the overlap factor of the ions with the electron beam (f_{q-1}) are known, cross-sections may be obtained from the rates, $R^I_{q-1\to q}$. The information obtained by monitoring the escaping ions suggests that at the confinement times where these rates were determined the ions are within the electron beam ($f \sim 1$). Therefore relative cross-sections may be obtained from these experiments and these could be placed on an absolute scale if the radius of the electron beam was known.

4. Concluding Remarks

In the near future, these preliminary experiments will be continued in order to determine ionisation rates and cross-sections in various targets. This sort of study is free from the complications of the effects of other process which affect the charge distribution within the trap and is applicable over a range of impact energies and charge states. In the forthcoming experiments it is envisaged that the electron beam radius will be measured simultaneously, enabling absolute cross-sections to be determined. It is anticipated that the understanding of the physics of the Tokyo EBIT will also be enhanced as a result of the information obtained by continuously monitoring the escaping ions.

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