Integrated Oscillator Strength for the Ar8$^+$ Formation from the Neutral Atom by Electron Impact

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By fitting the Bethe formula to experimental data available in the literature, we determined the integrated oscillator strength for the Ar^{8+} formation by electronic collision on neutral Argon. The results are compared with a previous empirical calculation and with a set of experimentally obtained multiple ionisation data.

I Introduction

The multiple ionisation reaction is a typical many-body problem. This is a class of processes where the Born approximation cannot be directly applied. However, semi-empirical expressions, usually based on the Bethe formula, have been used to describe the multiple ionisation reaction by electron impact within acceptable accuracy [1-3]. Considering the nature of the Coulomb interaction, the understanding of the mechanism relevant for multiple ionisation by electron impact promises important insight into electron correlation problem. This electronic correlation may reveal information about the structure of atoms and the dynamics of the collision mechanism.

Multiple ionisation cross sections (MICS) of atoms can be an appropriate tool to estimate optically allowed transition data [4]. The dependence of the cross section on the impact velocity shows distinct regions, where the Born approximation may or may not be supported, which are usually associated to two mechanism, optically allowed and optically forbidden processes. In most cases, both mechanisms are found to be of comparable magnitude in the asymptotic regime. Therefore, neither mechanism alone can explain the observed energy dependence. Hence, combining amplitudes for both processes may give a better description of the cross section behaviour as a function of the impact energy. MICS may result from two distinct processes: inner-shell ionisation with subsequent secondary electronic ejection, and outer-shell ionisation with simultaneous emission of n electrons. It is very complicated to detect all the products of the reaction in coincidence, in order to identify unequivocally the reaction channel. Up to date, only (e,2e) and (e,3e) experiments are possible [5], where two or three emerging electrons can be collected after the collision. Therefore, the photoionisation data can be helpful to investigate the multiple ionisation channels by electron impact.

The introduction of the generalised oscillator strength (GOS) in Bethe's formalism describes results from electron scattering experiments. For instance, Wight and Van der Wiel [6] performed the analysis of the GOS for double ionisation of He, Ne and Ar from threshold up to 200eV electron impact, and compared their results with photoionisation data. In addition, experimental GOS are required input by many theoretical models [7, 8]. Extensive calculations of GOS for electronic excitations have been performed by Kim and Inokuti [9] with accurate results for He. In multiple ionisation process, the contributions to the ionisation cross section arise from multiple electron transitions. Hence, it is worthwhile to integrate the GOS over all the energetically possible reactions to a particular final ion. Therefore, the integrated oscillator strength (IOS) is an important index of the distribution of the optical oscillator strength (OOS). In order to identify the different reaction channels that contributed to the measured IOS, it can be compared with the photoionisation cross section for ejection of a particular electron and the probability of formation of the final charged state n.

In the present work, we used the experimental data published in reference [10]. These data were acquired over the incident energy range from 1700 to 3000eV, under a single collision regime, with an uncertainty of about 18%. The static gas target technique was employed [11]. The final charged state of the target was identified using the time-of-flight spectrometry technique. The multiple ionisation cross section for Ar^{8+}, presented by Almeida and co-workers [10], does not have enough experimental points, above the maximum region, for an accurate Fano-plot [12] (plot of the product $E\sigma_{8+}$ against logE) of the asymptotic cross section portion. Nevertheless, the Bethe formula may be directly fitted to the experimental points, leading a reasonable prediction of the integrated oscillator strength (IOS) for the process.

II Results and discussion

The multiple ionisation reaction is given by

$$e^- + Ar \rightarrow Ar^{8+} + 9e^- \; . \tag{1}$$

The MICS can be estimated in good agreement by the Bethe formula [13] as a function of the incident energy. This expression derives from an *ab initio* quantum-mechanical theory where the terms are directly identified.

The cross section is given by

$$\sigma_n = 4\pi a_0^2 \left(\frac{R}{E}\right) \left\{ M_{8+}^2 \ln\left(\frac{E}{R}\right) + \gamma_{8+} \left(\frac{R}{E}\right) + C_{8+} \right\} \; . \tag{2}$$

where a_0 is the first Bohr radius of the hydrogen atom (0.529 Angstrom), R is the Rydberg energy (13.6eV), M_{8+}^2 is the integrated oscillator strength, γ_{8+} is a low energy correction and C_{8+} stands for high order terms associated with optically forbidden transitions.

In order to determine the IOS, it was assumed that the multiple ionisation cross section could be represented by equation (2) in the observed energy range. The MICS has been fitted through a least-squares method. The resulting fit is shown in Fig. 1 along with the original data.

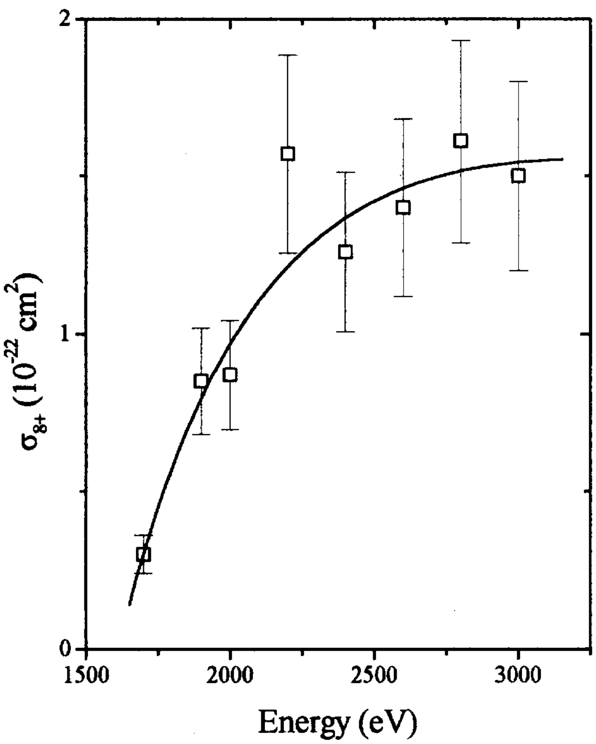

Figure 1. Fitting procedure of the electron-impact ionisation cross section σ_{8+} as a function of the incident energy. □ Experimental data from reference [10].

Since the term M_{8+}^2 appears explicitly in equation 2 this value can be directly estimated. The result is $M_{8+}^2 = (1.5\pm0.3)\times10^{-6}$. The total uncertainties in the present value arise from the statistical accuracy of the experimental data and the fitting procedure described above added quadratically.

More determined values of IOS can be found for Argon than for any other gas. These data are presented in Fig. 2 together with the present result, and the expression from Almeida and Godinho [14] is shown by a dashed curve. In ref. [14], an empirical model has been proposed to describe the dependence of the integrated oscillator strength for multiple ionisation reaction with the final ionic charge state, n. This expression, despite of its simplicity, confirms the qualitative trend of the IOS data for noble gases. The agreement between the experimental data and the empirical prediction for multiple ionisation of argon ranging from n=1 to 4 is quite good considering the small number of measurements available in the literature. Nevertheless, it overestimates the experimental values by a factor 2 to 5 for n higher than 5. The empirical formula [14], based on such a small number of experimental measurements as input and with only four adjustable parameters, cannot describe accurately the absolute values of IOS for high n where the indirect processes may have relevant contributions. M_{8+}^2 determined in this paper, shows to be in good accordance with the previous experimental data set. It must be stressed that these experimental values of M_{8+}^2 presented in Fig. 2 cover six orders of magnitude.

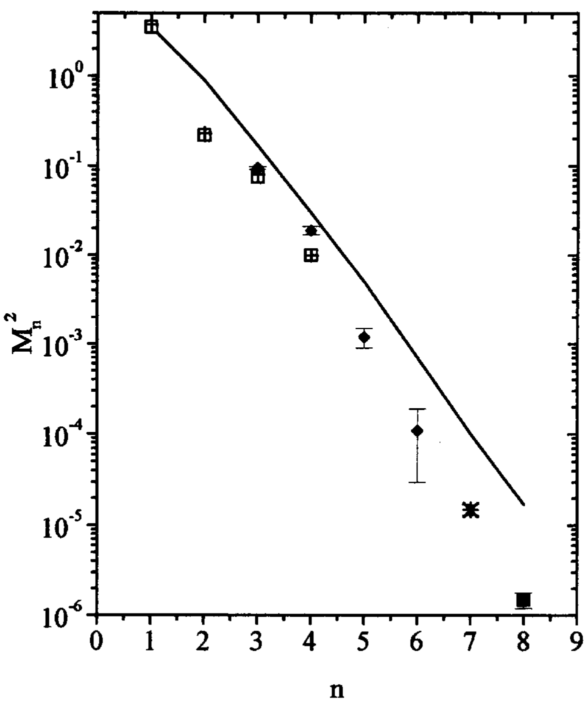

Figure 2. Integrated Oscillator Strength (M_n^2) of multiple ionised Argon as a function of the target final charged state: ■ present result; □ data from reference [4]; * data from reference [10]; ♦ data from reference [11]; + data from reference [15]; — empirical model from reference [14].

III Conclusions

The purpose of this work was to estimate the integrated oscillator strength from experimental data for multiple ionisation reaction of a neutral atom by electron impact. The determined IOS gives a good agreement with the expected behaviour of experimental data available in the literature. The prediction from the empirical expression is about a factor ten higher than the present value.

Although low degree multiple ionisation data by electron impact have been exhaustively measured and analysed, much less are available for $n > 4$. To the author's knowledge this is the first estimation of IOS for 8-fold ionisation of Argon by electron collision. The M_{8+}^2 presented here, even with its large uncertainty, seems to provide a reliable guide to discuss the origin of the ejected electrons during the collision.

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