Eur. Phys. J. D **27**, 23–26 (2003)
DOI: 10.1140/epjd/e2003-00226-2

THE EUROPEAN
PHYSICAL JOURNAL D

Electron-impact detachment from S^-

K. Fritioff[1,a], J. Sandström[1], D. Hanstorp[1], F. Hellberg[2], A. Ehlerding[2], M. Larsson[2], G.F. Collins[3], D.J. Pegg[4], H. Danared[5], and A. Källberg[5]

[1] Department of Physics, Chalmers University of Technology/Göteborg University, 412 96 Göteborg, Sweden
[2] Department of Physics, AlbaNova, Stockholm University, 106 91 Stockholm, Sweden
[3] Physics Department, Queen's University Belfast, Belfast BT7 1NN, Northern Ireland, UK
[4] Department of Physics, University of Tennessee, Knoxville, Tennessee 37996, USA
[5] Manne Siegbahn Laboratory, Frescativägen 24, 104 05 Stockholm, Sweden

Received 24 April 2003 / Received in final form 13 May 2003
Published online 29 July 2003 –

Abstract. Absolute cross sections for single and double electron-impact detachment of the S^- ion have been investigated over collision energy ranges of 0–60 eV and 0–30 eV, respectively. The experiment was performed at the ion storage ring, CRYRING. The threshold energies were measured to be 6.6 eV for single detachment and 19.8 eV in the case of double detachment. The single detachment cross section has a maximum of 6.7×10^{-16} cm^2 at 30 eV. The double detachment cross section was studied only in the threshold region. No sharp structures were observed in either of the cross sections.

PACS. 34.80.Dp Atomic excitation and ionization by electron impact – 34.80.Kw Electron-ion scattering; excitation and ionization

1 Introduction

Reliable measurements of cross sections for electron impact detachment from negative ions have been very limited until rather recently. This is especially true in the case of multiple detachment processes [1]. The advent of magnetic ion storage rings has, however, changed this situation dramatically. Now it is possible to investigate electron impact detachment from atomic or molecular negative ions over a wide range of collision energies using a merged beam technique [2–6]. The use of merged electron and ion beams allows one to use a large interaction volume and to easily access the detachment threshold.

In addition to the intrinsic interest in collision physics, single and multiple detachment from anions plays an important role in a variety of applications such as plasma physics, ion source development, laser physics and atmospheric science.

In the present paper we report on measurements of absolute cross sections for the electron-impact detachment of one and two electrons from the S^- ion. Specifically, the following processes

$$\begin{aligned} S^- + e^- &\rightarrow S + 2e^- \\ S^- + e^- &\rightarrow S^+ + 3e^- \end{aligned} \quad (1)$$

have been studied in the energy regimes 0–60 eV and 0–30 eV, respectively. Figure 1 is an energy level diagram showing electron-impact excitation of S^- into the first and second detachment continua.

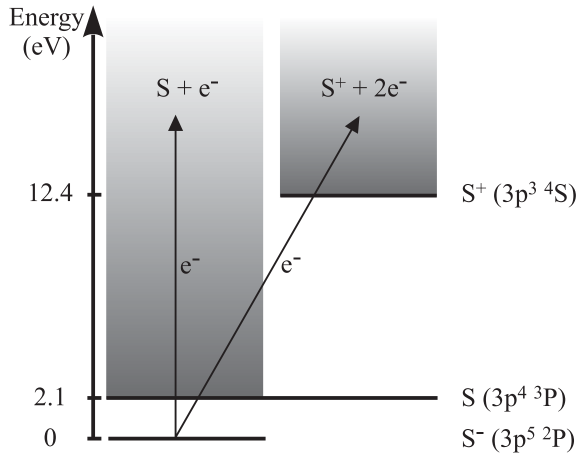

Fig. 1. Energy level diagram showing electron-impact excitation of S^- into the first and second detachment continua.

2 Experiment and data analysis

This experiment was conducted at the ion storage ring CRYRING at the Manne Siegbahn Laboratory in Stockholm [7]. Intense ion beams can be produced in the ring by a multi-turn injection method. The energy

[a] e-mail: f3aka@fy.chalmers.se

resolution in the collision process is significantly improved by the use of electron cooling [8].

Negatively charged sulphur ions were produced in a Cs sputter ion source [9]. They were accelerated to 40 keV and mass selected using a magnet. A current of several microamperes was measured directly after the magnet. The ions were injected into the ring and thereafter accelerated with a non-resonant-driven drift-tube to their maximum energy of 3.0 MeV. Typical ion currents were 1.5 μA at the end of the acceleration. The electrons in the cooler are merged with the ions after the acceleration and the phase space cooling of the ion beam starts. Velocity matched electrons travel collinearly with the ions for 85 cm. In the present experiment the temperatures of the electrons were 8 meV and 0.05 meV in the transverse and longitudinal direction, respectively. The electron energy at the cooling condition was 54.7 eV. In addition to cooling the ion beam, the electrons are used as collision partners in the detachment reactions. A wide range of collision energies was achieved by ramping the voltage on the electron gun in the cooler. The energy of the electrons was tuned from 54.7 eV to 229 eV in the single detachment measurement and from 54.7 eV to 165.7 eV in the double detachment measurement. This corresponds to collision energies ranging from 0 to 60 eV and 0 to 30 eV, respectively, in the center-of-mass (CM) frame. In the merged beam geometry the collision energy in the CM frame, $E_{\rm CM}$, is given by

$$E_{\rm CM} = \left(\sqrt{E_e} - \sqrt{E_{\rm cool}}\right)^2, \quad (2)$$

where E_e is the electron energy in the laboratory frame and $E_{\rm cool}$ is the electron energy in the laboratory frame when the cooling condition is met. In order to derive this equation, the reduced mass is approximated by the electron mass and the CM velocity, $v_{\rm CM}$, is taken to be the same as the detuning velocity, $v_d = |\overline{v}_e - \overline{v}_{\rm ion}|$. The latter approximation is valid since the reaction threshold energy in the CM frame is much greater than the electron temperature. After the ramping of the energy, the electron current was turned off and the magnets went back to initial settings. The beam was dumped and a new ring-injection started.

Neutral sulphur atoms produced in both electron impact detachment events and in collisions with the residual gas were not deflected by the magnetic field in the dipole magnet situated after the cooler. Instead they continued straight forward through the magnet. They were then detected with a surface barrier detector (SBD) positioned 4 m downstream of the cooler. For collision energies larger than 20 eV, double detachment processes can occur. The S^+ ions produced in this process were bent away from the S^- ion trajectory by the dipole magnet. They were then detected by a movable SBD. The regions where the electrons and ion beams were merged and where the detectors are placed are shown schematically in Figure 2. In another section of the ring a scintillation detector consisting of a combination of a BaF-window and a photomultiplier tube was used to detect S atoms neutralized by collisions with the residual gas. This signal was used for

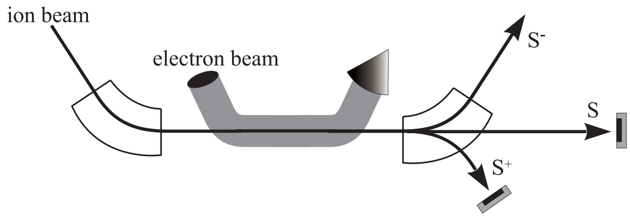

Fig. 2. A schematic diagram of the electron cooler and the detection regions. Electron-impact detachment collisions are studied by allowing negative ions and electrons to interact in the cooler region. The neutral atom and positive ion products of these collisions are detected using SBDs.

normalization purposes. The outputs of all the detectors were directed to multichannel scalers.

The ion current in the ring was determined separately using a DC transformer. For this measurement the current was maximized to enhance the accuracy. During data acquisition, however, the ion current was reduced in order to avoid pulse pile-up in the SBDs. A scintillation detector was used to relate the ion current measured with the DC transformer and the smaller current used during the data acquisition.

The collision energies used to measure cross sections were considerably larger than the energy spread of the electrons. We were therefore able to neglect the electron temperature and assume that the relative velocity between the electrons and ions, v, are equal to the detuning velocity, v_d. The cross section is then given, in terms of measurable quantities, by [10]

$$\sigma = \frac{R_s}{R_N} R_B \frac{C}{n_e v l}. \quad (3)$$

R_s is the count rate on the SBD from electron-impact induced detachment events. This rate is obtained by subtracting the exponentially decaying background from the total measured count rate on the detector. The background is determined by an interpolation between a time window before and a second time window after the electron energy ramp, when no electron beam is present in the cooler. R_N is the neutral count rate on the scintillation detector, C is the circumference of the ring, n_e is the electron density, v is the relative velocity between ions and electrons and l is the length of the interaction region. R_B is the normalized destruction rate due to collisions and it is obtained using the relation

$$R_B = \frac{R_{N'}}{I_{\rm ion}} \frac{v_{\rm ion} e}{C} \quad (4)$$

where $(I_{\rm ion} C)/(v_{\rm ion} e)$ is the total number of ions in the ring and $R_{N'}$ is the count rate on the scintillator during the ion current measurement. $I_{\rm ion}$ is the ion current, $v_{\rm ion}$ is the ion velocity and e is the elementary charge.

The signal on the SBD receives an additional contribution from the regions were the electron and ion beams merge and de-merge. The collision energy is higher in these so-called toroidal regions than in the straight section of the cooler. The measured cross section was corrected for this

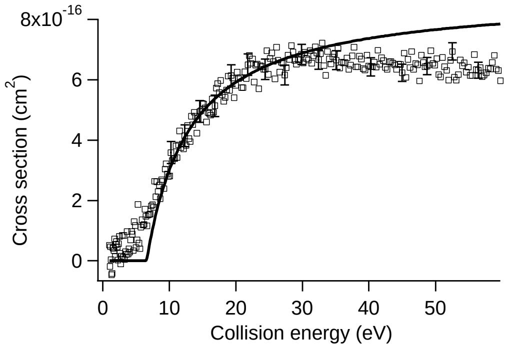

Fig. 3. The cross section for the detachment of a single electron from S^- following electron impact. The squares represent the measured data and the solid line is a fit to the data over the range 10–30 eV. The solid line is extended beyond the limits of the fit.

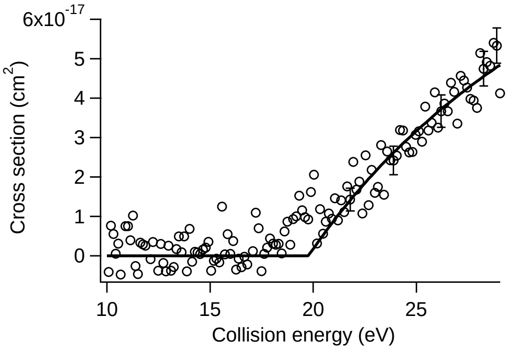

Fig. 4. Threshold behavior of the cross section for the detachment of two electrons from S^- following electron impact. The circles represent measured data. The solid line is a fit to the data over the range 22–30 eV. The solid line is extended beyond the limits of the fit.

effect by subtracting the calculated contribution from the toroidal sections. This correction amounted to about 30% of the measured cross section.

Another correction involved the energy scale. Individual electrons in the cooler experience a space charge as the result of being part of the electron beam. This effect will reduce the actual energy of the electrons compared to the value expected from the power supply connected to the electron gun in the cooler. This space charge correction can be calculated using the Poisson equation [11]. As a result, the threshold energies for single and double detachment were shifted down by 0.8 eV and 0.9 eV, respectively.

3 Results

In the experiment, single and double electron detachment processes were studied in the collision energy ranges 0–60 eV and 0–30 eV, respectively. The results are shown in Figures 3 and 4. The error bars represent statistical uncertainties associated with SBD signals.

Figure 3 shows the cross section for single detachment, which can be written as

$$S^- + e^- \rightarrow S + 2e^-. \quad (5)$$

The ground state configuration of S^- is $3p^5\ ^2P$ with the fine structure components $J = 1/2, 3/2$, which were unresolved. The ground state configuration of the S atom is $2p^4$, which splits into the three terms ^3P, ^1D and ^1S. These three states will all contribute to the signal shown in Figure 3. For higher electron energies, it is also possible that the residual atom is left in electronically excited states but their contribution to the cross section is expected to be small.

In the same figure, a curve fit to the data points is shown as a solid line. This fit is based on a semiclassical over-the-barrier (OTB) model. In this model a detachment reaction is assumed to occur if the electron comes within a distance R_{th} from the center of the negative ion and as long as the kinetic energy of the incoming electron is greater than the electron affinity (EA), the energy loss for the electron due to the Coulomb repulsion between the electron and the anion and the centrifugal barrier [12]. This fit is meaningful only in a region between the threshold and the maximum cross section. Nevertheless we use this restricted model to determine a value for the threshold, which we call the model threshold. The rise in the cross section below the model threshold originates in tunneling events. The model threshold for single detachment of S^- is determined to be 6.6 eV. This is some 3 times greater than the EA of S, which is 2.1 eV [13]. The larger model threshold for the electron impact detachment reaction is due to the Coulomb repulsion between the electron and the ion. Thus, a reaction only takes place if the collision energy is 4.5 eV in excess of the EA. The cross section rapidly increases from the threshold until the maximum cross section of 6.7×10^{-16} cm^2 is reached at 30 eV. Thereafter the cross section decreases linearly up to the maximum measured collision energy.

At higher energies, the projectile electron can detach two electrons from the anion:

$$S^- + e^- \rightarrow S^+ + 3e^-. \quad (6)$$

The ground state configuration for the S^+ ion is $3p^3$, which splits into the three terms ^4S, ^2D and ^2P. These three final states will all contribute to the cross section for this process. The near-threshold cross section for this process, together with a curve fit from the OTB model, is shown in Figure 4. The model threshold for the reaction is 19.8 eV. This value should be compared to the sum of the EA and the ionization potential of S, which is 12.4 eV. The excess energy needed in the double detachment reaction is therefore 7.3 eV.

In addition to the uncertainty in the SBD signal, shown as error bars in the figures, there are statistical fluctuations in the measurements of other quantities needed to determine the cross sections. These contribute with an additional statistical uncertainty of 5% at the maximum of the cross section for single detachment and 3% at the maximum collision energy for double detachment. The systematic uncertainty associated with the determination of the cross section is dominated by the uncertainty in the measurement of the ion current (10%) and the uncertainty in determining the length of the interaction region (5%). The toroidal correction contributes to the total uncertainty in the cross section with 3%. There are also uncertainties associated with the measurement of the electron current (2%), the radius of the electron beam (1%) and the length of the beam orbit in the storage ring (0.1%). Quadratically combining all these independent uncertainties yields an overall systematic uncertainty of 12%. The collection and detection efficiency are unity for both the SBDs since the ion beam is considerably smaller than the detectors. The overlap between the ion and electron beams is 100% in the interaction region and the smaller ion beam was directed through the uniform region of the electron beam. The uncertainty in the energy scale is 0.2 eV at the threshold for single and double detachment. The energy resolution is limited by the data collection time of the MCSs. In this experiment we had a resolution of 0.16 eV and 0.23 eV at the single and double detachment thresholds, respectively.

4 Summary

Absolute cross sections for single and double detachment from S^- following electron impact have been measured in a merged beams experiment. In the experiment collision energies ranged from 0–60 eV for the single detachment process and 0–30 eV for the double detachment process. The model threshold for single and double detachment were found to be at 6.6 and 19.8 eV, respectively. The maximum value of the single detachment cross section was measured to be 6.7×10^{-16} cm^2 at 30 eV.

This work was supported by the Swedish Research Council (VR) and partly by the European Community's Research Training Networks Program under contract HPRN-CT-2000-0142. AE was supported by the EOARD under contract F61775-01-WE035. We thank the staff of the Manne Siegbahn Laboratory for their invaluable help and use of the heavy ion storage ring facility.

References

1. H. Tawara, V.P. Shevelko, Int. J. Mass Spectrom. **192**, 75 (1999)
2. L. Vejby-Christensen, D. Kella, D. Mathur, H.B. Pedersen, H.T. Schmidt, L.H. Andersen, Phys. Rev. A **53**, 2371 (1996)
3. L.H. Andersen, M.J. Jensen, H.B. Pedersen, L. Vejby-Christensen, N. Djurić, Phys. Rev. A **58**, 2819 (1998)
4. H.B. Pedersen, R. Bilodeau, I.V. Makassiouk, M.J. Jensen, C.P. Safvan, L.H. Andersen, Phys. Rev. A **63**, 032718 (2001)
5. K. Andersson, D. Hanstorp, A. Neau, S. Rosén, H.T. Schmidt, R. Thomas, M. Larsson, J. Semaniak, F. Österdahl, H. Danared, A. Källberg, A. Le Padellec, Eur. Phys. J. D **13**, 323 (2001)
6. A. Le Padellec, K. Andersson, D. Hanstorp, F. Hellberg, M. Larsson, A. Neau, S. Rosén, H.T. Schmidt, R. Thomas, J. Semaniak, D. Pegg, F. Österdahl, H. Danared, A. Källberg, Phys. Scripta **64**, 467 (2001)
7. K. Abrahamsson, G. Andler, L. Bagge, E. Beebe, P. Carlé, H. Danared, S. Egnell, K. Ehrnstén, M. Engström, C.J. Herrlander, J. Hilke, J. Jeansson, A. Källberg, S. Leontein, L. Liljeby, A. Nilsson, A. Paál, K.G. Rensfelt, U. Rosengård, A. Simonsson, A. Soltan, J. Starker, M. af Ugglas, Nucl. Instr. Meth. Phys. Res. B **79**, 269 (1993)
8. H. Danared, Nucl. Instr. Meth. A **391**, 24 (1997)
9. R. Middleton, Nucl. Instr. Meth. **214**, 139 (1983)
10. C. Strömholm, J. Semaniak, S. Rosen, H. Danared, S. Datz, W. van der Zande, M. Larsson, Phys. Rev. A **54**, 3086 (1996)
11. D.R. DeWitt, R. Schuch, H. Gao, W. Zong, S. Asp, C. Biedermann, Phys. Rev. A **53**, 2327 (1996)
12. H.B. Pedersen, N. Djurić, M.J. Jensen, D. Kella, C.P. Safvan, H.T. Schmidt, L. Vejby-Christensen, L.H. Andersen, Phys. Rev. A **60**, 2882 (1999)
13. T. Andersen, H.K. Haugen, H. Hotop, J. Phys. Chem. Ref. Data **28**, 1511 (1999)