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Screening–antiscreening effects in one-electron loss by fast Li^+ and Li^{2+} ions in collisions with H, H_2 and He

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Abstract. Cross sections for one-electron loss by Li^+ and Li^{2+} in H, H_2 and He have been measured within the range 0.3-2.7 MeV. The results are considered in terms of recent descriptions of electron loss based on both screening and antiscreening effects involving the target electrons. Recent calculations based on the Born approximation are shown to provide improved agreement with experiment at high velocities when antiscreening effects are included. In all cases, cross sections attain maximum values at impact energies lower than those predicted. It is also shown that at high velocities, cross sections for one-electron loss by both Li^+ and Li^{2+} in H approximate closely to one half the corresponding cross sections in H_2.

1. Introduction

It is well known that collisions between fast partially ionized atoms and target atoms may result in excitation or ionization of the projectile. The latter process is usually termed 'electron loss'. Recent measurements by Zouros *et al* (1989) and Huelskoetter *et al* (1989) on both these processes have provided a better understanding of the effect of the target electrons which depends on the momentum transferred during the collision (Bates and Griffing 1953, 1954, 1955, McGuire *et al* 1981, Anhold 1986). In the past, both projectile excitation and electron loss have been usually attributed to the Coulomb interaction between a projectile electron and the target nucleus.

At large impact parameters corresponding to small momentum transfer the target electrons act coherently to reduce the effective nuclear charge, an effect which can be allowed for by the use of a screened Coulomb potential. However the measurements of Zouros *et al* (1989) and Huelskoetter *et al* (1989) were designed to provide evidence for the additional effect of the Coulomb interaction between the projectile electron and target electrons. For collisions at small impact parameters corresponding to large momentum transfer, the Z_t target electrons can act as incoherent scattering centres, thereby producing an 'antiscreening effect' (or electron–electron correlation); this can result in a significantly increased cross section. Anholt (1986) has shown that the largest relative increase would be expected for an atomic hydrogen target where $Z_t = 1$.

The measurements of Zouros *et al* (1989) for 1s–2p projectile excitation in collisions of fast O^{5+} and F^{6+} ions with H_2 and He provide evidence for the separate screening and antiscreening contributions to the measured cross sections. In a similar way, the studies by Huelskoetter *et al* (1989) of one-electron loss by fast C^{5+} and O^{7+} in collisions with H_2 and He provided data consistent with Born descriptions of screening and antiscreening.

The present measurements of cross sections for one-electron loss by fast Li^+ and Li^{2+} in collisions with H, H_2 and He are intended to further clarify the screening-antiscreening model of the collision. Of particular interest are the measurements with an atomic hydrogen target for which theoretical descriptions might be expected to be the most reliable. In previous work (Shah and Gilbody 1978a) we measured cross sections for one-electron loss by Li^+ and Li^{2+} in H and H_2 at energies within the respective energy ranges 167-1040 keV and 537-1176 keV. In the present work we have obtained measurements of improved accuracy and extended the upper energy limit to about 2700 keV where antiscreening effects are expected to be significant.

2. Experimental approach

The experimental arrangement together with the measuring and calibration procedures were similar to those described in our previous papers (Shah and Gilbody 1978a, b, Goffe *et al* 1979) and only a brief description need be given here.

A thermal source using lithium aluminium silicate (Lambert *et al* 1978) within the terminal of a 2.5 MV Van de Graaff accelerator was used to generate ground-state Li^+ ions. The beam of Li^+ ions from the accelerator at a selected energy was momentum analysed and, when required, could be stripped in passage through a gas canal to form Li^{2+} ions. The beam of either Li^+ or Li^{2+} ions was then passed through a tungsten tube furnace into which gas was flowed at a rate low enough to ensure single collisions. When heated to about 2400 K the furnace provided a highly dissociated target of hydrogen. At room temperature the furnace could be used as a simple target gas cell for measurements in both H_2 and He.

After passage through the furnace target, the fast Li^+, Li^{2+} and Li^{3+} components of the emergent beam were separated by electrostatic deflection and recorded by screened Faraday cups. Cross sections σ_{12} for one-electron loss by Li^+ ions and σ_{23} for one-electron loss by Li^{2+} ions were determined from measurements of the fractional yields Li^{2+}/Li^+ and Li^{3+}/Li^{2+} respectively under single collision conditions.

As in our previous work (Shah and Gilbody 1978a) measured electron loss cross sections in H and H_2 were normalized to the absolute one-electron capture cross section σ_{10} measured by McClure (1966) for H^+ in H and H^+ in H_2. Our electron loss cross sections in He were normalized to the absolute values of σ_{10} for H^+ in He measured by Stier and Barnett (1956).

3. Results and discussion

Our cross sections σ_{12} and σ_{23} for one-electron loss by Li^+ and Li^{2+} in H, H_2 and He are shown in tables 1 and 2. The uncertainties associated with individual values are assessed at the 67% confidence level and reflect the degree of reproducibility of the measurements. In addition, cross sections in H, H_2 and He have additional estimated uncertainties of 12%, 10% and 8% respectively in absolute magnitude as a consequence of our normalization procedure.

Figure 1 shows our measured cross sections σ_{23} for one-electron loss by Li^{2+} ions in H and H_2 compared with other relevant data. Our previously measured low-energy values of σ_{23} (Shah and Gilbody 1978a) exhibit greater scatter but are in generally satisfactory agreement with the present values in both H and H_2. In the case of H_2,

Table 1. Cross sections σ_{12} and σ_{23} for one-electron loss by Li^+ and Li^{2+} ions in H and H_2 targets. Ratios R of cross sections $\sigma(H)/\sigma(H_2)$ are also shown.

^{7}Li energy (MeV)	σ_{12} (cm$^2\times10^{-17}$)			σ_{23} (cm$^2\times10^{-18}$)		
	H	H_2	R	H	H_2	R
0.45	0.74 ± 0.05	0.89 ± 0.03	0.83	—	—	—
0.55	0.86 ± 0.04	1.21 ± 0.04	0.71	—	—	—
0.65	0.94 ± 0.05	1.48 ± 0.04	0.64	1.71 ± 0.06	2.03 ± 0.04	0.84
0.75	1.00 ± 0.05	1.71 ± 0.05	0.58	2.11 ± 0.07	2.90 ± 0.05	0.73
0.87	1.02 ± 0.05	1.84 ± 0.06	0.55	2.27 ± 0.07	3.70 ± 0.07	0.61
1.00	1.00 ± 0.05	1.96 ± 0.06	0.51	2.51 ± 0.09	4.30 ± 0.08	0.58
1.15	1.03 ± 0.05	1.96 ± 0.06	0.53	2.68 ± 0.16	4.78 ± 0.10	0.56
1.30	0.98 ± 0.06	1.89 ± 0.08	0.52	2.65 ± 0.16	5.06 ± 0.11	0.52
1.50	0.98 ± 0.06	2.00 ± 0.08	0.49	2.72 ± 0.09	5.35 ± 0.12	0.51
1.75	0.97 ± 0.06	1.95 ± 0.06	0.50	2.78 ± 0.08	5.47 ± 0.10	0.51
2.00	0.91 ± 0.05	1.80 ± 0.05	0.51	2.86 ± 0.10	5.42 ± 0.12	0.53
2.30	0.87 ± 0.04	1.75 ± 0.05	0.50	2.66 ± 0.10	5.42 ± 0.12	0.49
2.68	—	—	—	2.60 ± 0.13	5.30 ± 0.18	0.49

Table 2. Cross sections σ_{12} and σ_{23} for one-electron loss by Li^+ and Li^{2+} ions in helium.

^{7}Li energy (MeV)	σ_{12} (cm$^2\times10^{-17}$)	σ_{23} (cm$^2\times10^{-18}$)
0.27	0.47 ± 0.02	—
0.33	0.75 ± 0.02	—
0.40	1.05 ± 0.03	—
0.42	—	0.78 ± 0.03
0.48	1.34 ± 0.04	1.02 ± 0.03
0.55	1.58 ± 0.05	1.40 ± 0.04
0.65	1.84 ± 0.05	2.18 ± 0.06
0.75	2.09 ± 0.06	2.92 ± 0.09
0.87	2.20 ± 0.06	3.76 ± 0.11
1.00	2.31 ± 0.07	4.81 ± 0.15
1.15	2.44 ± 0.07	5.36 ± 0.17
1.30	2.38 ± 0.07	6.07 ± 0.18
1.50	2.35 ± 0.07	6.57 ± 0.20
1.75	2.29 ± 0.07	6.93 ± 0.22
2.00	2.19 ± 0.06	6.88 ± 0.21
2.30	2.07 ± 0.06	6.80 ± 0.21

the high-energy trend of our measurements can be seen to be in good general accord with recent measurements of σ_{23} reported by Meyerhof (1990) at energies within the range 5.7-21.5 MeV.

We include in figure 1 three curves S, A and B which are the results of recent calculations of σ_{23} for Li^{2+} in H by Meyerhof (1990) based on the Born approximation in which all final states of the target are included. Curve S are values of σ_{23} obtained when the H target is represented by a nucleus partially screened by the target electron. Curve S can be seen to be in very poor accord with our experimental values particularly at the higher energies where the theoretical values are too small. Curve A corresponds

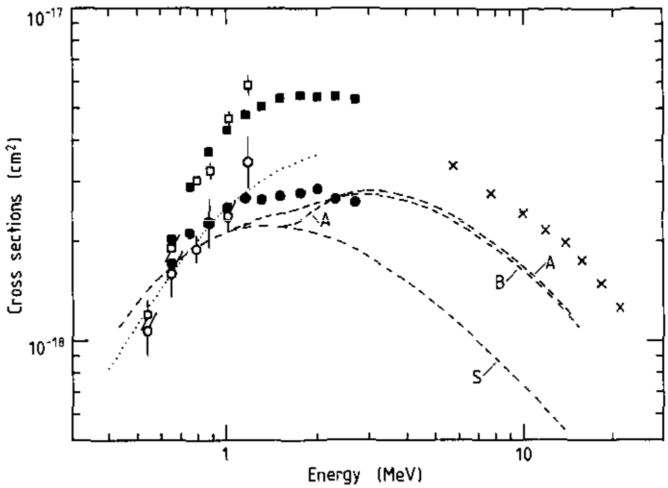

Figure 1. Cross sections σ_{23} for one electron loss by Li^{2+} ions in H and H_2. H target. Experiment: ●, present results; ○, our previous results (Shah and Gilbody 1978a). Theory: ----, Born approximation (Meyerhof 1990) where curve S is screening only, curve A includes antiscreening and curve B is the exact calculation using the formulation of Bates and Griffing (1955); · · · ·, binary encounter approximation (Shirai *et al* 1977). H_2 target. Experiment: ■, present results; □, our previous results (Shah and Gilbody 1978a); ×, Meyerhof (1990).

to calculations in which antiscreening contributions are included in accordance with the closure approximation treatment of Anholt (1986). This provides improved agreement with our high-energy values indicating that antiscreening effects are important. Curve B corresponds to exact calculations (within the framework of the plane-wave Born approximation) using the formulation of Bates and Griffing (1955). This provides better agreement with our experimental values than curve A at the lower impact energies. However both curves A and B predict a cross section maximum at rather higher energies than we observe. Theoretical predictions of σ_{23} for an H target based on the binary encounter approximation by Shirai *et al* (1977) are also shown in figure 1. It is assumed that the proton and electron in the target collide separately with the projectile. The calculations can be seen to be in reasonable accord with our measurements only over a very limited energy range.

In figure 2 we show our cross sections σ_{12} for Li^+ in H and H_2. Our results for an H target can again be compared (as in figure 1) with the recent theoretical predictions of Meyerhof (1990) shown as curves S, A and B. While the screening only calculations in curve S provide an underestimate of the cross sections at high energies, curves A and B, which include antiscreening, can be seen to provide cross sections which become too large with peak values shifted to higher energies than observed.

Our cross sections σ_{12} and σ_{23} for one-electron loss by Li^+ and Li^{2+} ions in He are shown in figure 3. Our values of σ_{23} can be seen to be in good accord with the recent higher energy measurements of Meyerhof (1990). The experimental data may also be compared with the theoretical predictions by Meyerhof (1990) in curve S (screening only) and curve A (including antiscreening). Curve S for both σ_{12} and σ_{23} at high energy again predicts smaller cross sections than those observed. The inclusion of antiscreening in curves A results in improved agreement but, again, predicted peak values of cross sections occur at higher energies than observed.

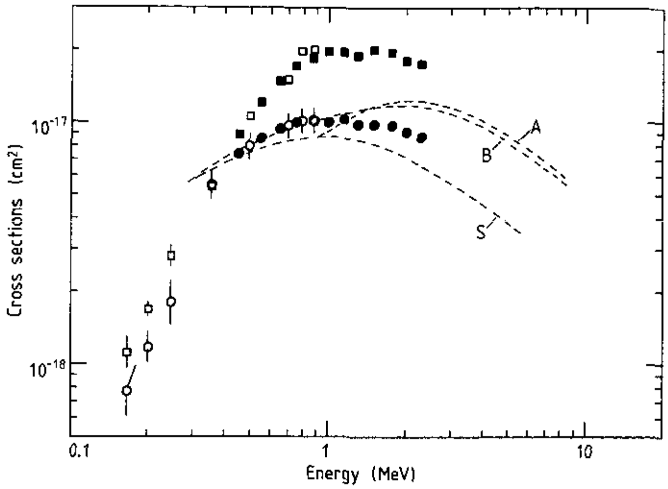

Figure 2. Cross sections σ_{12} for one-electron loss by Li^+ ions in H and H_2. H target. Experiment: ●, present results; ○, our previous results (Shah and Gilbody 1978a). Theory: - - - -, Born approximation (Meyerhof 1990) where curve S is screening only, curve A includes antiscreening and curve B is the exact calculation using the formulation of Bates and Griffing (1955). H_2 target. ■, present results; □, our previous results (Shah and Gilbody 1978a).

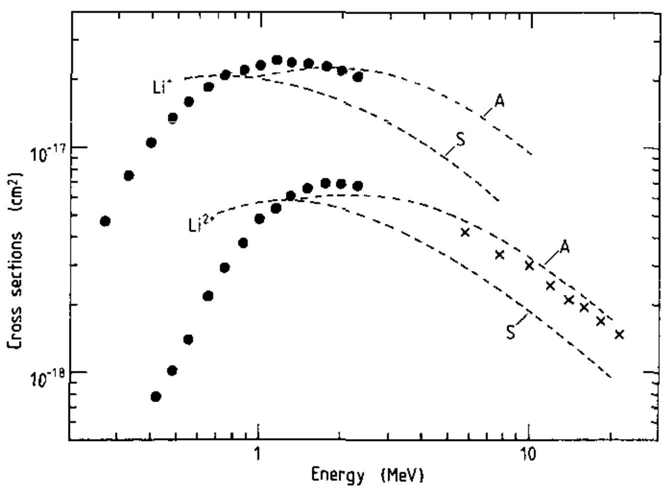

Figure 3. Cross sections σ_{12} and σ_{23} for one-electron loss by Li^+ and Li^{2+} ions in helium. ●, present results; ×, Meyerhof (1990); - - - -, Born approximation (Meyerhof 1990) where curve S is screening only and curve A includes antiscreening.

The present measurements of σ_{12} and σ_{23} in H and H_2 allow us to examine the extent to which the hydrogen molecule may be considered to approximate to two free hydrogen atoms in fast collisions involving one-electron loss. For electron capture and ionization by fast singly and multiply charged ions it is now well known (cf Goffe *et al* 1979, Shah and Gilbody 1982) that this approximation is not justified since cross sections at high velocities for H_2 targets become substantially greater than twice the corresponding values for H atom targets. In table 1 we include values of the ratios $R = \sigma(H)/\sigma(H_2)$ of our one-electron loss cross sections σ_{12} and σ_{23} in H and H_2

targets. It can be seen that ratios R attain values of about one half at our higher velocities showing that the approximation is at least justified for electron loss by lithium ions.

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