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ELECTRON CAPTURE AND LOSS IN COLLISIONS OF H^+ AND H WITH Pb VAPORS*

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Cross sections for single and double electron capture by protons and electron capture and loss from hydrogen atoms in lead vapors have been measured in the energy range 7.5–40 keV. Our results on Pb are compared with those on Mg reported by other workers. Analysis of electron capture collisions is complicated by the presence of multiple pseudocrossings of potential energy curves, though it may be inferred that the role of electron capture from inner shells becomes increasingly important at velocities larger than 2×10^8 cm/s. The double electron-capture processes are best described assuming the validity of the rule of conservation of electronic spin in the collisions.

1. Introduction

The information on charge-changing collisions of hydrogen atoms and ions with different targets has been reviewed recently by Fedorenko[1]). This information is restricted to collisions with molecules, noble gases, alkalis, H and Mg. It is of interest therefore, to study these processes in targets of different electronic configuration.

We have measured the cross sections for single and double electron capture by protons and single electron capture and loss from hydrogen atoms in collisions with vapors of lead in the energy range 7.5–40 keV by the method of analysis of the fast products of the collisions in a magnetic field.

2. Apparatus and measurements

The apparatus, shown in fig. 1, is essentially the same as was used for our study of collisions between He^+ and the vapours of Mg and Pb and which is described in detail elsewhere[2]). In brief, the apparatus consists of an accelerator to produce protons of energies between 7.5 and 40 keV, a 20° double-focusing analyzing magnet, a vacuum oven where the vapors of the lead target are produced, and beam measuring equipment. Neutral beams are produced by passage of a H^+ beam through a neutralization cell, the remaining charged particles being swept out by a voltage applied to a pair of deflecting plates. These plates are also used to determine the contribution to the measured beam currents by unwanted fast neutrals (formed by electron capture on beam collimating slits and background gas) when

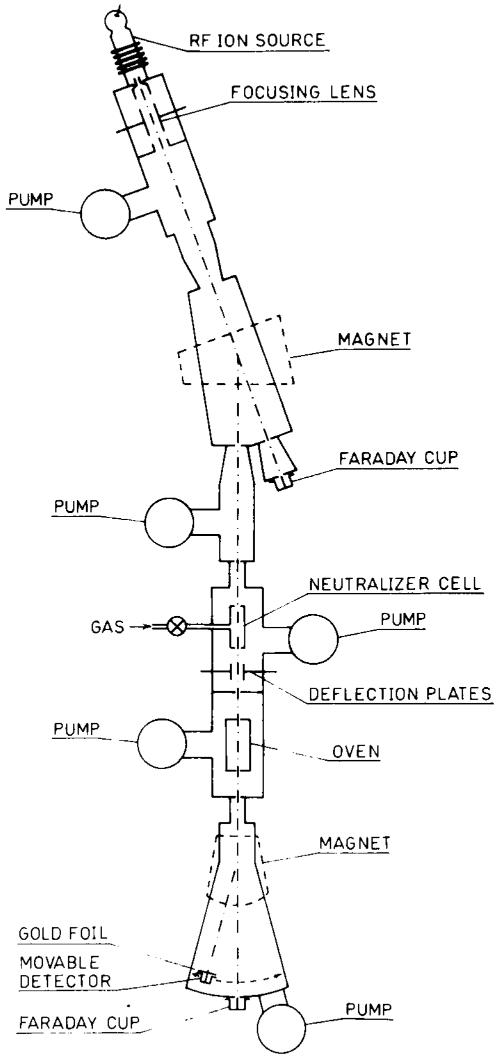

Fig. 1. Experimental apparatus.

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cross sections from H^+ are measured. This contribution is substracted as background[2]).

The neutralization cell is a tube 72 mm long and 14 mm in internal diameter. The beam enters and leaves the cell through channels which are 6 mm long and of internal diameters 1.0 and 1.2 mm respectively. Argon gas is admitted to the cell through a cold trap.

The interaction chamber is described in detail in ref. 2. Lead of purity greater than 99.999% was used for the measurements.

The different beam components resulting from charge-changing collisions in the target cell were analyzed according to their different charge states by a magnetic field and collected on a movable detector, whose response is independent of the charge of the impinging particles[3]).

Vacuum is maintained by diffusion pumps operating through cold traps at liquid nitrogen temperature. The background pressures ranged from 4 to 9×10^{-7} torr with the oven at room temperature. The pressure in the region outside the target cell was about 5×10^{-6} torr with the oven at 500°C.

3. Experimental procedure and results

The dependence of the charge fractions F_j on the target thickness π is given by[4])

$$\frac{\mathrm{d}F_j}{\mathrm{d}\pi} = -F_j \sum_k{}' \sigma_{jk} + \sum_k{}' \sigma_{kj} F_k, \quad \text{with} \quad \sum_j F_j = 1, \tag{1}$$

where σ_{if} are the cross sections for collisions which change the charge of the projectile from i to f. For an incident beam consisting only of neutral atoms, the solutions to eq. (1) can be expanded in a power series in π at low π values, as:

$$F_1(\pi) = a_{01} + \sigma_{01}\pi + \ldots, \tag{2}$$

$$F_{\bar{1}}(\pi) = a_{0\bar{1}} + \sigma_{0\bar{1}}\pi + \ldots, \tag{3}$$

where a_{01} and $a_{0\bar{1}}$ are constants which depend on the target thickness of the background gas and on cross sections for charge-changing collisions therein.

In the case of an incident beam consisting mainly of protons we substract from the measured signals the part due to unwanted neutrals as determined with the aid of the deflection plates[2]), and the solutions of eq. (1) become:

$$F_0(\pi) = a_{10} + \sigma_{10}\pi + \ldots, \tag{4}$$

$$F_{\bar{1}}(\pi) = a_{1\bar{1}} + \sigma_{1\bar{1}}\pi + \ldots. \tag{5}$$

In this way, by observing the initial linear growth of the charge fractions with π, we can determine the cross sections σ_{01}, $\sigma_{0\bar{1}}$· σ_{10} and $\sigma_{1\bar{1}}$.

The target thickness π is given by the effective length of the target cell, the vapour pressure, and its temperature. The effective length was calculated from the geometrical length plus a correction to take account for the Knudsen effusion of the vapor through the holes. This correction amounted to less than 3%. The vapor pressure as a function of temperature was taken from data given by Kim and Cosgarea[5]).

Hysteresis effects in the fractions measured with increasing and decreasing temperature, as observed by

TABLE 1

Electron capture and loss cross sections for H and H^- on Pb in units of 10^{-16} cm²/atom.

Energy (keV)	σ_{10}	$\sigma_{0\bar{1}}$	$\sigma_{1\bar{1}}$	σ_{01}
7.5	11.30		0.289	
10.0	15.60	0.752	0.302	0.687
15.0	11.18	0.586	0.361	1.100
20.0	8.48	0.449	0.253	1.473
25.0		0.332		1.799
30.0	5.90	0.237	0.099	2.092
35.0		0.172		2.360
40.0	3.27	0.116	0.0191	2.571

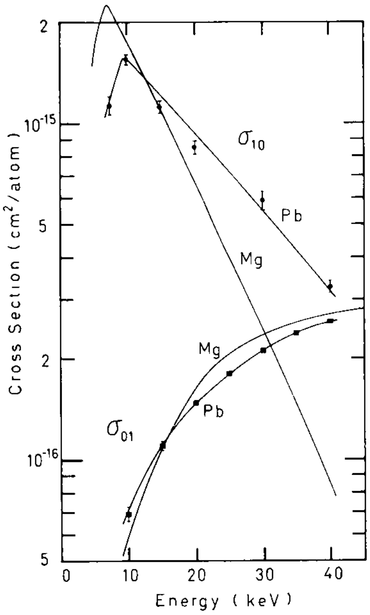

Fig. 2. Cross sections σ_{10} and σ_{01} for H^+ and H on Pb and Mg. Results for Mg are taken from refs. 13–15.

Schlachter et al.[6]), were avoided by waiting for equilibrium to be set among the oven, the vapor, and the thermocouple before taking data. At each measured point, the temperature was held constant to within 0.25 K.

The measured values of the cross sections σ_{10}, σ_{01}, $\sigma_{0\bar{1}}$ and σ_{11} are presented in table 1 and plotted in figs. 2 and 3 with their errors, which arise mainly from statistical uncertainties in the initial slopes of the $F_j(\pi)$ curves. Not included in the figures is the quoted 9% uncertainty[7]) in the vapor pressure which must be added to the errors mentioned above to obtain the absolute accuracy of our results.

A question of importance in our measurements is the possibility of the presence of excited atoms in the neutral beam, of sufficiently long mean life as to enter the collision chamber. The magnitude of the cross sections for the processes of electron capture and loss would be different for atoms in excited states as compared to those for atoms in the ground state.

The minimum time of flight from the neutralization chamber to the target cell is 7×10^{-8} s at 40 keV. The electric field in the deflection plates is strong enough (≈ 600 V/cm) to almost completely mix levels of different angular momenta, and therefore the lifetime of each level will not differ greatly[8]) from that of the shortest lived levels of given n. Thus, only atoms with $n \geqslant 7$ will have a probability greater than 0.25 to reach the target cell. Denoting respectively by g and n the ground and excited states, and assuming that the electron loss cross sections do not depend strongly[9]) on n for $n \gg 1$, the effect of the population ϕ_n of highly excited atoms on the apparent cross section σ_{01} will be given by:

$$\sigma_{01} = \sigma_{g1}(1+\phi_n f),$$

where

$$f = \frac{\sigma_{n\bar{1}} - \sigma_{g\bar{1}}}{\sigma_{g1}}. \tag{6}$$

Taking the values f to be the largest measured[10]) and ϕ_n for H^+ on Ar from calculations by Butler and May[11]) we find that $\phi_n f$ is always smaller than 0.014 and therefore, the measured loss cross section σ_{01} will be essentially equal to σ_{g1}.

The influence of the existence of highly excited atoms on the capture cross section $\sigma_{0\bar{1}}$ will be even smaller because the capture of an electron from a highly excited atom would lead preferentially to the formation of autoionizing doubly-excited states of H^- of very short lifetimes which would decay leaving the projectile as neutral ($\sigma_{n\bar{1}} \ll \sigma_{g\bar{1}}$).

The metastable 2S state of H is easily quenched by the electric field set by the deflection plates. The fraction of metastable atoms which survive the effect of the field will be

$$\phi = \phi_0 \exp[-t/\tau_{2s}(\varepsilon)], \tag{7}$$

where ϕ_0 is the original fraction of metastable atoms and t is the transit time in the field ε. At the higher energy used in the present work, with $\varepsilon \approx 600$ V/cm and taking $\tau_{2s}(\varepsilon)$ from ref. 8, $\phi \approx 10^{-3}\,\phi_0$, and since ϕ_0 is of the order of[12]) 10^{-2}, the influence of metastable atoms will be negligible.

Our results can be compared to those on Mg[13–15]) since this atom has its first and second ionization potentials very similar to the corresponding ones of Pb. The loss cross section σ_{01} is seen to be the same, within experimental errors, for both targets. The electron capture cross sections σ_{10}, $\sigma_{0\bar{1}}$ and $\sigma_{1\bar{1}}$ are larger for Pb than for Mg at high energies where electron pickup from inner shells becomes increasingly important because these processes are energetically more favoured for Pb than for Mg, as the corresponding energy defects are smaller. These processes are seen to become more important as the impact velocity rises from about 2×10^8 cm/s. At lower velocities, the

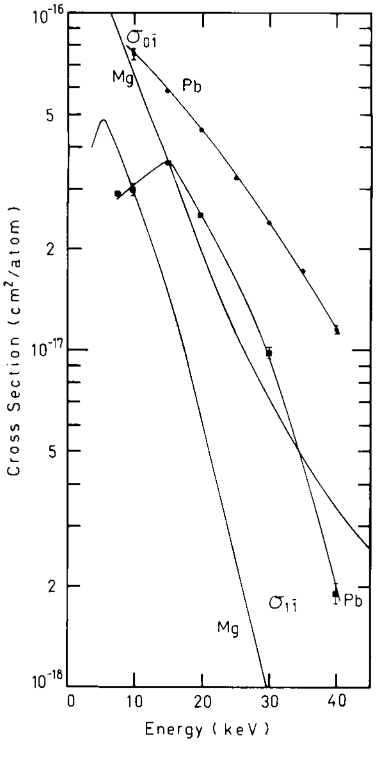

Fig. 3. Cross sections $\sigma_{0\bar{1}}$ and $\sigma_{1\bar{1}}$ for H and H^- on Pb and Mg. Results for Mg are taken from refs. 14 and 15.

electron capture from H^+ is complicated by multiple curve crossings between the incident channel and the exit channels $H+Pb^{+*}(Mg^{+*})$, where the star indicates that the particle is in an excited state. No estimation of these effects are made since the potential energy curves of the molecular complexes formed during the collision are not known.

The double electron-capture cross section $\sigma_{1\bar{1}}$ for H^+ on Pb has a maximum at about 15 keV as compared with ≈ 6 keV for the same cross section on Mg[14]), though the energy defects closest to resonance for both reactions (those leaving the target doubly ionized and in its ground state) are nearly the same (8.1 and 8.3 eV respectively). However, the process

$$H^+ + Pb(^3P) \rightarrow H^-(^1S) + Pb^{++}(^1S) - 8.3\,\mathrm{eV}$$

is not allowed since electronic spin is not conserved[16]). The allowed process of closest energy balance is:

$$H^+ + Pb(^3P) \rightarrow H^-(^1S) + Pb^{++}(^3P) - 15.6\,\mathrm{eV},$$

which, due to its larger energy defect, must have a maximum cross section at higher energies according to the near adiabatic criterion[17]) if no curvecrossings are involved, and in agreement with the experimental results.

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