Excitation to kinetic energy transformation in colliding hydrogen and argon atoms

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Abstract

A beam of 500 eV ground state(H(1s)) and metastable(H(2s)) hydrogen atoms was produced by protons from a plasma source having passed a Cs cell. The H(2s) and H(1s) atoms were charge exchanged into H^- within a subsequent Ar cell. Using an electric counter field, the kinetic energy of H^- produced from H(2s) has been measured to be larger than that of the H^- coming from H(1s), the difference being the 10 eV H(2s) electron excitation energy.

1 Introduction

In non- radiative transitions from upper to lower atomic or molecular energy levels due to collisional quenching in gases the potential energy stored

is transferred to the colliding partners. In an experiment performed by T. J. McCarthy et al.[1] Ne atoms were excited by an electron beam impinging on a gas mixture of hydrogen and neon with partial pressure of 0.13 mbar and 1 bar, respectively. Ne_2^* excimer molecules were formed which by collision transferred their energy to H_2 molecules leading to the dissociation of H_2. The Ne_2^* excitation energy also lead to an excitation of one of the hydrogen atoms (H(2s)) in addition to kinetic energy transferred to both H-atoms. This kinetic energy was tagged measuring a Doppler-broadening of the Lyman alpha transition line of the H(2s) atom of $d\lambda = \pm\lambda \cdot \beta_{H2} = 0.0385\mathring{A}$ with $\beta_{H2} = v_{H(2s)}/c$. This translates into a kinetic energy of $T_{H2} = 0.47eV$ transferred during the collision. The process, consisting of the Ne_2^* deexcitation, H_2 dissociation(4.48 eV), H excitation(10.20 eV) and the H(1s) and H(2s) atom motion, is resonant, where the energy, released by Ne_2^* after vibrational relaxation, is equal to the difference((14.8 ± 0.4) eV) between the excited H(1s)+ H(2s)($B'(^1\Sigma_u^+)$) and the H(1s)+H(1s)($X(^1\Sigma_g^+)$) electronic ground state[2]. The 0.8 eV width of the $B'(^1\Sigma_u^+)$ to $X(^1\Sigma_g^+)$ transition comes from a steep $B'(^1\Sigma_u^+)$ slope at small internuclear distances causing the remaining H(1s) and H(2s) atom kinetic energy to be about 0.5 eV at maximum which is consistent with the measured T_{H2}.

In order to study this energy transfer process with high precision and without background effects due to molecule formation and the high pressure gas mixture, single atom collisions must be studied with well defined kinematics of incoming and outgoing scattering partners. In this paper we describe an experiment studying the following charge exchange process using monoergetic metastable hydrogen atoms H(2s) with kinetic energies of 500 eV

$$H(2s) + Ar \rightarrow H^- + Ar^+ + E_{kin}, \tag{1}$$

where, in contrast to T_{H2} of the above Ne_2^* decay experiment, the H^- kinetic energy width is very small, if the H(2s) kinetic energy is sharp.

These measurements were motivated by a low energy particle physics experiment in which monoenergetic hydrogen atoms emerging from a new type of neutron decay have to be identified unambigously.

In this paper we will first describe the set-up of the atomic physics experiment and present the results as compared to the analysis of the process in eq. 1. We will then discuss an application of the findings based on a

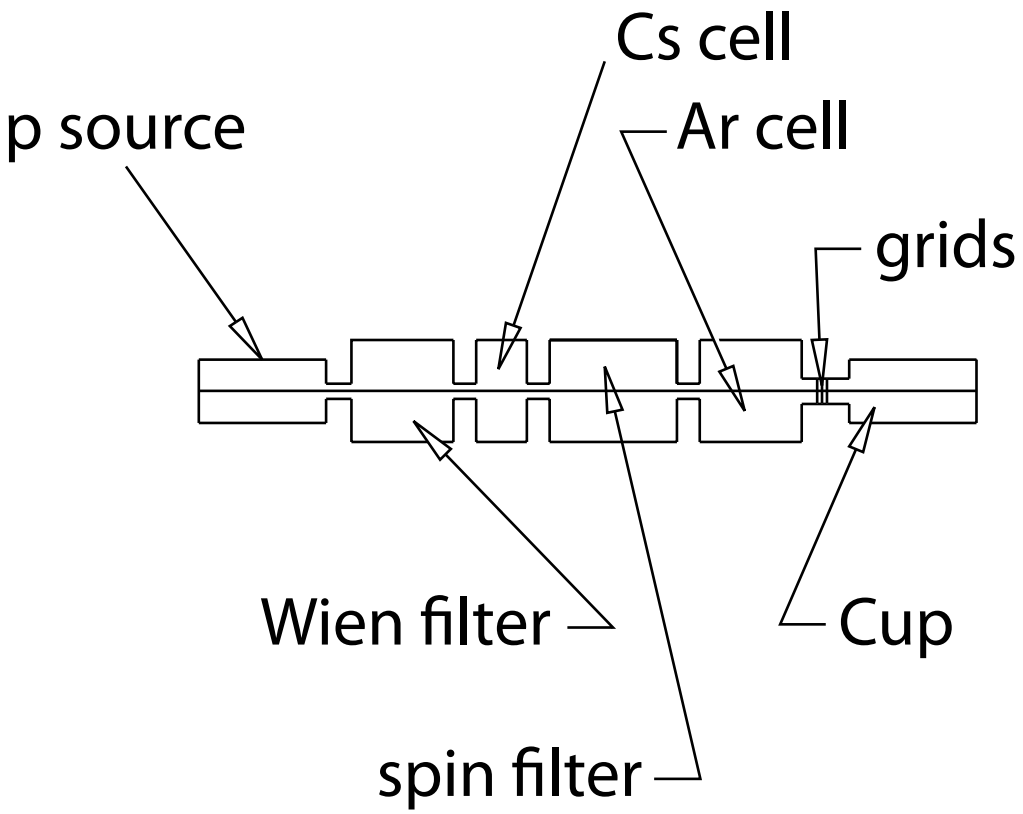

Figure 1: Sketch of the mockup setup to measure the kinetic energy difference of H^- ions produced by charge exchanged H(2s) and H(1s) atoms within an Ar cell.

new experiment to be installed at a research reactor which will allow us, to differentiate between the atomic states (1s vs. 2s) of fast, monoenergetic hydrogen atoms moving with $T_{H2} = 325.7eV$.

2 The Experiment

The set-up of the experiment is shown in fig. 1. Driven by a future application (see sec. 4) we have studied reaction 1 using high energtic H(2s) atoms. The production of fast H(2s) atoms was done in a two step process.

2.1 Beam preparation

2.1.1 Production of high energy hydrogen

Protons from a plasma proton source [3] have been extracted using a variable electric acceleration field, set to 500 V for the measurements described here. Selection of protons with well defined kinetic energy was performed by a Wien velocity filter which also discriminated against other particle species produced in the source (predominantly H_2^+ and N_2^+ from the rest gas) followed by a 5 mm diameter diaphragm. The resulting proton flux is of the order of μA. These monoenergetic protons were passed through a gas cell filled with Cs-vapour and differentially pumped at each side. Neutralisation of protons takes place producing hydrogen atoms in various atomic states predominantly in the 2s with an approximate admixture of 2% H(1s). The Cs vapour pressure was $1.5 \cdot 10^{-2}$ mbar, regulated by the temperature in the Cs cell, the bottom of the cell, holding the Cs being kept at 160^0 C. Length and pressure of the cell was chosen such as to guarantee at most one collision yielding a 10% H(2s) production efficiency, i. e., about 90% of the protons pass without neutralization. The H(2s) beam flux is about 10^{11} atoms/s over a beam area of 20 mm^2.

2.1.2 Selection of atomic state

Because of the large $H(2s) + Ar \rightarrow H^- + Ar^+$ cross section at the H(2s) kinetic energy T_{H2}=500 eV($5 \cdot 10^{-17}\, cm^2$ in comparison to $10^{-18}\, cm^2$ for H(1s)[4]) about 500 eV protons from the plasma source with an energy width reduced by the Wien filter and the diaphragm to ca. 9 eV are neutralized within the Cs cell to H(2s) and H(1s) atoms. Further downstream, the H atoms go through a spin filter, where atoms of one out of four possible H(2s) hyperfine spin states pass as H(2s) at a spin filter peak(fig. 2), thus, yielding a beam of H(2s) and H(1s) atoms after the filter, whereas at a between- the-peaks setting only H(1s) atoms remain. Together with the 50 % spin filter efficiency, a 10% spin selection probability results.

2.1.3 Beam flux measurement

For measuring the proton beam current, the Cs and Ar cells were evacuated, and the axial magnetic spin filter field was used for focusing the p beam (fig. 1). In fig. 3 the p beam cup current I_c vs. counter field grid voltage U_g

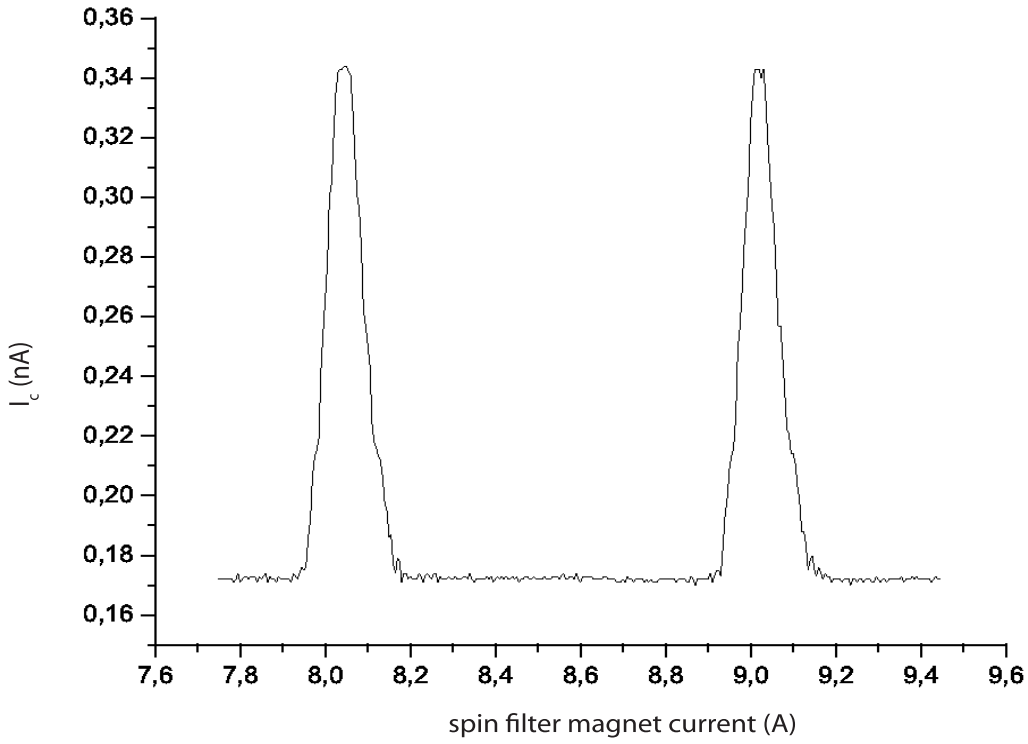

Figure 2: Cup H^- current I_c vs. spin filter magnet current. At the peak setting H(2s) and H(1s) atoms appear behind the filter, whereas at the valley setting(between the peaks) only H(1s) remain.

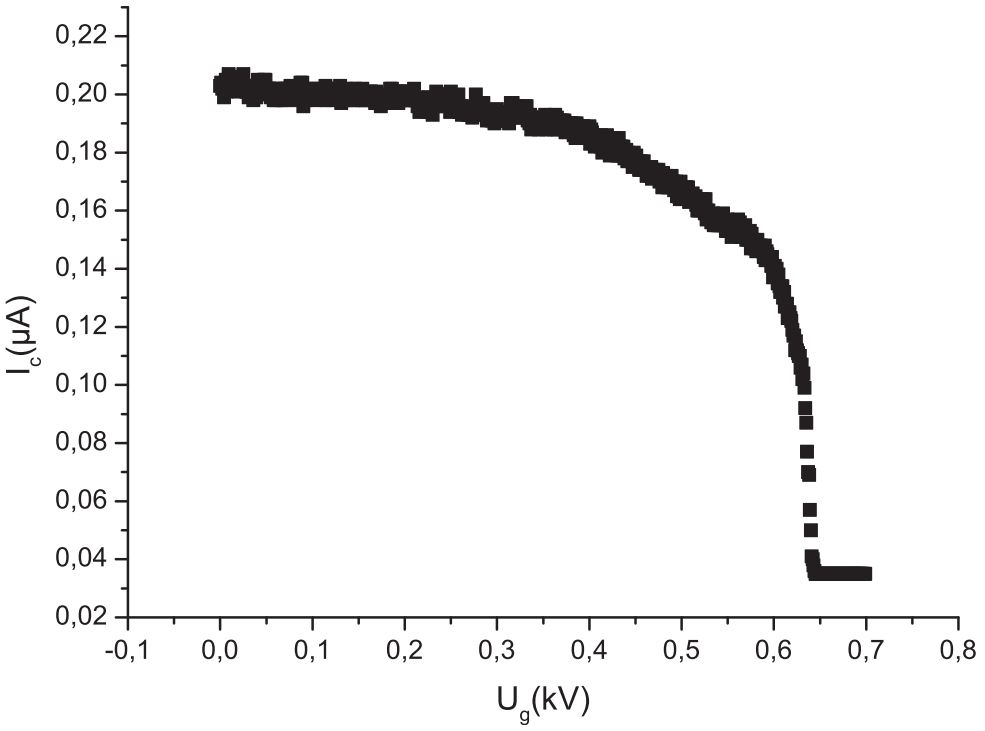

Figure 3: Proton cup current I_c vs. counter field grid voltage U_g. The plasma source accelerating voltage was set to about 640 V.

is drawn showing a rate of 10^{12} p/s for small U_g which is consistent with 10^{11} H(2s)/s after the Cs cell and 10^{10} H(2s)/s after the spin filter at a spin filter peak setting.

2.1.4 Measuring the beam energy-spread

In fig. 4 the differentiated p cup current points dI_c/dU_g vs. U_g are given which are fitted by a Gaussian of (9.02 ± 0.40) eV FWHM width.

2.2 Scattering chamber and H^- detection

In the Ar cell, part of the H(2s)(e. g., 10% at $p_{Ar} = 3.6$ mbar Ar pressure and Δz= 0.2 m cell length) and H(1s) atoms are charge exchanged to H^- resulting in a rate of $10^9\, H^-/s$ or a 0.2 nA H^- current after the cell at a

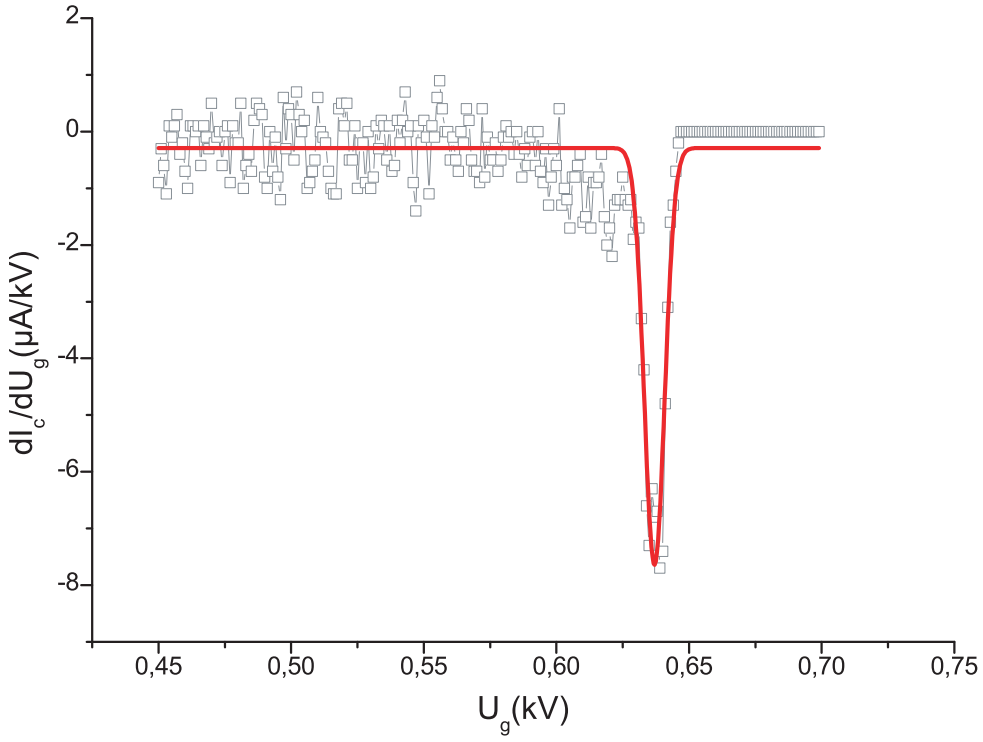

Figure 4: Differentiated proton cup current dI_c/dU_g vs. U_g. Points from fig. 3. Drawn curve: Fit to $f(x) = A \cdot exp(-(x - xc)^2/(2\sigma^2))$, $x = 10^3\, U_g$, $\sigma = (3.83 \pm 0.17)$ V.

spin filter peak setting as can be seen from fig. 2. The corresponding kinetic energies T_{H2^-} and T_{H1^-} are measured by a three grid electric counter field and a Faraday cup.

3 Measurement and Results

3.1 Kinematics of the collision process

The collision of neutral hydrogen atoms with argon leads to an electron transfer from the nobel gas to hydrogen resulting in a negatively charged hydrogen emerging. The electron ($3p^6$) picked up from the argon atom will be placed in the 1s-state in hydrogen. The difference $\Delta T_{H^-} = T_{H2} - T_{H1}$ results from inelastic charge exchanging collisions of H(2s) and H(1s) with Ar atoms yielding in both cases H^- ions with two 1s electrons(E_{H^-}) and an Ar^+ ion with a missing $3p^6$ electron(15.76 eV binding energy). During the H(2s) Ar collision the 2s to 1s electron transition occurs without photon emission. The incoming H(1s) and H(2s) atoms have the same velocity β_H. For the H(2s) Ar collision, the energy balance can be written as

$$T_{H2} + E_{H2} + E_{Ar} = T_{H2^-} + E_{H^-} + T_{Ar^+} + E_{Ar^+}$$

or

$$T_{H2} + Q_{H2} = T_{H2^-} + T_{Ar^+}, \tag{2}$$

$Q_{H2} = Q - Q_2$ with the H(2s) excitation energy Q = 10.2 eV, Q_2 = 15.01 eV and the electron binding energies 3.4 eV for H(2s), 13.6 eV for the first and 0.75 eV for the second H^- electron.
Alternatively, the ground state H(1s) Ar collision conservation of energy law is

$$T_{H1} + Q_{H1} = T_{H1^-} + T_{Ar^+} \tag{3}$$

with $Q_{H1} = -Q_2$.

The H(2s) Ar collision momentum conservation law is

$$p_{H2}c = p_{H2^-}c + p_{Ar^+}c$$

or

$$E_{H2}\beta_H = E_{H^-}\beta_{H2^-} + E_{Ar^+}\beta_{Ar^+} \tag{4}$$

yielding together with eq. 2(indices 1 and 2 mean laboratory collision angle $\theta_1 = 0$ and π, respectively)

$$\begin{aligned}(\beta_{H2^-})_{1,2} =&(E_{H2}E_{H^-}\beta_H \pm \\ &(E_{H^-}^2 E_{Ar^+}E_{H2}\beta_H^2 + 2E_{H^-}^2 E_{Ar^+}Q_{H2} + E_{Ar^+}^2 E_{H^-}E_{H2}\beta_H^2 + \\ &+ 2E_{Ar^+}^2 E_{H^-}Q_{H2} - E_{Ar^+}E_{H^-}E_{H2}^2\beta_H^2)^{1/2})/(E_{H^-}^2 + E_{Ar^+}E_{H^-}).\end{aligned}$$

With $E_{H^-}/E_{Ar^+} \approx (E_{H2}/E_{Ar^+})(1 + (E_e - B_{H2^-})/E_{H2})$, E_e the e^- rest energy, $B_{H2^-} = Q + B_{H1^-}$, B_{H1^-}=0.75 eV,

$$\begin{aligned}(\beta_{H2^-})_{1,2} \approx &\pm \beta_H\sqrt{E_{H2}/E_{H^-}} \pm Q_{H2}/(\beta_H\sqrt{E_{H^-}E_{H2}}) + \beta_H E_{H2}/E_{Ar^+} \pm \\ &\pm \beta_H\sqrt{E_{H2}/E_{H^-}}(E_e - B_{H2^-})/(2E_{Ar^+}) - \beta_H E_{H2}E_{H^-}/E_{Ar^+}^2 \mp \\ &\mp \beta_H\sqrt{E_{H^-}E_{H2}}/E_{Ar^+} \mp \beta_H\sqrt{E_{H^-}E_{H2}}(E_e - B_{H2^-}/(2E_{Ar^+}^2) \mp \\ &\mp Q_{H2}E_{H^-}\sqrt{E_{H^-}/E_{H2}}/(\beta_H E_{Ar^+}^2)\end{aligned} \tag{5}$$

comes. $(\beta_{H1^-})_{1,2}$ is obtained analogously exchanging E_{H2} with E_{H1}($E_{H1} = E_{H2} - Q$) and Q_{H2} with Q_{H1}. Taking the upper signs in eq. 5 and in $(\beta_{H1^-})_1$

$$(\beta_{H2^-} - \beta_{H1^-})_1 \approx Q/(\beta_H E_{H2})(1 - E_e/(2E_{H2})) - E_{H2}Q/(\beta_H E_{Ar^+}^2)$$

and

$$\begin{aligned}(\beta_{H2^-} + \beta_{H1^-})_1 \approx &2\beta_H(1 - E_e/(2E_{H2})) + (Q - 2Q_2)/(\beta_H E_{H2})(1 - E_e/(2E_{H2})) + \\ &+ 2\beta_H E_{H2}/E_{Ar^+} + \beta_H E_e/E_{Ar^+}(1 - E_e/(2E_{H2})) - \\ &- 2E_{H2}^2\beta_H/E_{Ar^+}^2(1 + E_e/E_{H2}) - 2\beta_H E_{H2}/E_{Ar^+}(1 + E_e/(2E_{H2})) - \\ &- \beta_H E_{H2}E_e/E_{Ar^+}^2(1 + E_e/(2E_{H2})) - E_{H2}/(\beta_H E_{Ar^+}^2)\cdot \\ &\cdot (1 + 3E_e/(2E_{H2}))(Q - 2Q_2)\end{aligned}$$

result up to the order of 10^{-10} leading to the kinetic energy difference

$$(\Delta T_{H^-})_1 = (T_{H2^-} - T_{H1^-})_1 = \tag{6}$$
$$= E_{H^-}/2(\beta_{H2^-} - \beta_{H1^-})_1(\beta_{H2^-} + \beta_{H1^-})_1 \approx$$
$$\approx Q(1 - (E_{H2}/E_{Ar^+})^2)(1 - (2Q_2 - Q)/(4T_{H2}))$$

= 10.09 eV for T_{H2} = 500 eV being very close to the 10.05 eV upper error limit of the above experiment.

Eq. 6 seems to be reasonable. $(\Delta T_{H^-})_1$ is zero for the minimum T_{H2} = 4.96 eV to which 10.2 eV is added at the charge exchanging process yielding ca. 15 eV being necessary for the Ar ionization. Furthermore, $(\Delta T_{H^-})_1$ vanishes if incoming and cell atom have equal mass, where the complete energy exchange occurs at a head- on collision.

The backscattering energy difference is

$$(\Delta T_{H^-})_2 = (T_{H2^-} - T_{H1^-})_2 \approx$$
$$\approx Q(1 - (E_{H2}/E_{Ar^+}))(1 - (E_{H2}/E_{Ar^+}) - (2Q_2 - Q)/(4T_{H2}) \cdot$$
$$\cdot(1 + (E_{H2}/E_{Ar^+}))$$

= 9.59 eV for T_{H2} = 500 eV with the minimum $(\Delta T_{H^-})_2 = 0$ energy T_{H2} = 5.21 eV being a bit larger than for $(\Delta T_{H^-})_1 = 0$ because of the slightly different kinematics(p_{H2^-} has a negative sign).

3.2 Measurement of the charge exchange reaction

When monoenergetic metastable hydrogen atoms pass a low pressure argon cell, a certain amount(10%) of the H(2s) are charge exchanged into H^- ions by collisional quenching and electron capture according to the reaction

$$H(2s) + Ar \rightarrow H^- + Ar^+, \tag{7}$$

where the total reaction(1) cross section for H(2s) with the kinetic energy $T_{H2} = 500\,eV$ is $\sigma_{H2\rightarrow H^-} = 5 \cdot 10^{-17}\,cm^2$[4]. The Ar cell pressure is given by $p_{Ar} = N_c\sqrt{(E_{Ar}/E_{H2}) \cdot kT \cdot T_{H2}}/(\sigma_{H2\rightarrow H^-} \cdot \Delta z)$, where N_c is the number of H(2s)- Ar collisions during passing the Ar cell, E_{Ar} the Ar rest energy, T the temperature and Δz the cell length. E. g., for N_c = 0.1, T = 300 K and

$\Delta z = 0.2$ m $p_{Ar} = 3.6$ mbar results. During the collision of the H(2s) with the Ar atom, the H(2s) electron state is deexcited to 1s without emission of a Lyman- α photon. Since the long- range Ar polarization dominates the H(2s)- Ar interaction[5], and the H(2s) collides essentially with the $3p^6$ Ar valence electron at a large H(2s)- Ar collision parameter, the H^- is produced in forward direction. Pure electron capture for ground state hydrogen H(1s) according to

$$H(1s) + Ar \rightarrow H^- + Ar^+ \tag{8}$$

occurs at the H(1s) kinetic energy $T_{H1} = 500$ eV with the much smaller cross section $\sigma_{H1 \rightarrow H^-} = 10^{-18}\, cm^2$[4] than that of the simultaneous collisional quenching and e^- capture for H(2s). If the H^- and Ar^+ final states for the reactions(1) and (8) are the same, i. e., $H^-(1s^2)$ with an electron pair in the 1s state and a $3p^6$ electron missing in Ar^+, the H^- kinetic energy T_{H^-} of reaction(1) must be larger than that of reaction(8) by about 10 eV, the H(2s) electron excitation energy being transferred to the H^- and Ar^+ collision partners according to their masses. The H(2s) density caused by a 10 nA/e H(2s) beam within the 5 mm diameter Ar cell is $n_{H2} = 3.5 \cdot 10^8\, m^{-3}$ yielding a H(2s)- H(2s) mean free path $l_m(H2 - H2) = 9 \cdot 10^8\, m$ with the H(2s)- H(2s) collision cross section $\sigma_{H2-H2} = 5.6 \cdot 10^{-19}\, m^2$, thus, preventing any H(2s) deexcitation.

3.3 Results

In fig. 5 the cup current I_c vs. counter field voltage U_g for the two spin filter settings are drawn. I_c decreases sharply at $U_g = T_H/e$. The slope corresponds to the energy width of the H^- ions. The differentiated curves dI_c/dU_g are given in fig. 6 yielding one peak for the spin filter valley setting with the kinetic energy T_{H1^-} and two peaks for the peak setting with T_{H1^-} and T_{H2^-}. For determining $\Delta T_{H^-} = T_{H2^-} - T_{H1^-}$ one Gaussian has been fitted to the fig. 6 H^-- from- H(1s) curve(fig. 7) resulting $T_{H1^-} = (502.26 \pm 0.09)$ eV. Two Gaussians were fitted to the fig. 6 H^-- from- H(1s)- and- H(2s) curve(fig. 8) keeping $T_{H1^-} = 502.26$ eV fixed yielding $T_{H2^-} = (512.03 \pm 0.19)$ eV and, thus, $\Delta T_{H^-} = (9.77 \pm 0.28)$ eV which is very close to the H(2s) 10.2 eV electronic excitation energy.

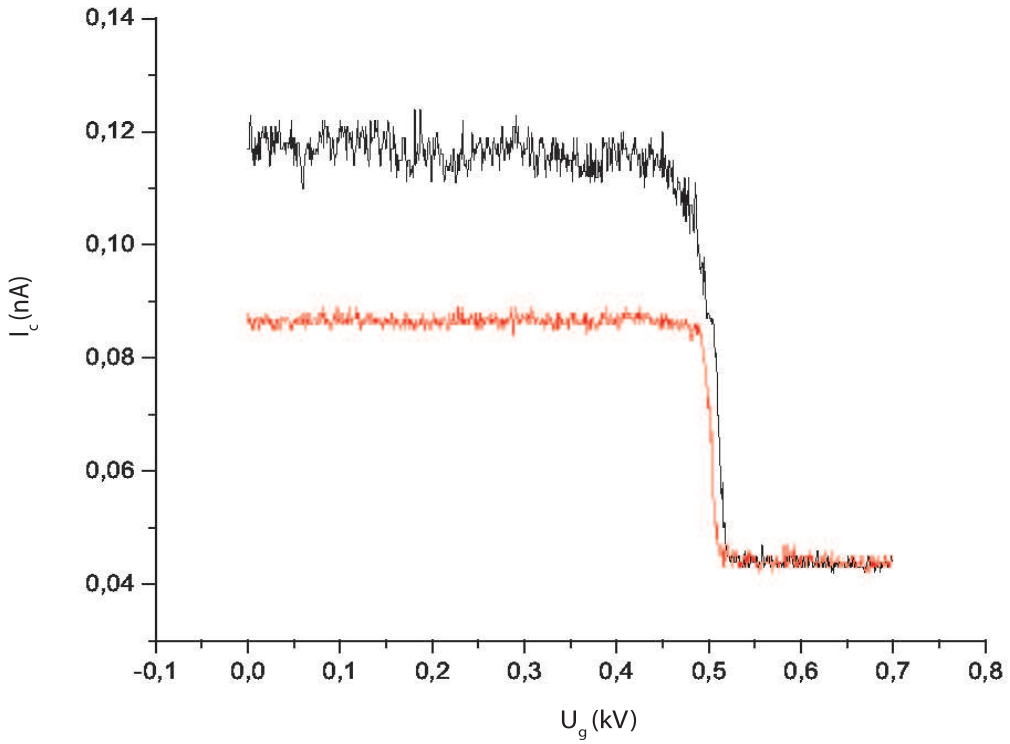

Figure 5: I_c vs. counter field grid voltage U_g. Upper curve: H^- from H(1s) and H(2s). Lower curve: H^- from H(1s).

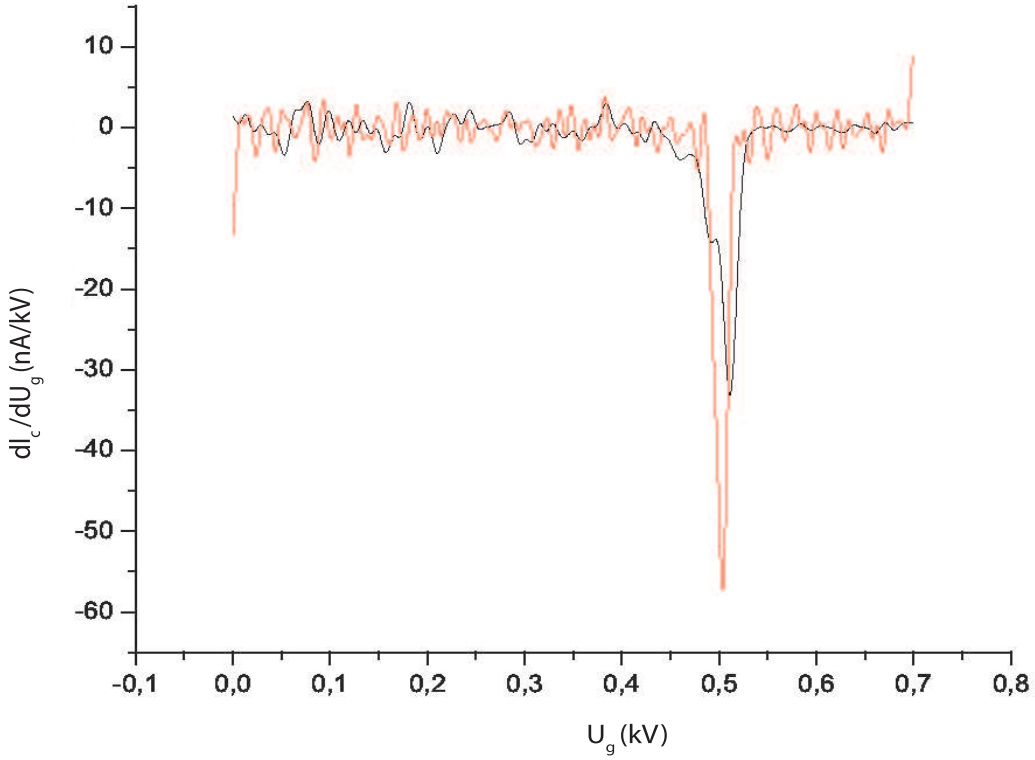

Figure 6: dI_c/dU_g vs. U_g. a. Narrow single peak: H^- from H(1s). b. Wider double peak: H^- from H(1s) and H(2s).

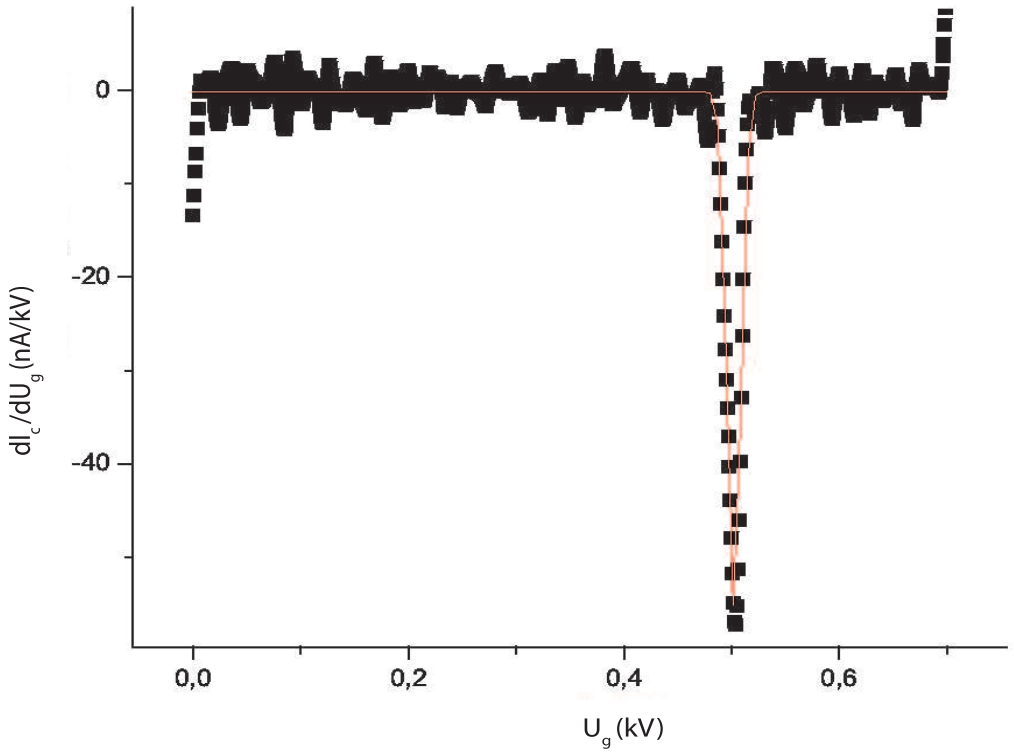

Figure 7: dI_c/dU_g vs. U_g. Points from fig. 6a. Drawn curve: Fit to $f(x) = A \cdot exp(-(x - xc)^2/(2\sigma^2))$, $x = 10^3\, U_g$. $xc = (502.26 \pm 0.09)$ V, $\sigma = (6.39 \pm 0.09)$ V.

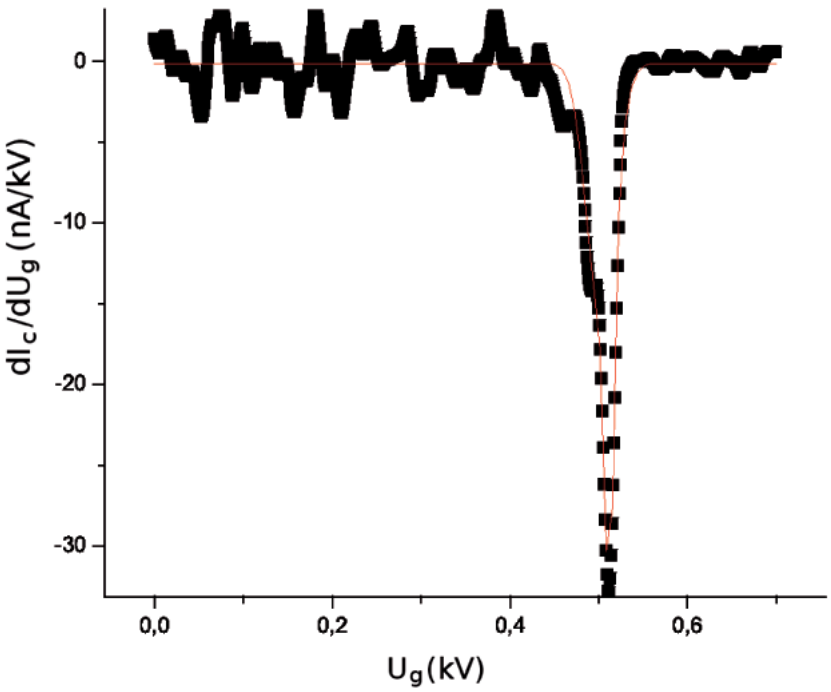

Figure 8: dI_c/dU_g vs. U_g. Points from fig. 6b. Drawn curve: Fit to $f(x) = A1 \cdot exp(-(x-xc1)^2/(2\sigma_1^2)) + A2 \cdot exp(-(x-xc2)^2/(2\sigma_2^2))$, $x = 10^3\, U_g$. $xc1 = 502.26$ V, $\sigma_1 = (16.07 \pm 0.41)\, V$, $xc2 = (512.03 \pm 0.19)$ V, $\sigma_2 = (5.04 \pm 0.19)$ V.

4 Application

The non- radiative transition due to collisional quenching from upper to lower atomic and molecular energy levels in gases causes a kinetic energy gain subdivided between the colliding partners according to their masses. E. g., in an electron beam excited 0.13 mbar hydrogen- 1 bar neon mixture at 300 K, the Lyman- α line emitted from metastable hydrogen(H(2s)) atoms produced by dissociation of colliding H_2 molecules, was measured to be Doppler-broadened by $d\lambda = \pm\lambda \cdot \beta_{H2} = 3.85$ pm($\beta_{H2} = v_{H(2s)}/c$)[1]. I. e., due to collisionally quenched energy transfer the H(2s) kinetic energy was

$$T_{H2} = E_{H2}\,\beta_{H2}^2/2 = 0.47 \text{ eV},$$

where E_{H2} is the H(2s) rest energy. T_{H2} is small compared to the deexcited atomic and molecular level differences which should result in a H(2s) atom energy gain of several eV. E. g., after a Ne atom ionization(21.6 eV) and a subsequent collisional H_2 molecule quenching yielding a H(2s) and a ground state H(1s) atom, the kinetic energy of the H atoms should be $T_H =$ 3.4 eV with the H_2 dissociation and the H excitation energies to be 4.5 eV and 10.2 eV, respectively.

However, the mean free path for H_2- H_2 collisions in the hydrogen- neon gas mixture with the H_2 density $n_{H_2} = 3 \cdot 10^{21}\,m^{-3}$ and the collision cross section $\sigma_{H_2-H_2} = 1.7 \cdot 10^{-20}\,m^2$ is $l_m(H_2 - H_2) = (\sqrt{32}\,n_{H_2}\,\sigma_{H_2-H_2})^{-1} = 3$ mm yielding 350 ns for the time between two collisions. Since the H(2s) lifetime can vary between ns and ms, depending on the present magnetic and electric fields, the accelerated H_2 molecules generally hit each other many times before the Lyman- α photon is emitted resulting in a certain thermalization of the H(2s) atom motion.

In a different setup, by collisional quenching a narrow beam of non- thermalized H^- ions wth a sharp energy gain can be obtained and used.

The kinetic energy difference between the H^- coming from the collisionally quenched H(2s) and from H(1s) can be used to separate the free neutron bound β- decay(BOB) metastable and ground state hydrogen atoms.

With the BOB neutron decay reaction into a hydrogen atom and an electron antineutrino

$$n \rightarrow H + \bar{\nu} \tag{9}$$

the hyperfine population of the emerging hydrogen atom, the neutrino left-handedness, a possible right-handed admixture and small scalar and tensor contributions to the weak force can be investigated [6]- [10]. The challenge lies in the very small branching ratio BR $= 4 \cdot 10^{-6}$ of the total neutron β-decay rate. The H kinetic energy is $T_H = 325.7$ eV corresponding to $\beta_H = v_H/c = 0.83 \cdot 10^{-3}$. Only states with zero angular momentum in the hydrogen atom are populated, the 1s and the metastable 2s with 83.2% and 10.4% probability, respectively.

The BOB BR is planned to be measured in a first experiment by detecting the eq. 9 reaction H(2s) atoms using the charge exchanging in a mbar Ar cell. The H(2s) 2s electron is deexcited during a collision with an Ar atom to the 1s state to which, in addition, an Ar electron is transferred leaving the H(2s) as $H^-(1s^2)$. With a two orders of magnitude smaller cross section an Ar electron goes to H(1s) at a H(1s)- Ar collision yielding the $H^-(1s^2)$, too. However, since the 2s to 1s transition occurs only non- radiatively at a H- Ar collision($\tau(2s) > 35$ ms for zero magnetic and <0.1 V/cm electric field at 0.8 μs H passage time through the Ar cell) the kinetic energy of the resulting H^- ions from the BOB H(2s) atoms is larger by the 10 eV H(2s) excitation energy than the kinetic energy of H^- coming from BOB H(1s) atoms. In contrast to the above mentioned Lyman- α line emitting H(2s) atoms[1], the BOB H(2s) make at most one single collision in the Ar cell. Therefore, the BOB H(2s) kinetic energy gain is exactly the H(2s) excitation energy(neglecting a very small kinematics effect, cf. above).

Thus, the two types of H^- atoms can be separated by an electric counter field with a MAC-E filter[11]. Assuming H^-- Ar elastic scattering, the H^- energy loss at the $\theta = \pm 140$ mrad H^- acceptance angle of the filter is
$dT_{H^-} \approx -T_{H^-}(1 - \alpha) sin\theta \, d\theta/2 = 0.15$ eV for $T_{H^-} = 325.7$ eV,
$\alpha = ((E_{Ar} - E_{H^-})/(E_{Ar} + E_{H^-}))^2$, $d\theta = \theta$, E_{H^-} is the H^- rest energy, yielding the energy spread $|dT_{H^-}|$ at the $d\theta = \pm 140$ mrad H^- acceptance angular width.

The separation should be possible even at a thermal neutron source, where the H energy width due to the thermal energy $T_n = 25$ meV of the decaying

neutrons is $dT_H = E_H \beta_H \beta_n = 5.7$ eV with $\beta_n = \sqrt{2T_n/E_n}$. The above mentioned kinetic energy difference of the two H^- atom types has been measured with the mockup experiment(fig. 1) described above.

5 Conclusion

The kinetic energy difference of forward- scattered bound β-decay 325.7 eV H(2s) and H(1s) atoms after charged exchanging into H^- within an Ar cell is $(\Delta T_{H^-})_1 = 10.04$ eV which is large enough to separate the H(2s) and H(1s) atoms having a 5.7 eV energy width due to the thermal motion of the decaying neutrons.

6 Acknowledgement

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