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Abstract

X-rays of Balmer and Lyman transitions in antiprotonic hydrogen and of Balmer transitions in antiprotonic deuterium were observed at pressures below 300 hPa using Si(Li) semiconductor detectors. The measurement was performed at the LEAR-facility at a beam momentum of 202 MeV/c. In order to stop antiprotons in a low pressure gaseous target with high efficiency, a novel technique, the cyclotron trap has been used. Absolute yields were determined and compared with cascade calculations. A distinct difference in the cascade of antiprotonic hydrogen and deuterium is found. The parameters of strong interaction in antiprotonic hydrogen are determined to be $\epsilon_{1s} = -(620 \pm 100)$ eV, $\Gamma_{1s} = (1130 \pm 170)$ eV and $\Gamma_{2p} = (32 \pm 10)$ meV.

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1 Introduction

Antiprotonic hydrogen and deuterium are sensitive probes for studying strong interaction effects near threshold. A direct measurement of the influence of the strong interaction requires the determination of the deviation of a measured transition energy from the value calculated from quantum-electrodynamics (QED) as well as a broadening of the line shape. In hydrogen the electromagnetic energies for the Lyman α ($2p \rightarrow 1s$), Balmer α ($3d \rightarrow 2p$) and Paschen α ($4f \rightarrow 3d$) transitions are 9409 eV, 1737 eV and 607 eV, respectively [1,2]. The shifts and widths due to the strong interaction of the corresponding states are expected to be $\epsilon_{1s} \simeq -500$ eV, $\Gamma_{1s} \simeq 1000$ eV, $\Gamma_{2p} \simeq 20 - 50$ meV and $\Gamma_{3d} \simeq 0.4 \mu\text{eV}$ [3,4,5,6,7,8,9,10,11]. The strong width of the 2p-state is about one hundred times larger than the radiative width ($\Gamma_{2p}(\text{rad}) = 0.38$ meV [12]) while for the 3d level this ratio is reversed.

Unambiguous information about the strong interaction parameters of the ground state is gained only from the Lyman α transition, because higher Lyman transitions differ in energy by less than the 1s-broadening. Presently the total (spin averaged) width and shift of the ground state are accessible to a direct measurement; the strong width of the 2p-state can be inferred from an intensity balance.

A measurement of X-ray transitions in antiprotonic hydrogen entails the following difficulties :

- The intensity of the Lyman α transition is expected to be about 1 % of the population of the 2p level. In measuring this transition, it is essential to reduce the large amount of background due to annihilation.
- The intensities of the X-ray transitions which populate the 2p-level are pressure dependent due to different deexcitation processes of the antiprotonic atom. The population of the 2p level is expected to range from 90 % at 1 hPa to about 10 % at 1000 hPa [14].

For studying this pressure dependence, neither the Paschen or higher transitions nor the Lyman transitions can be used for a survey measurement. The energies of the Paschen transitions are too low to measure them with conventional Si(Li) semiconductor detectors while the intensities of the Lyman transitions are too low.

A precise measurement of the pressure dependence of the absolute Balmer transition yields and a comparison with the results obtained by a cascade code permit inferences about the different cascade processes to be made in the most sensitive pressure region ≤ 500 hPa. Absolute yield is here defined as number of emitted X-rays in a transition per formed antiprotonic atom. Further, an optimal pressure region for the measurement of the Lyman transitions can be deduced. This pressure region is determined by maximizing the product of the transition yield and the number of stopped antiprotons. The strong width of the 2p-state Γ_{2p}^{abs} is then determined by means of an intensity balance according to

$$\Gamma_{2p}^{abs} = \left(\frac{\sum_{n>2}^{\infty} Y(nd \rightarrow 2p)}{Y(2p \rightarrow 1s)} - 1 \right) \Gamma_{2p}(rad) \quad (1)$$

2 Description of the Cascade Model

The cascade code we have used to analyse the measured intensities of the Balmer transitions was written by Bethe, Borie and Leon [13,14]. In these calculations the antiprotonic cascade is started at principle quantum numbers $n \approx 30$, a choice which is justified by recent calculations of Cohen [15].

Following the arguments of Leon and Bethe, a mean kinetic energy of about 1 eV is a reasonable value for the antiprotonic atom.

2.1 Electromagnetic Deexcitation Processes Including Stark Mixing

The different deexcitation processes which are taken into consideration in the cascade code can be subdivided into elastic and inelastic processes. Inelastic processes, those changing the kinetic energy of the antiprotonic atom, are the Coulomb deexcitation and the chemical deexcitation due to the dissociation of hydrogen molecules. Coulomb deexcitation, as described by Fiorentini for muonic atoms [18], designates the transfer of the transition energy to the relative motion of the colliding molecules.

Elastic processes include radiative transitions and, to a good approximation, Auger transitions due to the external Auger-effect. External Auger-effect designates a process, in which an electron of a neighbouring molecule is ejected.

The relative importance of the deexcitation processes is illustrated in Fig.1 for circular levels ($n, l=n-1$; l denotes the orbital quantum number) at a pressure of 30 hPa hydrogen. At this pressure radiative deexcitation prevails for principal quantum numbers $n \leq 6$. The corresponding value at a pressure of 1000 hPa is $n \leq 4$.

Men'shikov [16] found that Fiorentini [18] overestimated the Coulomb rates and that Leon and Bethe [13] underestimated the Auger rates for high principle quantum numbers ($n > 10$). These corrections have a small influence on the intensity of the X-ray transitions at low principle quantum numbers but can affect the kinetic energy of the antiprotonic atom.

The largest influence on the population of states at high principle quantum numbers is due to the fact, that the small and neutral antiprotonic hydrogen system can pass through the high electric fields of neighbouring molecules (Stark effect). The shuffling model used in the computer code describes the Stark effect as dipole transitions between states with different orbital but the same principal and magnetic quantum numbers.

The dominance of the Stark-effect can be illustrated in liquid hydrogen.

The frequency of Stark transitions ω_{St} is given by [12]

$$\omega_{St} = n(n^2 - l^2)^{1/2} \cdot 4 \cdot 10^{13} s^{-1} \quad (2)$$

Assuming a kinetic energy of 1 eV, the antiprotonic atom needs a characteristic time τ_{St} of about 10^{-14} s to pass through the hydrogen atom. For high principal quantum numbers : $\omega_{St} \cdot \tau_{St} \gg 1$, a condition which implies many transitions between neighbouring orbital quantum states during the time τ_{St} . The consequence is a tendency to populate the orbits according to their statistical weight. Even at lowest pressures the Stark rates always dominate at high principle quantum numbers (see Fig.1). Therefore, no information can be deduced about the initial distribution of the antiprotons in the antiprotonic atom by measuring Balmer X-rays.

2.2 Influence of Strong Interaction

The strong interaction effects are taken into consideration by the computer code via $\epsilon_{1s}, \Gamma_{1s}, \Gamma_{2p}$ and Γ_{3d} . For higher principal quantum numbers the strong widths are obtained by scaling relations [14].

The dominant feature of the cascade in antiprotonic hydrogen is the large strong width of the 2p-state. This is shown in Fig.2, which compares the sum of the electromagnetic widths for (np)-levels, $\Gamma_{np}^{deex} = \Gamma_{np}^{Coulomb} + \Gamma_{np}^{chemical} + \Gamma_{np}^{Auger} + \Gamma_{np}^{radiative}$, the Stark width Γ_{np}^{Stark} and the absorption width Γ_{np}^{abs} as a function of the principle quantum number. The probability for annihilation per atom from a (np)-level Y_{np}^{ann} is given by

$$Y_{np}^{ann} = P_{np} \cdot \frac{\Gamma_{np}^{abs}}{\Gamma_{np}^{deex} + \Gamma_{np}^{Stark} + \Gamma_{np}^{abs}} \quad (3)$$

P_{np} denotes the population of the (np)-levels. For principle quantum numbers $n < 22$, the absorption width is at least one order of magnitude larger than the deexcitation and the Stark widths. Because $\Gamma_{np}^{abs} \gg \Gamma_{np}^{deex} + \Gamma_{np}^{Stark}$ relation (2) implies

$$Y_{np}^{ann} \simeq P_{np} \quad (4)$$

Antiprotons which are shuffled into a (np)-state annihilate. The annihilation probabilities for different values of the strong width of the 2p-state and for two different pressures are listed in Tab.1. At a pressure of 30

hPa, the cascade is not affected by a variation of the strong width of the 2p-state within the range of the theoretically predicted values because the annihilation rate always dominates (see column 1 and 2). Furthermore, as long as $\Gamma_{np}^{abs} \gg \Gamma_{np}^{deex}$, the yields of the Balmer transitions are not sensitive to Γ_{np}^{abs} . This behaviour changes when the strong width of the 2p-state approaches the same order of magnitude as the radiative width (column 3). The probability for transitions induced by the Stark effect are proportional to the target gas pressure. Therefore, at very low pressures, fewer antiprotons are shuffled to (np)-states from which they annihilate, and almost all antiprotons reach the 2p-state via Balmer-transitions (column 4 of Tab.1).

It should be remarked that in the shuffling model, the influence of the shifts and widths of the s-levels is masked by the large (np)-annihilation widths, because the antiprotons which populate the (ns)-states must pass always a (np)-state.

3 Experimental Method

Two other experiments, PS171 [19] and PS174 [20,21], have also measured X-rays in antiprotonic hydrogen and deuterium. To produce a high fraction of antiprotons stopped in a small volume at a pressure below 300 hPa, the cyclotron trap, a superconducting magnetic focussing device, has been developed [22]. This device (Fig.3) provides a novel method for determining both the number of stopped antiprotons and the absolute yields with high accuracy.

The incoming antiproton beam enters the target chamber and penetrates a moderator within the magnetic field. After passing the moderator, a thin defining scintillator counts the incoming particles. The antiprotons then loose energy by collisions with the target gas atoms and are guided by the weak focussing magnetic field to the center of the trap where they stop and form antiprotonic atoms.

Scintillators have been attached to the target chamber walls and the walls of the gap of the magnet. They are labelled 'annihilation counters' in Fig.3 and serve as a tool to identify stops in the target gas by measuring charged particles arising from the annihilation products. The defining scintillator and the annihilation counters allow the time development of the

stopping process of the antiprotons to be studied in a time of flight measurement. The spectrum obtained permits the identification of three groups of annihilation events; an example is shown in Fig.4. Group 1 stems from annihilations in the defining scintillator and main moderator configuration, group 2 from an additional moderator inserted to increase the deceleration after the first revolution, and group 3 from stops in the target gas.

The distinct separation of the groups of annihilation events in time is used at three stages of the experiment. First, the injection scheme is optimized by requiring both a maximum intensity and minimum width in the distribution of the stops in the target gas as a function of the adjustment parameters. Second, the time separation permits setting a time-window in order to correlate X-rays to stops in the target gas. This reduces the background in the X-ray spectrum. Third, the absolute number of stops in the target gas can be determined. The last two stages permit the determination of absolute yields.

3.1 Determining the Number of Stopped Antiprotons

The quantities which determine the number of stopped antiprotons as well as the absolute yields (see 3.2) are the number of incoming antiprotons N_{in} , the number of X-rays measured without the time-window N_x , the number of X-rays measured in coincidence with the time-window $N_x \wedge N_{ann}$, the number of annihilation events N_{ann} , and the absolute efficiencies of the X-ray detectors and the annihilation counters.

The number of X-rays measured in coincidence with annihilation events in the target gas is

$$N_x \wedge N_{ann} = Y_x f_s N_{in} \int \int \int \epsilon_x(\vec{r}_x, \vec{r}_s) \epsilon_{ann}(\vec{r}_{ann}, \vec{r}_s) \rho(\vec{r}_s) d\Omega_{\vec{r}_x} d\Omega_{\vec{r}_{ann}} d\Omega_{\vec{r}_s} \quad (5)$$

with

Y_x : number of emitted X-rays in a transition per stopped antiproton

f_s : fraction of antiprotons stopped in the gas volume

N_{in} : number of incoming antiprotons

ϵ_x : probability for the X-ray detection

$\vec{r}_x$: distance of the X-ray detector to the center of the cyclotron trap

ϵ_{ann} : detection probability of the annihilation counters

$\vec{r}_{ann}$: distance of the annihilation counters to the center of the cyclotron trap

$\rho(\vec{r}_s)$: stop distribution of the antiprotons ($\int \rho(\vec{r}_s) d\Omega_{\vec{r}_s} = 1$)

$\vec{r}_s$: distance of the annihilation point to the center of the cyclotron trap

Numerical calculations show that the stop distribution $\rho(\vec{r}_s)$ is smaller than 100 cm^3 and symmetrical with respect to the center of the cyclotron trap. For a symmetrical arrangement of detectors with respect to the center of the stop distribution, the detection probability is equal for all points of the stop distribution. This condition is approximately fulfilled for the annihilation counters. The X-ray detector is asymmetrically mounted (Fig.3), which favours the detection of X-rays produced closer to the detector. However, the detection probability of X-rays produced at different points of the stop distribution is constant within a maximal error of 14 %. This uncertainty is taken into consideration in the calculation of the total error. The assumption of a constant detection probability allows the factorization of (5)

$$N_x \wedge N_{ann} = Y_x f_s N_{in} \int \epsilon_x(\vec{r}_x) d\Omega_{\vec{r}_x} \int \epsilon_{ann}(\vec{r}_{ann}) d\Omega_{\vec{r}_{ann}} \int \rho(\vec{r}_s) d\Omega_{\vec{r}_s} \quad (6)$$

The first two integrals in (6) can be determined experimentally and will be denoted $\langle E_x \rangle$ and $\langle E_{ann} \rangle$, respectively. Thus, the number of X-rays coincident with annihilation events is

$$N_x \wedge N_{ann} = Y_x f_s N_{in} \langle E_x \rangle \langle E_{ann} \rangle \quad (7)$$

The number of X-rays not correlated with stops in the gas is

$$N_x = Y_x f_s N_{in} \langle E_x \rangle \quad (8)$$

The trigger efficiency of the annihilation counters $\langle E_{ann} \rangle$ is provided by X-ray measurements with and without the time-window.

$$\langle E_{ann} \rangle = \frac{N_x \wedge N_{ann}}{N_x} \quad (9)$$

The number of annihilation events due to stops in the target gas is

$$N_{ann} = f_s N_{in} < E_{ann} > \quad (10)$$

Combining relations (9) and (10) provides the fraction of antiprotons stopped in the target gas

$$f_s = \frac{1}{N_{in}} \frac{N_x N_{ann}}{N_x \wedge N_{ann}} \quad (11)$$

3.2 The Determination of Absolute Yields

The relations (7) and (10) permit the determination of absolute yields.

$$Y_x = \frac{1}{< E_x >} \frac{N_x \wedge N_{ann}}{N_{ann}} \quad (12)$$

The determination of the in-beam response function i.e. the energy-, resolution- and efficiency-calibration of a Si(Li)-semiconductor detector is particularly difficult in the energy region below 5 keV. This problem was solved with a novel method. At pressures below 100 hPa, light antiprotonic atoms are completely ionized due to non-radiative deexcitation processes [23]. As a consequence, the intensities of circular transitions are almost identical. Therefore after correction for self-absorption, the intensities of circular transitions in a measured spectrum reflect directly the relative efficiency of the X-ray detector. This is shown in Fig.5 for antiprotonic nitrogen in the energy range smaller than 22 keV. The obtained relative efficiency curve is related to absolute efficiencies with a calibrated ^{57}Co radioactive standard source. The energy and resolution calibration was also performed with the help of the numerous nitrogen lines. In the energy range considered here, there is no influence of the strong interaction on the energy levels and they can therefore be calculated with high accuracy [24].

4 Analysis and Results

The measurement was performed at the LEAR-facility at CERN at a beam momentum of 202 MeV/c. The delivered intensity of antiprotons varied between $2 \cdot 10^4$ $\bar{p}$ /s to $2 \cdot 10^5$ $\bar{p}$ /s. The extraction cycle, designated a 'spill', lasted about 1 hour. The characteristics of the Si(Li)-semiconductor detectors used for this measurement are listed in Tab.2.

4.1 Balmer X-rays

The intensities of the Balmer transitions were determined for antiprotonic hydrogen at 16 hPa, 30 hPa, 60 hPa, 300 hPa and for antiprotonic deuterium at 16 hPa and 60 hPa. The measurements are performed within 7 spills, 5 spills, 4 spills, 2 spills, 3 spills and 3 spills, respectively. Fig.6 shows as an example the measured spectra of antiprotonic hydrogen for 16 hPa and 300 hPa and of deuterium for 16 hPa normalized to the same number of incoming antiprotons. From the measured intensities absolute yields were calculated. The results are given together with the number of incoming and the fraction of stopped antiprotons in Tab.3.

The pressure dependence of the absolute yields was compared with cascade calculations [14]. The strong interaction parameters used for all calculations were $\epsilon_{1s} = -620$ eV, $\Gamma_{1s} = 1130$ eV and $\Gamma_{2p} = 32$ meV (see section 4.2). The strong width of the 3d-state $\Gamma_{3d} = 0.4\mu\text{eV}$ was taken from [5].

Given these parameters, a variation of only the kinetic energy T_{kin} of the system and of the Stark mixing parameter k_{Stk} were necessary to describe the data measured in antiprotonic hydrogen. T_{kin} is defined to be constant; slowing down or acceleration processes during the cascade are not taken into account. The Stark mixing parameter k_{Stk} is a phenomenological factor which multiplies all Stark mixing rates globally. This parameter is introduced to take into consideration two approximations in the model of Leon and Bethe [13] and does not depend on quantum number. First, an angle dependent term in the set of differential equations describing the cascade was neglected. Second, in calculating the s-state occupation probability, the phase difference between adjacent Stark states was averaged and set to a constant. Vermeulen [25] has calculated correction factors for the Stark mixing rates in pionic hydrogen including the angle dependent term. His results depend on the principal quantum number and vary between 1.5 and 3.9.

As shown in Fig.7, the measured X-ray intensities in antiprotonic hydrogen can be reproduced very well over the whole pressure region using the theoretically predicted value for the width of the strong 3d-state from Ref.[5]. The best fit with $\chi^2 = 2.25$ yielded a Stark mixing parameter

$k_{Stk} = (2.16^{+0.23}_{-0.20})$ and a kinetic energy $T_{kin} = (1.0^{+0.3}_{-0.2})$ eV. χ^2 is defined as

$$\chi^2 = \sum_i \frac{1}{\sigma_i^2} (Y_i^{th} - Y_i^{exp})^2. \quad (13)$$

Y_i^{exp} and σ_i denote the measured absolute yield and the corresponding 1-sigma error; Y_i^{th} denotes the result of the cascade calculation at a pressure i . The same parameter set also reproduces the measured yields of pionic and muonic hydrogen [26,27].

In antiprotonic deuterium the Balmer line intensities are drastically reduced compared to antiprotonic hydrogen. This cannot be reproduced by the cascade code using both the cascade parameters obtained from antiprotonic hydrogen and the theoretically predicted strong width of the 3d-state of about 5 μ eV [29]. A drastical increasement of the Stark effect seems to be no reason for the reduced intensities, because a stronger Stark mixing would require a higher kinetic energy. On the contrary, due to the larger mass of antiprotonic deuterium a lower kinetic energy and slightly increased yields are expected.

However, the data can be fitted by assuming that the strong width of the 3d-state is much larger than theoretically predicted. Using the cascade parameters obtained from antiprotonic hydrogen, a strong width of $\Gamma_{3d} = (50^{+17}_{-11})$ μ eV fits the data ($\chi^2 = 0.4$). The allowed region (1 σ -error of T_{kin} and k_{Stk}) for the yield of the Balmer α transitions in antiprotonic hydrogen and deuterium are summarized in Fig.8.

4.2 Lyman X-rays

The measurement of Lyman transitions was performed at a pressure of 30 hPa with 11 spills and a total number of $2.35 \cdot 10^9$ incoming antiprotons.

To study the behaviour of the background, a spectrum uncorrelated with stops in the hydrogen gas has been recorded (Fig. 9a). The contamination lines in the part of the spectrum shown are $\bar{p}O(8 \rightarrow 7)$ at 7.21 keV, $\bar{p}O(7 \rightarrow 6)$ at 11.11 keV and an electronic Lyman α fluorescence line of copper at 8.04 keV. No other contamination lines were found. The measured intensities of $I(\bar{p}O(8 \rightarrow 7)) = 2562 \pm 594$ and $I(\bar{p}O(7 \rightarrow 6)) = 2269 \pm 670$ correspond to a partial pressure of about 10^{-2} hPa oxygen with 30 hPa hydrogen.

This contamination was confirmed by means of a mass spectroscopy measurement. The copper fluorescence line is produced inside the neck of the X-ray detector. This was checked by an irradiation measurement with a ^{60}Co standard source. Except for the contamination lines the background is flat. Thus, smooth functions may be used to describe the background in the spectrum recorded with correlations to stops in the target gas (Fig. 9b). The spectrum shows, that the gate has reduced the background at energies above about 5 keV by a factor of four. It was checked very carefully that above this energy there was only a linear intensity reduction of X-rays, which amounts to a factor of 1.6. A nonlinear intensity reduction in the background, however, could not be excluded.

Fig.10 shows the fit of the gated spectrum. The background is fitted with a gaussian function describing the shape of the threshold at low energies and an exponential tail to describe the behaviour at higher energies. The parameters of the background function were treated as free parameters. The errors obtained from the fit to these parameters were smaller than 1.2 percent. A fit of the background using a polynomial function of third order yielded the same results within the errors but with a worse χ^2 [28].

The fit of the gated spectrum shows the lorentzian line profiles of the Lyman α transitions at 8.79 keV and an unresolved structure at 11.92 keV. This structure contains the transitions, $np \rightarrow 1s$, for $n \geq 10$. Consistent with the prediction of the cascade calculations, the yields of the (np) -transitions to the ground state for $3 \leq n < 10$ are too small to be detected at a pressure of 30 hPa. The energy difference of the higher transitions is too small to be resolved.

In the fit the lorentzian broadening of the higher transitions was assumed to be equal to the broadening of the Lyman α transitions. The intensity ratio of the two lines was deduced from the cascade calculations to be 0.484. In addition to this intensity ratio, the well-known intensities of the contamination lines and their energies as predicted by QED were kept fixed to restrict the behaviour of the background.

The global shift of the $1s$ -state is found to be $\epsilon_{1s} = -(620 \pm 100)$ eV; the strong width of the $1s$ -state to be $\Gamma_{1s} = (1130 \pm 170)$ eV. The number of Lyman α X-rays is (4140 ± 582) , which corresponds to a yield of $(6.2 \pm 1.7) \cdot 10^{-3}$. The total yield of all Lyman transitions is $(9.1 \pm 1.9) \cdot 10^{-3}$. The

χ^2 per degree of freedom is 1.09. The peak to background ratio, which is defined as ratio of the integral of the peak and the background within a 1 keV broad region around the center of the Lyman α peak, is $2.2 \cdot 10^{-2}$.

The strong width of the 2p-state is deduced to be $\Gamma_{2p} = (32 \pm 10)$ meV from the intensity balance of (1).

A comparison with theoretical predictions given in table 4 shows that the experimental errors are still too large to distinguish among the range of different theoretical models.

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Table Captions

Table 1 : The probability for absorption in percent from (np)-levels in antiprotonic hydrogen at a pressure of 30 hPa and 1 hPa for different values of the strong width of the 2p-state. The results are obtained from the cascade code of Bethe, Borie and Leon (Ref.[10]).

Table 2 : Characteristics of the Si(Li) semiconductor detectors used for the measurement. Si(Li) I was used for the measurement of the Balmer X-rays; Si(Li) II for the measurement of the Lyman X-rays.

Table 3 : Measured absolute yields of Balmer X-rays, the number of incoming (N_{in}) and the fraction of stopped antiprotons (f_s) versus pressure for antiprotonic hydrogen and deuterium.

Table 4 : The predictions of different theoretical models for the strong shift and widths of antiprotonic hydrogen. For the calculation of the global shifts and widths of the ground states, the triplet and singlet state have been weighted 2.2 : 1. The widths of the p-states have been calculated according to their statistical weight.

	30 hPa $\Gamma_{2p} = 40$ meV	30 hPa $\Gamma_{2p} = 10$ meV	30 hPa $\Gamma_{2p} = 1$ meV	1 hPa $\Gamma_{2p} = 30$ meV
n = 30	2.02	1.50	0.35	1.24
n $\geq$ 25	6.70	5.40	1.64	2.33
n $\geq$ 20	18.74	16.31	6.69	3.10
n $\geq$ 10	41.52	38.06	20.50	3.22
n $\geq$ 5	42.15	38.69	21.03	3.27
n < 5	55.66	55.28	46.10	94.43

Tab.1

	active area /mm ²	in-beam resolution at 6.4 keV /eV	Be-window thickness / μ m
Si(Li) I	30	220	8
Si(Li) II	300	450	50

Tab.2

$\bar{p}p$					
pressure /hPa	Y(Balmer α) /%	Y(Balmer β) /%	Y(Balmer <i>tot</i>) /%	N _{in} /10 ⁸	f _s /%
16	51.9 $\pm$ 11.0	9.2 $\pm$ 2.5	70.6 $\pm$ 11.6	3.8	19.9 $\pm$ 3.0
30	40.7 $\pm$ 8.5	3.7 $\pm$ 1.3	52.3 $\pm$ 8.9	5.6	28.2 $\pm$ 4.3
60	34.7 $\pm$ 7.5	3.5 $\pm$ 1.5	47.7 $\pm$ 8.0	2.7	36.6 $\pm$ 5.6
300	9.5 $\pm$ 2.6	1.6 $\pm$ 1.1	17.8 $\pm$ 3.6	1.5	61.2 $\pm$ 9.3
$\bar{p}d$					
16	24.7 $\pm$ 4.6	2.3 $\pm$ 0.9	35.2 $\pm$ 5.0	3.5	23.9 $\pm$ 3.6
60	16.5 $\pm$ 3.4	3.4 $\pm$ 1.0	29.3 $\pm$ 4.1	2.1	35.9 $\pm$ 5.5

Tab.3

$-\epsilon_{1s}$ /eV	Γ_{1s} /eV	Γ_{2p} /meV	Reference
980	1430	-	[4]
690	940	33	[5]
-	-	50	[6]
450	900	20	[7]
780	1279	37	[8]
750	1060	33	[9]
550	850	19	[10]
520	1180	17	[10]
1130	200	-	[11]

Tab.4

Figure Captions

Figure 1 : The rates for deexcitation processes taken into account in the cascade code of Bethe, Borie and Leon versus the principle quantum number of circular levels at a pressure of 30 hPa hydrogen. The curves denote : ——— Auger deexcitation rate, ——— radiative deexcitation rate, ——— chemical deexcitation rate, — · — · — Coulomb deexcitation rate and — · — Stark-mixing rate.

Figure 2 : A comparison of the total widths of the deexcitation processes $\Gamma_{np}^{deex} = \Gamma_{np}^{Auger} + \Gamma_{np}^{radiative} + \Gamma_{np}^{chemical} + \Gamma_{np}^{Coulomb}$ with the Stark width Γ_{np}^{Stark} and the absorption width Γ_{np}^{abs} for $\Gamma_{2p}^{abs} = 30$ meV at a pressure of 30 hPa hydrogen. The curves denote : ——— Γ_{np}^{deex} , — · — Γ_{np}^{Stark} and ——— Γ_{np}^{abs} .

Figure 3 : The cross-section of the cyclotron trap is shown. The target chamber is placed within the gap and the axial bores of the magnet. The positions of an X-ray detector and of the annihilation counters are indicated. The dot denotes the beam injection point into the cyclotron field.

Figure 4 : The measured time structure of annihilation events for decelerating antiprotons in the cyclotron trap at a pressure of 30 hPa hydrogen. The identification of the different peaks is explained in section 3.1.

Figure 5 : The spectrum of antiprotonic nitrogen measured at a pressure of 21 hPa with the detector Si(Li) I.

Figure 6 : A selection of spectra of antiprotonic hydrogen and deuterium containing Balmer X-rays. The spectra are normalized to the same number of incoming antiprotons.

Figure 7 : Absolute yields in percent versus pressure for antiprotonic hydrogen. The curves are the best fit to the measured yields as obtained from the cascade code of Bethe, Borie and Leon. The curves denote: ——— Balmer *tot*, ——— Balmer α and — · — Balmer β . Balmer *tot* denotes the sum of all Balmer transitions. The notation of the

measured yields is : $\blacktriangle$: Balmer *tot*, $\bullet$: Balmer α and $\blacksquare$: Balmer β .

Figure 8 : Measured absolute yields in percent versus pressure for the Balmer α transitions in antiprotonic hydrogen ($\bullet$) and deuterium ($\blacksquare$). The hatched areas correspond to the $1\text{-}\sigma$ error band of the best fit to the measured yields as obtained by the cascade code of Bethe, Borie and Leon. The error band is due to the errors of the parameters T_{kin} and k_{Stk} .

Figures 9 :

- a) A spectrum of antiprotonic hydrogen measured at 30 hPa not correlated to stops in the hydrogen gas. The energy range of the Lyman X-rays is shown.
- b) The corresponding spectrum as in a) correlated to stops in the hydrogen gas. The binning for both spectra is 278 eV/channel.

Figure 10 : A fit to the spectrum 9 b). The binning is 140 eV/channel.

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6

Fig.7

Fig.8

Fig.9a

Fig.9b

Fig.10