Precision Spectroscopy of Pionic Hydrogen

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The measurement of the pion–nucleon scattering lengths constitutes a test of the methods of Chiral Pertubation Theory, which is the low–energy approach of Quantumchromodynamics. The s–wave scattering lengths are related to the strong–interaction shift and width of the ground state of pionic hydrogen. Shift and width are determined from the energy and the line width of the characteristic X–radiation from transitions to the atomic ground state of the pionic–hydrogen atom. The new experiment set up at the Paul–Scherrer–Institut (PSI) has completed a first series of measurements. Preliminary results are given.

1 INTRODUCTION

In pionic hydrogen the strong pion–nucleon interaction manifests itself by a change of the energies and of the natural line widths of X–ray lines as compared to a purely electromagnetic bound atomic system. Experimentally accessible are the transitions to the 1s ground state emitted in the last de–excitation step of the atomic cascade. Any observed influence of the strong interaction can be attributed fully to the 1s state, because hadronic effects in p states are negligibly small. Hence, the s–level shift and width are exclusively owing to the pion-nucleon s–wave interaction. Hadronic shift and broadening are related to the scattering lengths of elastic $a_{\pi^-p} \rightarrow a_{\pi^-p}$ and charge exchange scattering $a_{\pi^-p} \rightarrow a_{\pi^0n}$ by the Deser–type formulae [1, 2]

$$\frac{\epsilon_{1s}}{B_{1s}} = -\frac{4}{r_B}\, a_{\pi^-p\rightarrow\pi^-p}(1+\delta_\epsilon) \quad (1)$$

$$\frac{\Gamma_{1s}}{B_{1s}} = 8\frac{q_0}{r_B}(1+\frac{1}{P})[a_{\pi^-p\rightarrow\pi^0n}(1+\delta_\Gamma)]^2, \quad (2)$$

where B_{1s} is the binding energy of the ground state. The kinematic quantity $q_0 = 0.1421 fm^{-1}$ is the CMS momentum of the π^0 in the reaction $\pi^-p \rightarrow \pi^0n$ and $P = 1.546 \pm 0.009$ [3] the branching ratio of charge exchange and radiative capture $\pi^-p \rightarrow \pi^0n/\gamma n$ (Panofsky ratio).

At threshold, the two basic parameters of the πN interaction are the isoscalar and isovector s-wave scattering lengths a^+ and a^-. They are given in terms of the elastic reactions by

$$a^\pm = \frac{1}{2}\,(a_{\pi^-p\rightarrow\pi^-p} \pm a_{\pi^+p\rightarrow\pi^+p}). \quad (3)$$

In the limit of exact isospin conservation the elastic channels are related to charge exchange by

$$a_{\pi^-p\rightarrow\pi^-p} - a_{\pi^+p\rightarrow\pi^+p} = -\sqrt{2}\, a_{\pi^-p\rightarrow\pi^\circ n} \quad (4)$$

and the interaction at threshold is described completely by two (real) numbers. Obviously $\epsilon_{1s} \propto (a^+ + a^-)$ and $\Gamma_{1s} \propto (a^-)^2$ holds.

Nowadays, up to fourth order calculations of a^+ and a^- in the framework of Heavy Baryon Chiral Perturbation Theory have been performed [4]. Consequently, the experimental information obtained from hadronic shift ϵ_{1s} and level broadening Γ_{1s} should at least reach a precision at the level of the calculations.

The parameters $\delta_{\epsilon,\Gamma}$ prevent a direct extraction of the pure hadronic scattering lengths from the experimental results. They account both for nuclear–Coulomb interference and terms arising from the chiral expansion treating electromagnetic corrections and isospin breaking effects. In the πN case, higher order terms of the chiral expansion contain low–energy constants (LECs), parameters of the effective theory to be fixed from experiment [5, 6]. At present the correction for ϵ_{1s} is calculated to $\delta_\epsilon = (-7.2 \pm 2.9)\%$, the uncertainty of which is given mainly by one particular LEC (f_1 [6, 7]). The correction δ_Γ is subject of detailed theoretical studies. Here f_1 does not appear in next-to-leading order, which reduces the uncertainty substantially [8].

The previous precision measurement yielded $\epsilon_{1s} = +7.108 \pm 0.047$ eV and $\Gamma_{1s} = 0.868 \pm 0.078$ eV [9]. Whereas the precise determination of $(a^+ + a^-)$ is hindered by the large theoretical error of δ_ϵ, the uncertainty of Γ_{1s} is dominated by the correction for Coulomb de–excitation. Coulomb de–excitation is an important non–radiative de–excitation channel of the excited atom πH, where the released energy for the step $n \to n'$ is converted into kinetic energy of the collision partners πH and H (from a molecule H_2), which leads to a Doppler broadening of the X–ray lines. This process dominates the upper part of the atomic cascade (Fig. 1) but is also important for the lower lying states.

The contribution of this process is up to now not yet understood quantitatively well enough. Consequently, a large part of the uncertainty of 7% of the hadronic broadening is given by the badly known correction to the measured line width [9]. For that reason the precisely measured 1s–level shift in pionic deuterium was used together with the shift of hydrogen in the determination of the πN scattering length [10]. This procedure, however, requires a sophisticated treatment of the 3–body system πD. In addition, molecule formation (see below) may affect the X–ray energies [11]. Up to now it cannot be excluded that the radiative decay channel after molecule formation is enhanced in deuterium compared to hydrogen [12, 13].

2 EXPERIMENTAL APPROACH

To improve on the accuracy for the hadronic parameters as compared to previous measurements, a thorough study of a possible influence of de–excitation processes is essantial. Identifying and quantifying cascade processes is, therefore, the central part of the new pionic–hydrogen experiment set up at the Paul–Scherrer–Institut (PSI)[14]. The new experiment uses the cyclotron trap II to provide a bright X–ray source by stopping pions in a cryogenic target (Fig. 2). The density of the target gas is increased by cooling. Temperatures of 20 K are reached, which is sufficient to liquify the hydrogen gas. X–rays emitted from the exotic atoms are reflected by a Bragg crystal spectrometer, which is equipped with spherically bent silicon and quartz crystals and a large–area CCD array for position–sensitive X–ray recording. A first series of measurements has

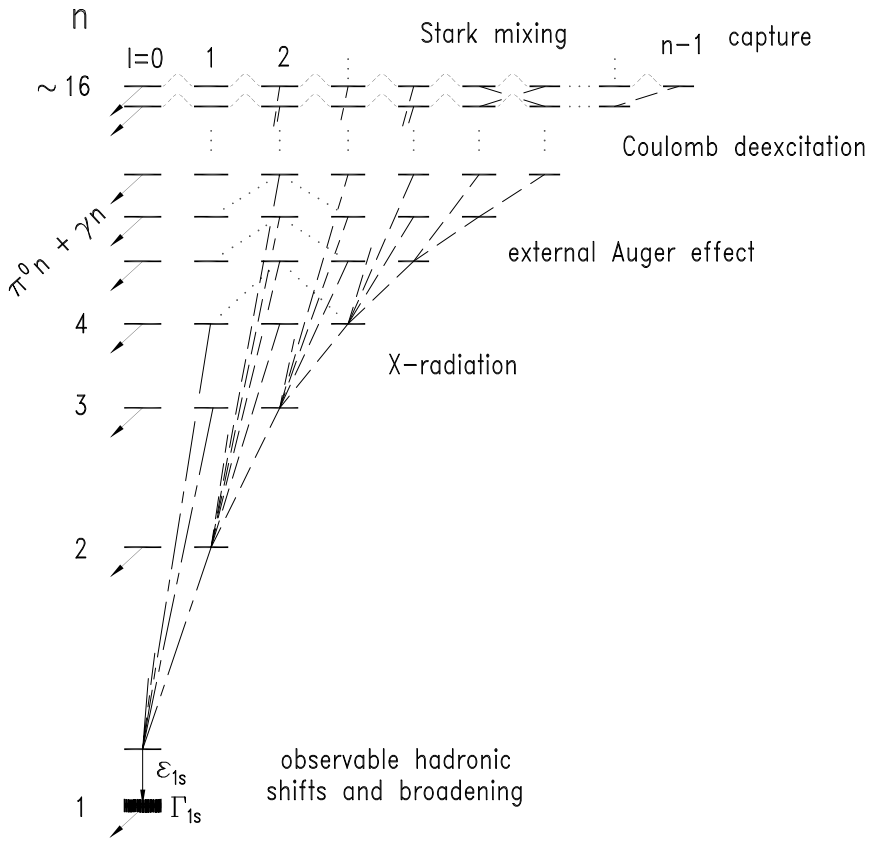

Figure 1: Atomic cascade in pionic hydrogen.

been completed in 2002.

In order to identify radiative de–excitation of the πH system, when bound into complex molecules formed during collisions $\pi^- p + H_2 \rightarrow [(pp\pi^-)p]ee$ [11], the energy of the $\pi H(3p-1s)$ transition was measured at various target densities. X–ray transitions from molecular states should show up as low–energy satellites with density dependent intensities because of different collision probabilities.

Beyond this study of the pressure dependence of the $\pi H(3p-1s)$ transition, the data base on the line broadening due to Coulomb de–excitation was extended by investigating also the $\pi H(2p-1s)$ and the $\pi H(4p-1s)$ lines. These transitions were studied at a target density equivalent to 10 bar.

2.1 Energy Calibration

The energy calibration is performed in a relative measurement to the $\pi O(6h-5g)$ transition. Pionic oxygen represents a purely electromagnetic bound hydrogen–like atomic system, because for the circular orbits $6h$ and $5g$, finite size effects and with that the influence of the pion–nucleus interaction are negligible. Screening effects from remaining electrons are also small because the electron shells are practically completely removed when the $6h-5g$ transition occurs [15]. The level energies can be calculated with an

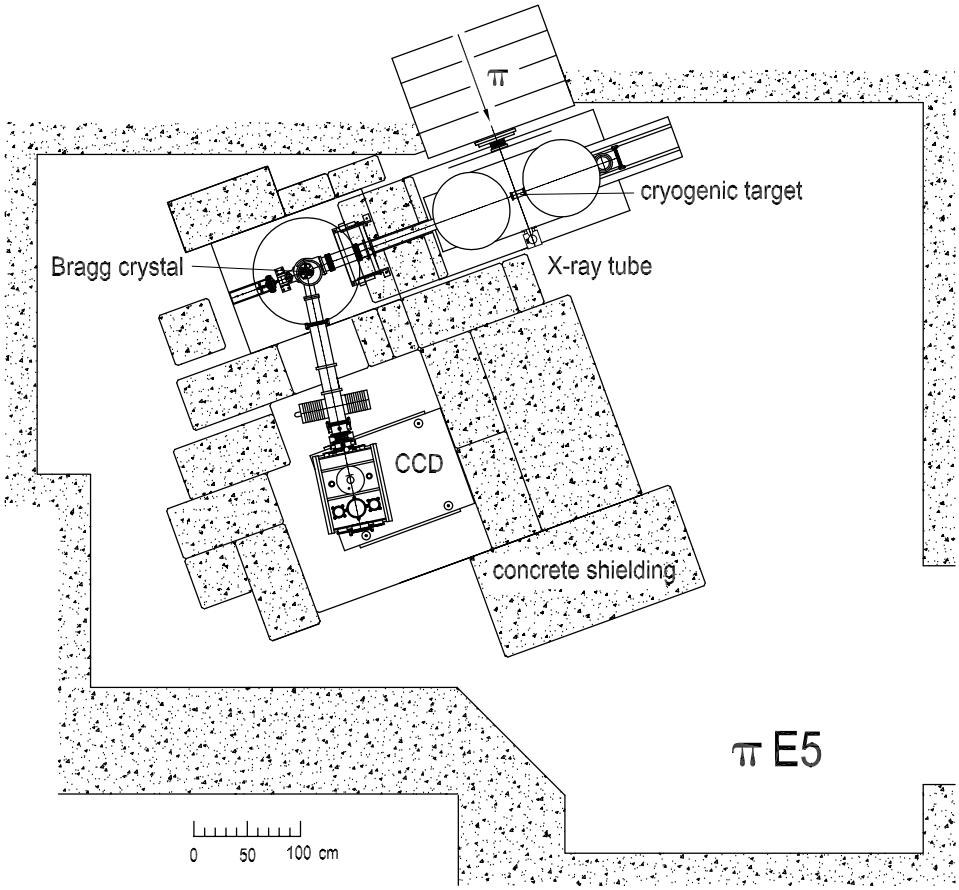

Figure 2: Setup of the pionic hydrogen experiment in the $\pi E5$ area at PSI.

accuracy of a few meV [16].

At low density, the $\pi O(6-5)$ and the $\pi H(3p-1s)$ lines were measured simultaneously by using a hydrogen–oxygen gas mixture of H_2/O_2 (98%/2%) (Fig. 3). At higher densities, i. e. lower temperatures, hydrogen and oxygen were measured alternately (Fig. 4). In one of these measurements, a mixture of $^4He/^{16}O_2/^{18}O_2$ (80%/10%/10%) was used, where the oxygen isotopes serve as a check for the dispersion of the spectrometer. The admixture of helium reduces the self absorption of the X–rays in oxygen.

Unfortunately, only in the case of the $\pi H(3p-1s)$ transition a suitable pionic–atom transition close in energy exists. Hence, the hadronic shift results are exclusively from this transition.

2.2 Resolution Function

The response of the spectrometer – either equipped with a silicon or a quartz crystal – was first obtained from the $\pi^{12}C(5g-4f)$ line (Fig. 3). The natural line width of this transition is negligibly small compared to the experimental resolution. As target gas CH_4 was used, where broadening effects from Coulomb explosion [17] were expected to be very small [18]. The statistics of such a measurement, however, and with that the

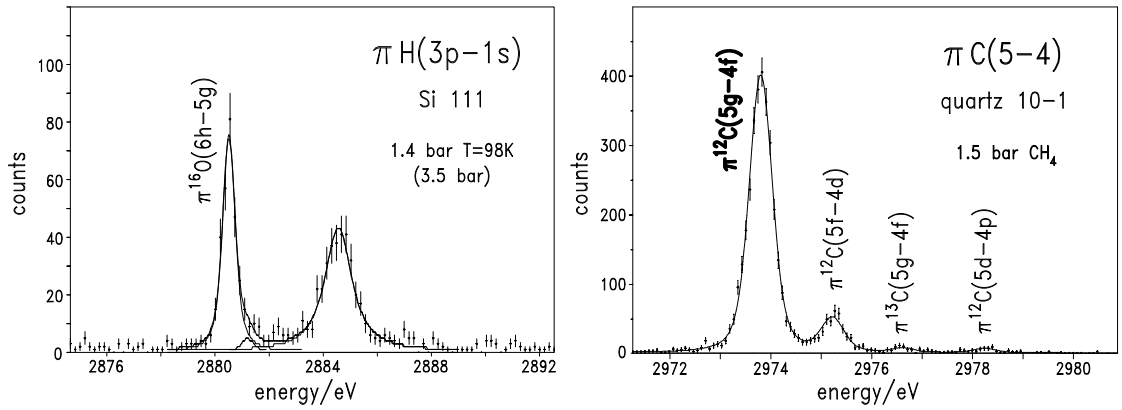

Figure 3: Left: Ground–state transition $3p-1s$ in pionic hydrogen measured simultaneously with the calibration transition $\pi^{16}O(6h-5g)$. Right: Pionic carbon $5-4$ transitions measured with a quartz crystal used to determine the spectrometer response function. A resolution of about 450 meV was achieved.

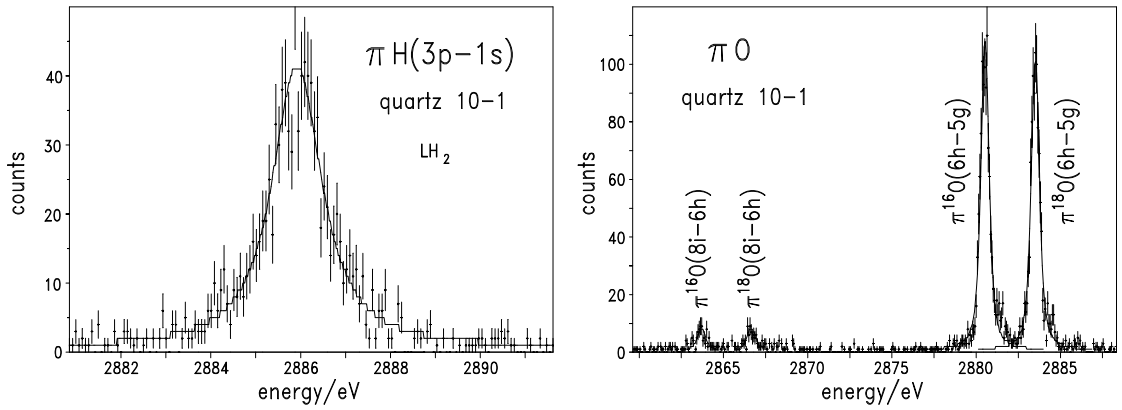

Figure 4: Ground–state transitions $3p-1s$ in pionic hydrogen and the pionic oxygen $6h-5g$ transitions used for energy calibration measured with a quartz crystal.

accuracy for the response function, is limited due to the low count rates.

For a thorough study of the crystal response an Electron–Cyclotron–Resonance Ion Trap (ECRIT) is being set up at PSI [19]. In the ECRIT hydrogen– and helium–like electronic atoms are produced, which emit with high rate X–rays of a line width much smaller than the experimentally achievable resolution. During commissioning, the resolutions of the silicon and the quartz crystal have been determined with the M1 transition from helium–like argon with an order of magnitude better statistics than for pionic carbon. Compared to the $\pi^{12}C(5g-4f)$ data, a slightly improved resolution was found for both crystals. This effect is interpreted as Doppler broadening from Coulomb explosion of the molecule CH_4.

3 RESULTS

3.1 Hadronic Shift

No density dependence was observed for the energy of the $\pi H(3p-1s)$ transition between 3.5 bar and liquid, i. e. over a density range of about 200 [20]. It is concluded that the decay of molecules is dominated in hydrogen by Auger emission. The energy values obtained are consistent within the errors and a weighted average was calculated. For the pure electromagnetic $(3p-1s)$ transition energy, a value of $E^{QED}_{3p-1s} = 2878.809\,eV$ is used.

$$\epsilon_{1s} = 7.120 \pm 0.008 \begin{array}{l} +\ 0.009 \\ -\ 0.008 \end{array} eV$$

The first error represents the statistical accuracy. The second one includes all systematic effects, which are due to the spectrometer setup, imaging properties of extended Bragg crystals, analysis and instabilities. The contribution from the uncertainty of the pion mass is still negligible because the energy calibration was performed with a pionic–atom transition itself. The value for ϵ_{1s} from this experiment is in agreement with the result of the previous experiment, where the energy calibration was performed with argon Kα fluorescence X–rays [9].

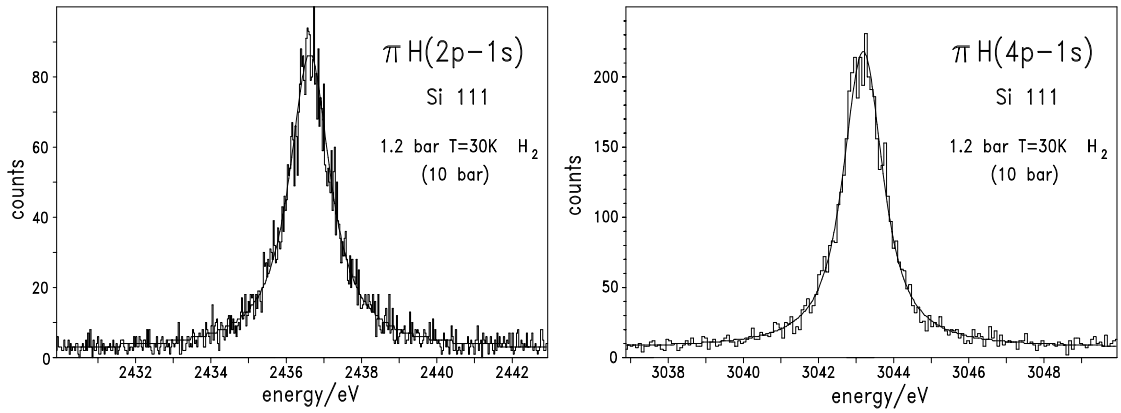

Figure 5: Ground–state transitions $2p-1s$ and $4p-1s$ in pionic hydrogen measured with a silicon crystal at 10 bar equivalent density.

3.2 Hadronic Broadening

The measured line shape of the pionic hydrogen K transitions is a convolution of a Lorentz line according to the natural width Γ_{1s}, the resolution of the crystal spectrometer and in general several contributions to the Doppler width caused by Coulomb de–excitation. For the $\pi H(3p-1s)$ transition the total line width, i. e. after deconvolution of the response function, an increase of about 10% was found compared to the result of Schröder et al. [9]. This may be due to the significantly improved background conditions in the new experiment, which results in a better sensitivity to the tails.

A further increase of the total width was found for the $2p-1s$ line compared to the $3p-1s$ transition, which is attributed to the higher energy release available for the acceleration of the pionic–hydrogen system. This result is corroborated by a reduced line width of the $4p-1s$ line (Fig. 5).

Whereas the hadronic width Γ_{1s} has to be the same for all densities and all initial states, the Doppler broadening depends on density and initial state of the X–ray transition. The kinetic energy distribution and consequently the Doppler broadening is rather complicated because it results from the superposition of all cascade steps modified by the subsequent collisions.

Kinetic energy distributions according to the $4p$, $3p$, and $2p$ inital state have been reconstructed in the framework of the cascade model of Jensen and Markushin [21] from the Doppler broadening observed in the neutron time–of–flight spectra of the charge exchange reaction $\pi^- p \rightarrow \pi^0 n$ with stopped pions [22]. The charge exchange reaction, however, occurs from s–states only, whereas the pions finally creating the K X-ray transitions follow de–excitation through higher angular momentum states. The analysis showed that these energy distributions cannot explain the measured pionic X–ray line shapes. This observation is attributed to the different atomic cascades ending in ns levels with $n > 1$ and the $1s$ state fed by X–ray transitions via the outer cascade.

For that reason only an upper limit can be extracted for the pure hadronic broadening from such an analysis:

$$\Gamma_{1s} < 0.850\, eV \tag{5}$$

This limit is extracted from the $3p-1s$ and $4p-1s$ transitions only, where Coulomb de–excitation contributes less than for the $2p-1s$ line. Obviously a better approach to the kinetic energy distribution is indispensible to improve on the starting position for the width determination.

4 OUTLOOK

As a next step, the Bragg crystals will be studied in detail with the narrow X–ray lines from hydrogen– and helium–like atoms produced with the ECRIT. This allows to disentangle precisely the influence of the Coulomb de–excitation from the spectrometer resolution when measuring the K transitions in muonic hydrogen, where strong interaction effects are absent. With the cascade code, the appropriate kinetic energy distributions for pionic hydrogen will be constructed to extract the hadronic broadening from the line shape of the pionic hydrogen transitions. Together with a high statistics measurement of the pionic–hydrogen transitions, an accuracy at the level of about 1% will be achievable.

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