# PIONIC HYDROGEN AT PSI

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The measurement of the pion–nucleon scattering lengths constitutes a high–precision test of the methods of Chiral Pertubation Theory ($\chi$PT), which is the low–energy approach of QCD. The $\pi$N s–wave scattering lengths are related to the strong–interaction shift $\epsilon_{1s}$ and width $\Gamma_{1s}$ of the $s$–states of the pionic hydrogen atom. $\epsilon_{1s}$ and $\Gamma_{1s}$ are determined from the measured energies and line widths of X–ray transitions to the 1$s$ ground state when compared to the calculated electromagnetic values. A new experiment, set up at the Paul–Scherrer–Institut (PSI), has completed a first series of measurements.

## 1 Introduction

The scattering lengths of elastic $a_{\pi^- p} \rightarrow a_{\pi^- p}$ and charge–exchange reaction $a_{\pi^- p} \rightarrow a_{\pi^0 n}$ are related to $\epsilon_{1s}$ and $\Gamma_{1s}$ by Deser–type formulae[1,2]. Rewritten in terms of two isospin scattering lengths, they describe completely the $\pi N$ interaction at threshold in the isospin symmetric limit. Furthermore, from $\Gamma_{1s}$ the $\pi N$ coupling constant $f^2_{\pi N}$ is obtained by the Goldberger–Miyazawa–Oehme sum rule[3]. Within the frame work of Heavy Baryon $\chi$PT the exotic–atom parameters $\epsilon_{1s}$ and width $\Gamma_{1s}$ and the scattering lengths unambiguously related. In an expansion in momenta, the fine structure constant $\alpha$ and quark mass difference, $(m_d^2 - m_u^2)$ in the case onf pions, both electromagnetic and strong interaction are taken into account on the same footing[4,5].

The extracted values for the isospin scattering lengths and for $f^2_{\pi N}$ may be compared to the zero order results as given by current algebra[6]. The diffrences are due to the higher order terms from the chiral expansion including isopspin–breaking effects not only from the electromagnetic interaction but also the from the mass difference of the $u$ and $d$ quark. Such contributions may be expressed as correction terms $\delta_{\epsilon,\Gamma}$ in the Deser formulae[7]. In addition, the pionic–atom results must be consistent with the extrapolation of $\pi$N scattering data to threshold and phase–shift analyses[8].

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Higher–order terms of the chiral expansion contain low–energy constants (LECs) to be fixed from data[4]. Their uncertainty may be denoted as the theoretical error. A recent calculation for $\delta_\epsilon$ yields $(-7.2\pm2.9)\%$[9], the uncertainty of which is given mainly by one particular LEC ($f_1$). At present, $\delta_\Gamma$ is subject of detailed theoretical studies. Here $f_1$ does not appear in next–to–leading order, which reduces the uncertainty substantially[10]. Hence, the new experiment[11] aims at a significant increase in accuracy for $\Gamma_{1s}$.

## 2 Experimental Approach

The pionic atom, which is formed in a highly excited state, de–excites by X–ray emission and various non–radiative mechanisms. The atomic cascade ends in an $s$ state, where a nuclear reaction takes place (Fig. 1). One important cascade mechanism is Coulomb de–excitation, where the energy release for step $n \to n'$ is converted into kinetic energy of the collision partners $\pi H$ and $H$ (from a molecule $H_2$) leading to Doppler broadening of subsequent X–ray transitions.

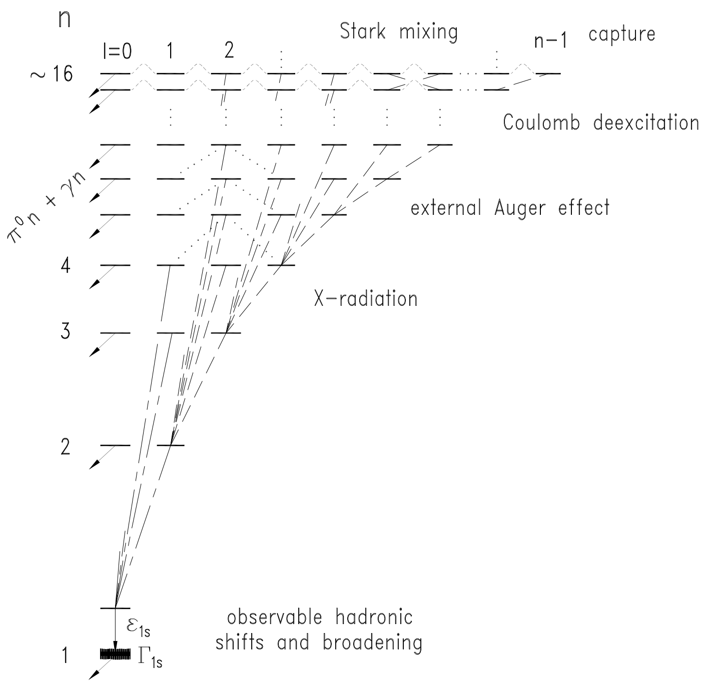


Figure 1: Atomic cascade in pionic hydrogen. The pure electromagnetic energies of the $2p-1s$, $3p-1s$, and $4p-1s$ transitions are 2.43, 2.88, and 3.04 keV. The hadronic parameters $\epsilon_{ns}$ and $\Gamma_{ns}$ scale with $1/n^3$.

The previous precision experiment – measuring the $3p-1s$ transitions at a density equivalent of 15 bar – yielded $\epsilon_{1s} = +7.108 \pm 0.047$ eV and $\Gamma_{1s} = 0.868 \pm 0.078$ eV[12]. Whereas the precise extraction of the isospin scattering lengths from $\epsilon_{1s}$ is hindered at present by the large theoretical error of $\delta_\epsilon$, the uncertainty of $\Gamma_{1s}$ is dominated by the correction for the Doppler broadening, because the contributions from Coulomb de–excitation are quantitatively not well understood.

For that reason the precisely measured $1s$–level shift in pionic deuterium was combined with $\epsilon_{1s}$ from hydrogen to determine the $\pi N$ scattering lengths and $f^2_{\pi N}$ [13]. This procedure, however, requires a sophisticated treatment of the 3–body system $\pi D$. Furthermore, collisions of the $\pi D$ atom probably lead to the formation of complex molecules like [(πdd)d]ee, a process well known in the case of muons. Up to now it cannot be excluded that such systems decay with a significant fraction by X–ray emission[14]. This leads to small energy shifts hidden by the large line width[15].

Both Coulomb de–excitation and molecule formation are collisional processes and, hence, depend on the collision rate, i. e., on density. Consequently, the strategy of the new experiment is to measure the density dependence of energy and line width to identify and/or quantify the above-mentioned cascade effects:

- Any contribution to $\epsilon_{1s}$ from the formation of a molecular complex like [($\pi$pp)p]ee has to be excluded by establishing a density independent value for the transition energy.
- Information on Coulomb de–excitation is obtained by measuring besides the $3p-1s$ also the $4p-1s$ and the $2p-1s$ transitions and at least one of these at various densities.
- Measure the line widths in muonic hydrogen, where no strong–interaction broadening occurs, for various transitions and densities.

The new experiment is based on techniques developed and applied to the precision spectroscopy of X–rays from antiprotonic and pionic atoms together with substantial improvements in background suppression[16]. The cyclotron trap provides a concentrated X–ray source for a focusing low–energy crystal spectrometer. X–rays emitted from the stop volume are reflected by spherically bent silicon or quartz Bragg crystals of 10 cm diameter and are detected by a large–area two–dimensional position–sensitive detector built up from an array of six Charge–Coupled devices (CCDs)[17]. The hydrogen density is varied by temperature in a cryogenic target.

For the precision study of the $\pi H$ X–ray line shapes the knowledge of the crystal spectrometer response is required at a higher level than available up–to–now. Narrow fluorescence X–rays or few keV $\Gamma$ lines for testing Bragg crystals are not available in practical cases. Therefore, the crystal response had been obtained from narrow pionic–atom transitions in previous experiments[12,16]. However, the limited rates even at high–flux pion channels lead to unacceptable long measuring times for precision studies. For that reason, an Electron–Cyclotron–Resonance Ion Trap (ECRIT) source is being set up to produce hydrogen– and helium–like electronic atoms. In such few–electron atoms, fluorescence lines are narrow and can be used for thorough high–statistics studies of Bragg crystals[18].

## 3 First results

A first series of measurements took place at the high–intensity pion channel $\pi$E5 of PSI. At a target density equivalent to 3.5 bar and using a $H_2/O_2$ gas mixture the $\pi$O(6h–5g) calibration line and the $\pi$H(3p–1s) transition were measured simultaneously (Fig 2). This calibration method is basically free of systematic errors due to long–term instability. At higher densities hydrogen and oxygen have to be measured alternately to prevent the oxygen gas from freezing.

No density dependence was observed for the energy of the $3p-1s$ transition, which is interpreted as the absence of radiative decay during molecular formation. The energy values obtained are consistent within the errors. The weighted average for the hadronic shift reads $\epsilon_{1s} = 7.120 \pm 0.008 \ {}^{+0.009}_{-0.008} \ eV$. The first error represents the statistical accuracy. The second one includes systematic effects, which are due to spectrometer setup, imaging properties of extended Bragg crystals, analysis and instabilities.

The measured line shape of the pionic hydrogen K transitions is a convolution of a Lorentz profile according to the natural width $\Gamma_{1s}$, the resolution of the crystal spectrometer and in general several contributions to the Doppler width caused by various $n \to n'$ Coulomb transitions. A significant increase of the total width was found for the $2p-1s$ line compared to the $3p-1s$ transition (after deconvolution of the spectrometer response), which is attributed to the higher energy release available for the acceleration of the pionic–hydrogen system[19]. This result is corroborated by a reduced line width of the $4p-1s$ transition. On the other hand, no evidence for an increase of the line width with density was found even in the liquid phase. From the $3p-1s$ and $4p-1s$ transitions, a save upper limit of can be extracted $\Gamma_{1s} < 0.850\, eV$, which is slightly below the result of[12]. A more refined analysis is going on.

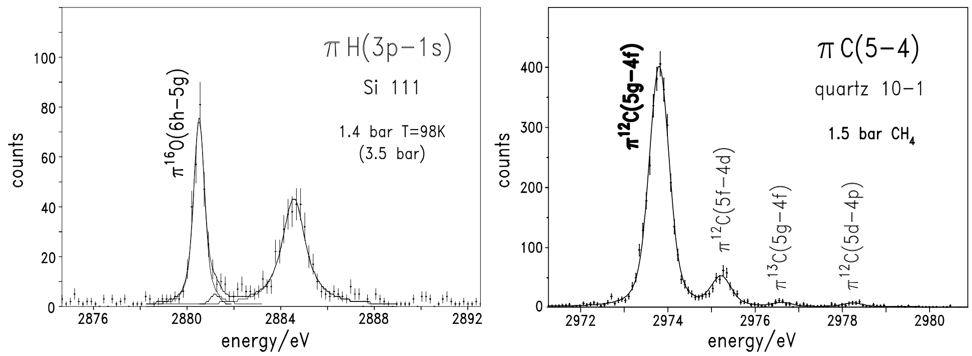


Figure 2: Left: Ground–state transition $3p-1s$ in pionic hydrogen measured simultaneously with the calibration transition $\pi^{16}O(6h-5g)$. Right: Pionic carbon $5-4$ transitions measured with a quartz crystal used to determine the spectrometer response function. A resolution of about 450 meV was achieved.

## 4 Conclusions and Outlook

The preliminary result from this experiment corroborates the value for $\epsilon_{1s}$ found earlier[12]. The previous value for the hadronic width $\Gamma_{1s}$, however, exceeds the upper limit derived from this data indicating that the contributions from Coulomb de–excitation are substantially underestimated.

The forthcoming steps include in a detailed investigation of Bragg crystals by using the PSI ECRIT and of Coulomb de–excitation by measuring muonic hydrogen. The line width in $\mu H$ – after deconvolution of the spectrometer response – will be interpreted in terms of a new dynamical cascade picture involving the velocity of the exotic atom and the results from recent calculations for the cross section of the various collision processes[20].

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