# Pionic Hydrogen: Status and Outlook

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**Abstract.** The measurement of the strong interaction shift and width of the ground state in the pionic hydrogen atom determines two different linear combinations of the two isospin separated s–wave scattering lengths of the pion nucleon system. If both quantities are measured with a precision of about 1% a stringent test of chiral perturbation theory and a determination of the pion nucleon coupling constant can be obtained. Past measurements determined the shift with an accuracy better than 1%, and the width with an accuracy of 9%. Additional information from pionic deuterium measurements has been used in order to extract isospin separated scattering lengths with sufficient accuracy. Future measurements plan to directly measure the width of pionic hydrogen with an accuracy on the level on 1%.

## 1 Introduction

The pion–nucleon interaction has been subject both to experimental and theoretical studies since the very beginning of the development of particle

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physics. On the theoretical side the description of the pion–nucleon system with QCD is considered to be a fundamental issue in the development of this theory. The understanding of strong interaction in the confinement regime has advanced recently, as chiral perturbation theory was developed to perform calculations at low energies [1,2].

Its extension to heavy baryon chiral perturbation theory (HBCHPT)[3] allows to calculate many of the experimentally accessible processes in the meson nucleon sector. The check of the soundness of this approach requires high precision experiments. This resembles the situation in the development of QED during the last 50 years, where the measurement of the Lamb shift contributed much to the development of QED. In a comparable way the measurement of strong interaction shift and width in pionic hydrogen may be a key experiment in strong interaction physics at low energies.

Pionic hydrogen atoms are produced by stopping negatively charged pions in hydrogen gas. At energies of some eV pions ionize the hydrogen molecule and form an electromagnetically bound system, the so-called pionic hydrogen atom. This atom is dominated by the electromagnetic interaction of its constituents. Their strong interaction is only effective if the wave functions of pions and the proton significantly overlap. In the ground state it results in a broadening of $\approx 1\ eV$ and a shift of $\approx 7\ eV$, which has to be compared to an electromagnetic binding energy of $E_{1s} = 3238\ eV$. The relations of the measured quantities to the hadronic scattering lengths $a^h$ describing the $\pi^- p \to \pi^- p$ and the $\pi^- p \to \pi^0 n$ process, respectively, are given by the Deser–type formulae [4,5]:

$$\frac{\epsilon_{1s}}{E_{1s}} = -4\frac{1}{r_B} a^h_{\pi^- p \to \pi^- p}(1 + \delta_\epsilon) \tag{1}$$

$$\frac{\Gamma_{1s}}{E_{1s}} = 8\frac{Q_0}{r_B}(1 + \frac{1}{P})(a^h_{\pi^- p \to \pi^0 p}(1 + \delta_\Gamma))^2 \tag{2}$$

Here $r_B$ is the Bohr radius of the pionic hydrogen atom with $r_B = 222.56$ fm, $Q_0 = 0.142\ fm^{-1}$ is a kinematical factor and P=1.546±0.009 is the Panofsky ratio [6]. $\delta_\epsilon$ and $\delta_\Gamma$ are electromagnetic corrections, which have recently been calculated with a potential model with an accuracy of about 0.5% [7]. In a recent study the problem of the electromagnetic corrections is discussed and the potential model ansatz is critizised [8].

The relations of the measured quantities with the isospin separated scattering lengths $b_0$ (isoscalar) and $b_1$ (isovector) are given by:

$$a^h_{\pi^- p \to \pi^- p} = b_0 - b_1 \tag{3}$$

and

$$a^h_{\pi^- p \to \pi^0 p} = \sqrt{2} b_1 \tag{4}$$

The unique features in using exotic atoms should be recalled:

- Pionic hydrogen is one of the simplest hadronic systems bound electromagnetically. Its electromagnetic binding energies are known with an accuracy of $3 \cdot 10^{-6}$, which is the precision in the mass of the pion [9]. Any deviation caused by strong interaction can therefore be studied with high precision.
- Conventional scattering experiments are restricted to energies higher than ≈10 MeV and have to rely on an extrapolation to zero energy in order to extract the scattering lengths. With exotic atoms, however, linear combinations of the isospin separated scattering lengths are directly measured with extremely high intrinsic accuracy.

The shift and the width of the ground state in pionic hydrogen and deuterium have been determined in a series of experiments of the ETHZ-Neuchâtel-PSI collaboration by measuring the 3–1 transition at 2886 eV with a reflection type crystal spectrometer [10]. An array of 6 cylindrically bent quartz crystals had been used in order to increase the statistics of the experiment. The pions were stopped in a cryogenic target inside a superconducting magnet (cyclotron trap I) and the X–rays were detected with CCD detectors developed at the University of Neuchâtel.

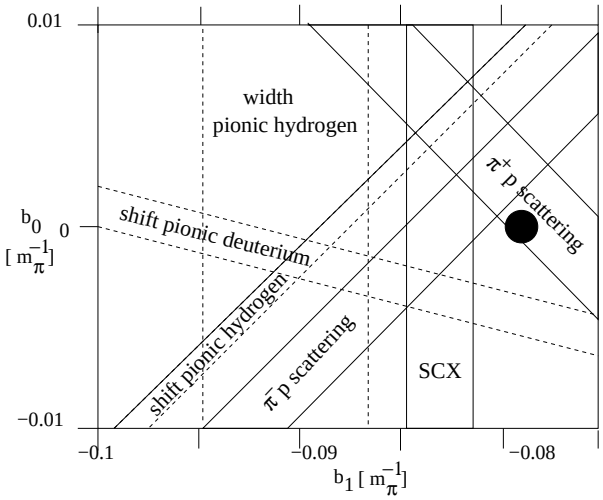


**Fig. 1.** Information on $b_0$ and $b_1$ from scattering experiments and exotic atom data

The results improved the value for the strong interaction shift by almost two orders of magnitude compared to earlier work. In addition first results for the width of the ground state were obtained. The error in the width, however, is still almost an order of magnitude bigger than the one in the shift. This excludes the extraction of the isospin separated scattering lengths with errors

on the %–level from the hydrogen experiment alone. The measurement can be useful, however, to put constraints on the different work in phase shift analysis of the scattering experiments in the pion nucleon system.

An illustration of the most recent evaluations for $b_0$ and $b_1$ from atomic data as well as from scattering data is shown in Figure 1. The data from scattering experiments lead to the bands limited by full lines. They have been obtained by critically investigating the different cross sections for the $\pi^+ p$ (proportional to $b_0 + b_1$), and $\pi^- p$ (proportional to $b_0 - b_1$) and charge exchange processes SCX (proportional to $b_1$) and extrapolating them to zero energy [11]. All three bands from the different linear combinations of $b_0$ and $b_1$ coincide in a narrow region in the $(b_0, b_1)$ plane with corresponding values of about $b_1 = -0.082 m_\pi^{-1}$ and $b_0 = 0.003 m_\pi^{-1}$ each with errors of about $\pm 0.001 m_\pi^{-1}$. As the three different constrains originate from many different sets of experiments, the common intersection can be considered as a quite impressive result. Some criticism was expressed, however, concerning the validity of the model used [12]. It should be mentioned that earlier evaluations of scattering data lead to quite different results [13,14]. Especially the value of $b_0 + b_1$ extracted from the Karlsruhe-Helsinki evaluation with a value of $-0.101 m_\pi^{-1}$ contradicts the evaluation mentioned above which assumes $b_0 + b_1 = -0.077 \pm 0.002 m_\pi^{-1}$

The data from pionic atoms lead to the regions limited by the dashed lines. As stated before the large error in the width measurement precludes an extraction of $b_0$ and $b_1$ with sufficient precision. Moreover the band resulting from the shift measurement alone is at variance with the corresponding $\pi^- p$ scattering data. A recent evaluation of pionic deuterium shift data results in a a small overlapping area if combined with the pionic hydrogen shift data [15]. The results in terms of scattering lengths are $b_0 = -0.0017 \pm 0.001 m_\pi^{-1}$ and $b_1 = -0.09 \pm 0.0012 m_\pi^{-1}$. An evaluation of the ETHZ-PSI-Neuchatel group using earlier theoretical input for the evaluation of the deuterium data resulted in almost the same value for $b_0$ but gave a somewhat different value of $b_1 = -0.0868 \pm 0.0014 m_\pi^{-1}$ [16].

For sake of illustration the dot at $b_0 = 0.0 m_\pi^{-1}$ and $b_1 = -0.079 m_\pi^{-1}$ shows the early current algebra work of Weinberg and Tomozawa [18,19]. A recent HBCHPT calculation to third order expresses the two scattering lengths as a sum of directly calculated values plus terms which are functions of low energy constants [20]. In an evaluation of the low energy constants different authors extract values between $-.01$ and $.006 m_\pi^{-1}$ for $b_0$ and between $-0.083$ and $-0.093 m_\pi^{-1}$ for $b_1$ [21]. A consistent set of experimental data is needed to fix the values for the low energy constants and to check the predictive power of the theory.

A precise measurement of the width is important from a different viewpoint also: it determines the isovector scattering length directly from which a value of the pion nucleon coupling constant can be extracted via the Goldberger-Miyazawa-Oehme sum rule.

In conclusion it can be stated that the results from scattering data and atom experiments are still contradictory and therefore need further investigation. From the side of the atom experiments it should be clarified whether the shift and the width values of pionic hydrogen and deuterium are true strong interaction effects and are not spoiled by the interaction of the pionic atom with the surrounding molecules. In other words the shift and the width measurements for pionic hydrogen and deuterium should be extrapolated to zero pressure. In a second step state of the art electromagnetic corrections should be applied.

## 2 Proposed measurements of the strong interaction shift and width in pionic hydrogen

In a recent proposal to PSI it is planned to determine the ground state width (and shift) from the 2–1 (2433 eV) and the 3-1 (2886 eV) as well as the 4–1 (3042 eV) transitions at 3 different pressures between 3 and 15bar [17]. The planned set-up is shown in Figure 2.

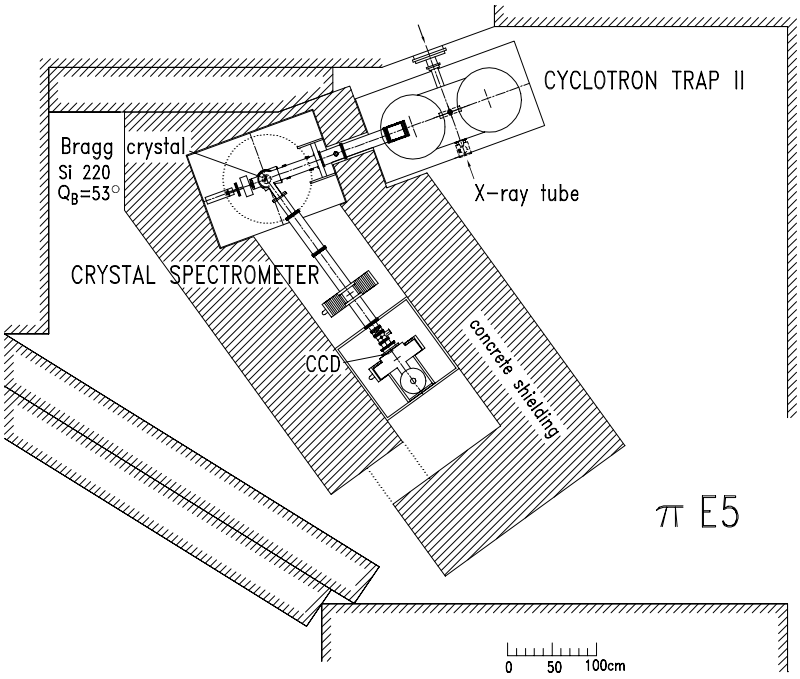


**Fig. 2.** Set-up

At the basis of the experiment are a newly designed cyclotron trap (cyclotron trap II), a single spherically bent crystal (silicon or quartz) and a new CCD detector array. This will result in an improved luminosity for the detection of X–rays together with a better resolution. In addition a much improved shielding is foreseen, which together with the background reduction features of the CCD detector, should lead to a much lower background. Low background is important to extract reliable data for the Lorentzian width of a transition. First experiments with pionic deuterium showed the correctness of the proposed approach [22]. An enhancement in intensity by more than an order of magnitude and a further reduction of background compared to earlier experiments (Figure 3) could be established in spite of the fact that the newly developed CCD detector was not yet in place.

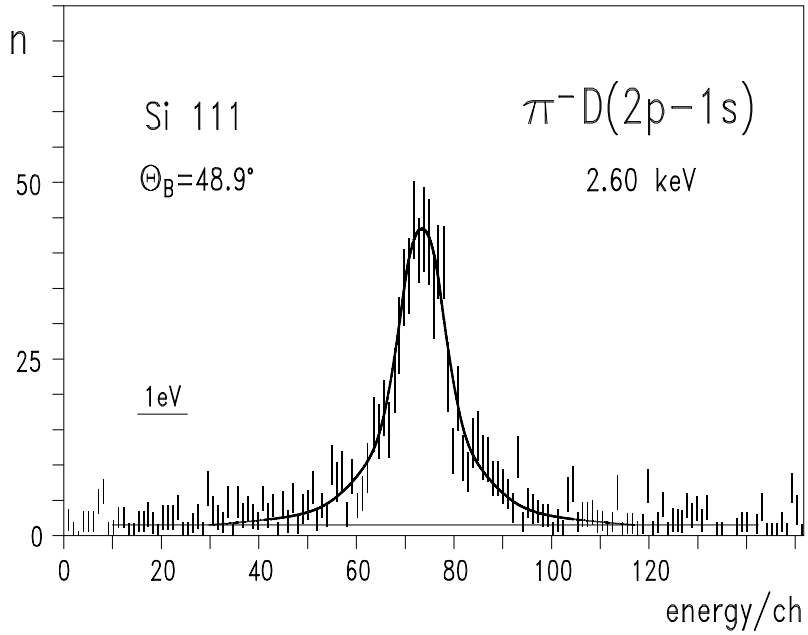


**Fig. 3.** The 2–1 transition in pionic deuterium measured with the Jülich spectrometer and cyclotron trap II

The planned measurements will be able to accumulate an intensity of more than 10000 events per transition enabling a determination of the transition energy with a statistical accuracy of better than 3 meV. For the 3-1 and 4-1 transitions in pionic hydrogen pionic oxygen and carbon transitions adjacent in energy are available as calibration lines, thus avoiding the systematic errors in the former experiment. In a first step the experiment will establish a result for the shift independent of pressure. In order to achieve this the position of

the 3-1 and 4-1 lines will be measured as a function of pressure in the region between 1 and 40 bar. In case of a pressure shift an extrapolation to zero pressure will lead to a reliable value for the strong interaction shift.

The limitation in the determination of the strong interaction width is mainly given by the Doppler effect caused by the so-called Coulomb deexcitation acceleration.

In the first step of the experiment (with the 3-1 and the 4-1 transitions being measured at at least 3 different pressures) the width can be extracted from a simultaneous fit of all transitions, which keeps the different Doppler broadenings free, but leaves the resolution for the different transitions fixed at its known value. In addition the strong interaction width is assumed to be the same for all transitions. With this procedure a common value for the strong interaction width can be extracted with an accuracy of about 2.5%.

The still necessary increase in accuracy requires an additional effort. A simultaneous spectroscopy of pionic and muonic hydrogen atoms is planned as the muonic X–rays do not show any strong interaction broadening, but exhibit Doppler broadening similar to pionic atoms. A method was found to measure pionic and muonic X–rays simultaneously. The reduced masses of pionic and muonic hydrogen exhibit almost the same ratio as two lattice plane differences of quartz. With a two crystal set up the pionic and muonic X–rays can be Bragg reflected to the same CCD detector.

A computer simulation of the muonic 2–1 transition is shown in Figure 4. It comprises 20000 measured muonic X–rays which corresponds to a measuring time of 2 weeks at a pressure of 15 bar. The line is broadened by Doppler effect gained from converting the transition energies of the 4-3 and the 3-2 transitions into kinetic energies via the Coulomb deexcitation process. The corresponding distribution of the kinetic energies had been calculated with a modern cascade program. A resolution of 220 meV is assumed for a quartz crystal and a statistically populated hyperfine splitting of 180 meV is taken into account. The peak to background ratio corresponds to recent experience.

Recent experiments determined the velocity state of the pionic hydrogen atom at the moment of the charge exchange reaction [23]. These results constrain the input parameters for the cascade calculations as well as the direct X–ray measurements from muonic hydrogen. The results of the cascade calculations can then be used to correct for the influence of the Doppler broadening.

### 2.1 Calibration procedures

A successful X–ray spectroscopy of the quality required for the pionic hydrogen experiment is based on a narrow and well understood response function of the crystals. An energy calibration or an optimization can not be achieved with fluorescence X–rays produced with X–ray tubes. Their width is an order of magnitude broader than the resolution of the crystals. The line shape is moreover influenced by poorly determined satellite lines.

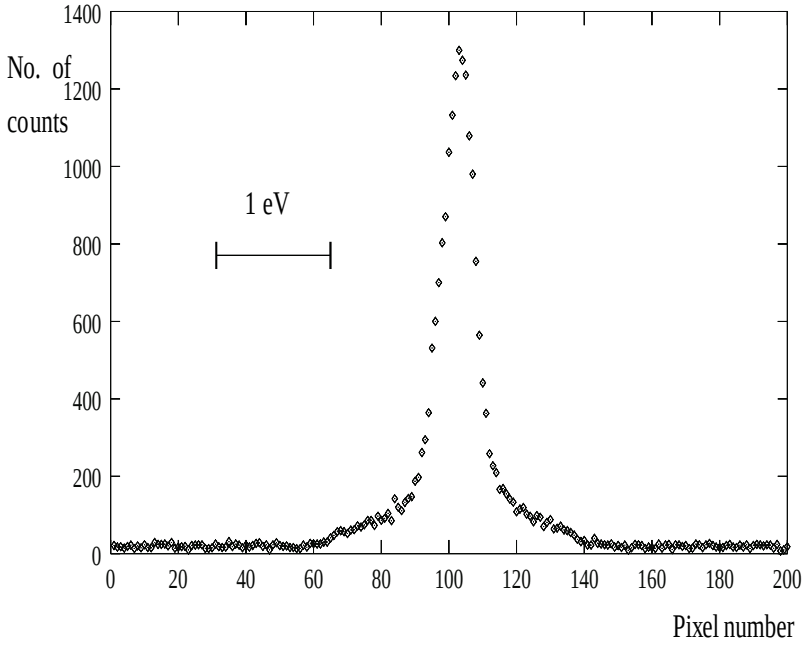


**Fig. 4.** A simulation of the 2–1 transition in muonic hydrogen. The structure of the line reflects the different contributions from Coulomb deexcitation processes

There are about 10 useful pionic X–ray transitions in the energy region between 2 and 3 keV available from low Z gases. Their rates, however, are not sufficient to do a time consuming optimization of the crystal resolution. A solution of this problem is the production of X–rays from one- or two–electron atoms. They can be delivered copiously by electron cyclotron resonance (ECR) sources, which have been developed as ion sources for accelerators. The line width of the X–rays is determined almost exclusively by a very much reduced Doppler effect which leads to negligible broadenings compared to the intrinsic resolution of the crystals. Presently such a source is being set up at PSI. It is planned to test it first with Si crystals which have been studied extensively during recent years. In a second step the response function of quartz crystals will be optimized and fluorescence sources will be calibrated. During the measurement with pions and muons the crystals can then be routinely surveyed with pionic X–rays which in turn can be used to energy calibrate the ECR measurement on the ppm level.

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