Measurement of the ground-state shift and width in pionic hydrogen to the 1% level: A new proposal at PSI

D. Gotta

Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

Abstract

In the non-perturbative regime of QCD, the pion-nucleon s-wave scattering lengths play a decisive role. They are accessible by measuring the level shift and broadening of the ground-state in pionic hydrogen and deuterium atoms. To pin down the inconsistencies arising from the analysis of the present data, an improvement on the accuracy of the hadronic broadening by almost an order of magnitude is highly desirable, which is the aim of an experiment being set-up at PSI.

In the framework of Chiral Perturbation Theory (ChPT) [1,2], a quantitative description of the low-energy pion-nucleon interaction became possible. The two basic parameters at threshold, the πN isoscalar and isovector s-wave scattering lengths a^+ and a^-, are given in terms of the elastic reactions by

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

Furthermore, from dispersion relation theory a^- is connected to the πN coupling constant $f^2_{\pi N}$ by the Goldberger-Miyazawa-Oehme (GMO) sum rule [3]

$$(1+\frac{m_\pi}{M_N})\frac{a^-}{m_\pi} = \frac{2f^2_{\pi N}}{m^2_\pi-(m^2_\pi/2M_N)^2} + \frac{1}{2\pi^2}\int_0^\infty \frac{\sigma^{tot}_{\pi^-p}(k_\pi)-\sigma^{tot}_{\pi^+p}(k_\pi)}{\omega(k_\pi)}dk_\pi. \tag{2}$$

At present, the integral is known with an accuracy of 1% [4].

From the isospin decomposition follows $a_{\pi^-p\to\pi^-p} = (a^+ + a^-)$ and $a_{\pi^-p\to\pi^0n} = -\sqrt{2}\,a^-$. Hence, a^+ and a^- are directly related to the hadronic shift ϵ_{1s} and level broadening Γ_{1s} of the atomic ground state in the pionic hydrogen [5,6].

$$\frac{\epsilon_{1s}}{E_{1s}} = -\frac{4}{r_B}\,a_{\pi^-p\to\pi^-p}(1+\delta_\epsilon) \tag{3}$$

$$\frac{\Gamma_{1s}}{E_{1s}} = 8\frac{q_0}{r_B}(1+\frac{1}{P})(a_{\pi^-p\to\pi^0n}(1+\delta_\Gamma))^2. \tag{4}$$

E_{1s} is the electromagnetic binding energy of the atomic ground state for a point nucleus, $q_0 = 0.1421 fm^{-1}$ the CMS momentum of the π^0 in the charge exchange reaction $\pi^-p \to \pi^0n$, and r_B the Bohr radius of the πH atom. To obtain the pure hadronic scattering lengths, electromagnetic corrections $\delta_{\epsilon,\Gamma}$ of the order of a few percent must be taken into account [6,7]. A general discussion on the accuracy of electromagnetic corrections is presently going on [8]. A precise value for the branching ratio of charge exchange and radiative capture, the Panofsky ratio P is also required. The experimental value is $P = 1.546 \pm 0.009$ [9].

The shift and width of the 1s ground state of the pionic atom are determined from the spectroscopy of the Lyman X-ray transitions, which are the last deexcitation step of the atomic cascade. For intensity reasons, only the three low-lying transitions $K\alpha$, $K\beta$, and $K\gamma$ were considered. X-ray energies of 2–3 keV and the smallness of ϵ_{1s} and Γ_{1s} required the use of a reflection-type crystal spectrometer. In order to obtain sufficiently high X-ray yields, the cyclotron trap is necessary to stop the pion beam in a gaseous target. As X-ray detectors, only Charge-Coupled Devices (CCDs) fulfill the requirements of both good position resolution and efficient background suppression. The recent experiments for πH [10–12] and πD [13,14] achieved a precision of the order of 1% for ϵ_{1s} and 10% for Γ_{1s} (Table 1). The results for a^+ and a^- are shown in Fig. 1.

Table 1. Transitions from pionic hydrogen and deuterium used for the most recent determinations of ϵ_{1s} and Γ_{1s}. In the second column, the pure electromagnetic energy values are given. A positive /negative) sign for ϵ_{1s} stands for an attractive (repulsiv) interaction. The method of energy calibration (en.c.) and determination of the spectrometer resolution function (res.f.) is indicated.

transition	energy /eV	ϵ_{1s} /eV	Γ_{1s} /eV	p /bar	calibration en.c./resp.f.	ref.
$\pi H(3p-1s)$	2878.808	$+7.108 \pm 0.036$	0.865 ± 0.069	15	Ar $K\alpha/\pi Be(4-3)$	[11,12]
$\pi D(3p-1s)$	3077.95	-2.43 ± 0.10	1.02 ± 0.21	15	Ar $K\alpha/\pi Be(4-3)$	[13]
$\pi D(2p-1s)$	2695.527	-2.469 ± 0.055	1.093 ± 0.129	2.5	Cl $K\alpha/\pi Ne(7-6)$	[14]

In the πD system, the hadronic shift ϵ_{1s} is in leading order proportional to the (small) isoscalar scattering length a^+ because of an almost cancellation of the $\pi^- p$ and $\pi^- n$ contributions. Hence, the analysis faces the problem, that the next to leading order (double scattering) is proportional to the square of the (large) isovector scattering length a^-. These higher order contributions (SS+DS+HC) and in addition absorption corrections (AB) are almost one order of magnitude larger than the isoscalar scattering length a^+ itself.

$$\Re a_{\pi d} = 4\frac{M_N + m_\pi}{2M_N + m_\pi} a^+ + (SS + DS + HC) + AB \tag{5}$$

Considerable discrepancies occur in the determination of a^+ from $\epsilon_{1s}^{\pi d}$ (Table 1). Whereas the two experiments are in good agreement [13,14], the values obtained for a^+ in the approaches of [15] and [16] differ by several standard deviations (bands denoted TL'80 and BBLM'98 in Fig. 1). The results of [19] and [20] lie in between these two extreme values. The uncertainty of a^+, applying the corrections of [15], is dominated by the uncertainty of the corrections and not by the accuracy of the experiments, the error of which corresponds to the widths of the bands denoted BBLM'98. Because of such large uncertainties for the multiple-scattering corrections, Coulomb corrections to the Deser formula (3) have been omitted up to now for πD.

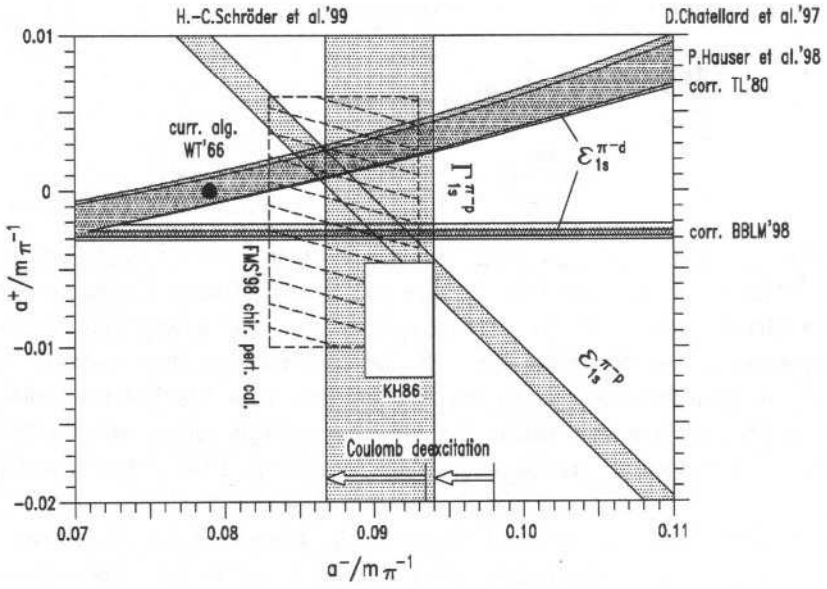

Figure. 1. Isoscalar and isovector πN scattering lengths a^+ and a^-. The bands labeled $\epsilon^{\pi p}$ and $\Gamma^{\pi p}$ show the results from the recent πH experiments [11,12]. The correction for the Doppler broadening due to Coulomb deexcitation is indicated by the two arrows. The value derived from current algebra (WT66) [1] corresponds to the leading order in ChPT, in which a^+ vanishes. The rectangle FMS is the result of an up to third order calculation [17] and the rectangle KH86 is obtained from a phase-shift analysis [18]. The bands labeled $\epsilon^{\pi d}$ were obtained from the results of [13,14] for the 1s level shift in πD according to [15] (TL'80) or [16] (BBLM'98).

In view of the significant discrepancies, even a combined analysis of the πH and πD data will not yield precise values for a^+ and a^- despite the small experimental errors for ϵ_{1s} (see [12]). Also, an identification of strong isospin violation in the πN system, which is expected to amount to 1–2% [21], seems to be difficult. Figure 1 demonstrates, that the accuracy of an unambiguous determination depends practically on the error of Γ_{1s}. In the same way, the accuracy of $f^2_{\pi N}$ determined from the GMO sum rule is mainly determined by Γ_{1s}. The values for $f^2_{\pi N}$, as derived from πN scattering data, phase shift analysis, photo production, radiative capture and the πH atom scatters up to 10% [22], which is regarded to be unsatisfactory for such a basic quantity.

Two major problems exist for a substantial improvement of the accuracy of Γ_{1s}.

- An accurate determination of the resolution function of the crystal spectrometer is essential. Because of the large Auger widths of fluorescence X-rays, the response function had been determined up to now only from pionic X-ray spectra of limited statistics.

- In exotic hydrogen atoms, Auger and X-ray emission compete with Coulomb deexcitation, where the deexciation energy is transferred into kinetic energy during collisions with neighbouring target molecules. This leads to a Doppler broadening of the X-ray lines. At present, the uncertainty of the correction due to Coulomb deexcitation dominates the error of Γ_{1s} as determined from the $\pi H(3p-1s)$ transition[11,12].

The strategy of the experiment being set-up at PSI [23], aiming at an accuracy of 1% for Γ_{1s}, is based on new techniques in the determination of the response function. Besides that, new insights in the atomic cascade will play a decisive role.

- In order to allow for an thorough investigation of the reflection properties of the Bragg crystals, a Electron-Cyclotron-Resonance (ECR) source is being set-up inside the new cyclotron trap [14]. This will allow to produce hydrogen-like electronic atoms, which have natural line widths of a few tens of meV only. The Doppler broadening from the temperature in the ECR source is expected not to exceed 100 meV. In this way, the crystal tests can be performed without time-consuming measurements at the secondary beam lines at PSI. This first step of the experiment will result in an accuracy of 2–3% for Γ_{1s}.

- By measuring the pressure dependence of the line shape of Lyman transitions from muonic hydrogen, the Coulomb deexcitation will be studied without the influence of the strong interaction. Using a cryogenic gas target, measurements in the pressure range of 1–40 bar are planned. Additional information on Coulomb deexcitation comes from time-of-flight measurements of neutrons stemming from the charge-exchange reaction $\pi^- p \rightarrow \pi^0 n$ at rest [24]. The structures of the time-of-flight distribution were found to correspond to deexcitation steps in the atomic cascade.

  The results will serve to set-up an improved cascade code, which takes into account the velocity distribution at all stages of the deexcitation [25]. The parameters fixed in that way will be used to model the cascade of pionic hydrogen. Monte-Carlo simulations show, that a knowledge on the 10% level for the Doppler contributions is sufficient to achieve the final goal for an accuracy of 1% for Γ_{1s} [23].

A test measurement has been performed at the $\pi E5$ channel of the PSI in order to investigate count-rate and background conditions. $\pi D(2p-1s)$ and $\pi Ne(7-6)$ transitions were measured by using the new cyclotron trap and a crystal spectrometer equipped with a spherically bent Si 111 crystal [14]. Results from this experiment are included in Fig. 1 ($\epsilon^{\pi D}$ – narrower bands).

By using the new cyclotron trap and a spherically bent Si crystal, the X-ray count rate increased by almost an order of magnitude. A massive concrete shielding improved the peak-to-background ratio by a factor of about 6. It is worthwile to mention that the total measuring time including the detection of the πNe response function amounted to

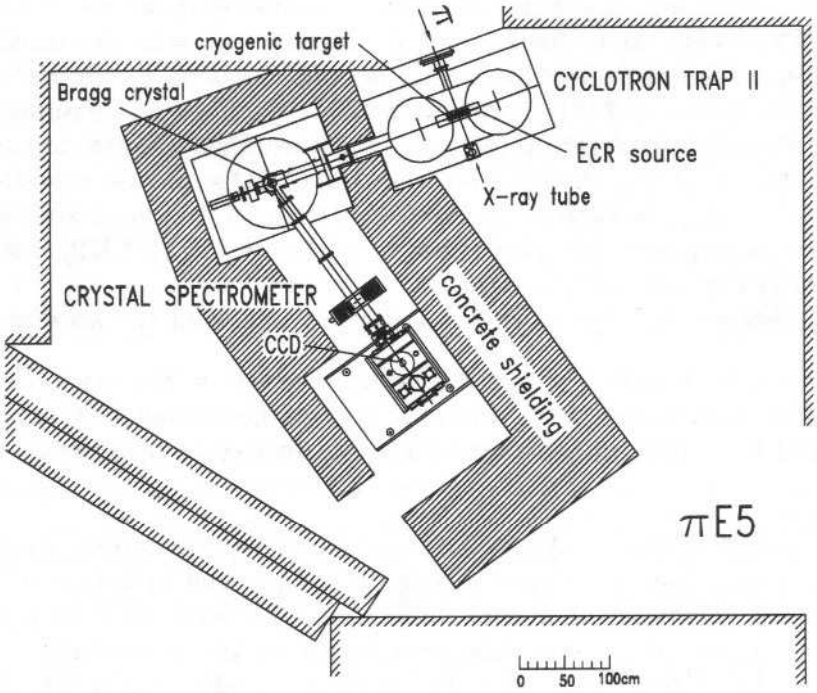

Figure. 2. Set-up of the pionic hydrogen experiment being set-up at PSI.

one day only and yielded a better result than a 9 days measurement during the previous experiments. A new large-area CCD will complete the spectrometer [26]. The set-up of the ECR source and the first measurements at the pion beam are planned for the end of the year 2000.

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