The pionic hydrogen experiment at PSI

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The measurement of the strong–interaction effects in pionic hydrogen gives access to fundamental properties of the pion–nucleon interaction. Methods developed within the framework of Heavy–Baryon Chiral Perturbation Theory allow calculations with an accuracy of a few per cent, which should be tested by experiment.

Techniques advanced for recent experiments on the precision spectroscopy of X–rays from antiprotonic and pionic atoms will be used in a new series of measurements for pionic hydrogen. The aim is to achieve finally an accuracy of 0.2% for the hadronic shift ϵ_{1s} and most important of about 1% for the broadening Γ_{1s}.

An essential part of the experimental program is an improved understanding of the atomic cascade. At first, the value of ϵ_{1s} has to be proven not to be influenced by molecular formation. Secondly, a more accurate determination of Γ_{1s} requires a detailed study of Coulomb deexcitation.

Keywords: exotic atoms, pionic hydrogen, pion–nucleon interaction, cascade

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1. Introduction

The investigation of the pion–nucleon system experiences continuous interest since decades. Processes involving the pion, being the lightest meson, exhibit symmetry properties of the underlying interaction described nowadays in the framework of quantum chromodynamics.

Neglecting isospin–breaking effects, the s–wave pion–nucleon interaction at threshold is completely determined by two independent scattering lengths, e. g., the isoscalar and the isovector amplitudes a^+ and a^-, which may be expressed in terms of the experimentally accessible elastic channels [1].

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

If isospin conservation is strictly valid, the elastic channels are related to charge exchange by

$$a_{\pi^- p\to\pi^- p} - a_{\pi^+ p\to\pi^+ p} = -\sqrt{2}\,a_{\pi^- p\to\pi^0 n}, \quad (2)$$

and all other elastic or charge–exchange πN reaction channels at threshold can be written as linear combinations of a^+ and a^-.

The leading order result for a^+ and a^- derived from current algebra [2] revealed already an important feature of the underlying symmetry. The symmetric combination a^+ vanishes in the chiral limit, i. e, in the limit of vanishing pion mass.

$$a^+ = 0 \quad (3)$$

$$a^- = -\,0.079/m_\pi \quad (4)$$

When higher orders are taken into account as calculated from Heavy–Baryon Chiral Perturbation Theory (HBχPT), a^+ remains small and also the value of a^- is still close to the one obtained in the chiral limit (Fig. 1).

The relation between exotic–atom parameters and scattering lengths is given by Deser–type formulas [3–5], where $q_0 = 0.1421 fm^{-1}$ is the CMS momentum of the π^0 in the charge–exchange reaction $\pi^- p \to \pi^0 n$. The Panofsky ratio $P = 1.546 \pm 0.009$ [6] is the branching ratio of charge exchange and radiative capture. B_{1s} and r_B denote binding energy and Bohr radius of the atomic system.

$$\frac{\epsilon_{1s}}{B_{1s}} = -\frac{4}{r_B}\;a_{\pi^- p\to\pi^- p}(1+\delta_\epsilon) \quad (5)$$

$$\frac{\Gamma_{1s}}{B_{1s}} = 8\frac{q_0}{r_B}(1+\frac{1}{P})[a_{\pi^- p\to\pi^0 n}(1+\delta_\Gamma)]^2, \quad (6)$$

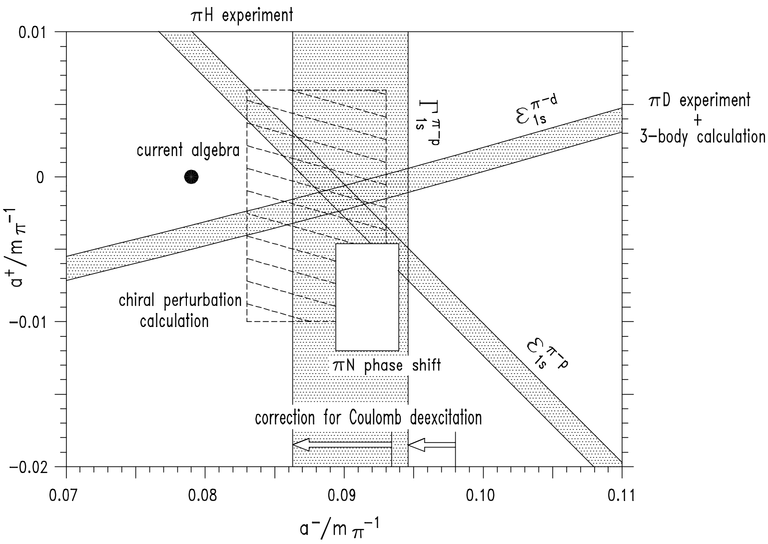

Figure 1. Isoscalar and isovector πN scattering lengths a^+ and a^-. The bands labeled $\epsilon^{\pi p}$ and $\Gamma^{\pi p}$ show the results derived from the previous πH experiment using the (3p–1s) transition [7]. The correction for the Doppler broadening due to Coulomb deexcitation is indicated by the two arrows. The band labeled $\epsilon^{\pi d}$ is obtained from the πD(2p–1s) transition [8] corrected for 3–body effects according to [9]. The dot marks the leading order given by current algebra [2] and the dashed rectangle the range resulting from a third order HBχPT calculation [10]. The solid rectangle is based on the Karlsruhe–Helsinki πN phase–shift analysis [11].

Disregarding for the moment the correction terms $\delta_{\epsilon,\Gamma}$, the relation between the strong–interaction effects in pionic hydrogen and the scattering lengths are directly given by $\epsilon_{1s} \propto a^+ + a^-$ and, assuming isospin invariance, $\Gamma_{1s} \propto (a^-)^2$. Consequently, the precise determination of both the ground–state shift and the width is mandatory for the extraction of the two scattering lengths. Furthermore, from Γ_{1s}, the pion–nucleon coupling constant is obtained by the Goldberger–Miyazaw–Oehme sum rule [9,12].

The correction terms $\delta_{\epsilon,\Gamma}$ take into account higher orders of the chiral expansion and include the electromagnetic and isospin breaking effects. HBχPT, being an effective field theory, involves so–called low–energy constants (LECs) to be derived from experiment, which are not all known at the same level of precision. Second order terms for the shift ϵ_{1s} contain the three LECs c_1, f_1, and f_2, where in the case of the width Γ_{1s}, the problematic LEC f_1 does not appear [5]. As seen from Fig. 1, Γ_{1s} is the most important quantity to be measured for an improved sensitivity to the various approaches.

Table 1
Most recent results of strong–interaction effects in pionic hydrogen and deuterium. E_{QED} represents the pure electromagnetic transition energy. The $\pi^- p$ interaction is attractive. In the $\pi^- d$ case the interaction is repulsive.

transition	E_{QED} /eV	ϵ_{1s} /eV	Γ_{1s} /eV	p /bar	ref.
$\pi H(3p-1s)$	2878.808	$+7.108 \pm 0.036$	0.865 ± 0.069	15	[7]
		$+7.080 \pm 0.035$		3	[13]
$\pi D(3p-1s)$	3077.95	-2.43 ± 0.10	1.02 ± 0.21	15	[14]
$\pi D(2p-1s)$	2695.527	-2.469 ± 0.055	1.093 ± 0.129	2.5	[8]

At some level, isospin breaking effects must occur because of the electromagnetic interaction, and more important because of the inequality of the masses of the u and d quark. In the framework HBχPT the treatment of electromagnetic and strong isospin–breaking effects are possible on the same footing. Their size is expected to be of the order of a few % and the identification may become possible when data beyond that accuracy are available.

A series of precision experiments has been performed in the past yielding an impressive increase of knowledge (Fig. 1 and Table 1). The improved flux at the pion channels at the Paul–Scherrer–Institut (PSI) as well as the use of a particle concentrator – the cyclotron trap – and modern X–ray detectors like Charge–Coupled Devices (CCDs) allow the efficient use of high–resolution crystal spectrometers.

2. Atomic cascade and strong–interaction effects

A further increase in precision requires a careful reinvestigation of the atomic cascade. Though experiments have been performed in gaseous targets, the interaction of pionic–hydrogen atoms with the environment affects the line widths and may affect the X–ray transition energies. Hence, an essential part of the experimental program is an improved understanding of collision and deexcitation processes within the duration of the atomic cascade. Two mechanisms will be considered in detail:

- Molecular complexes like $(\pi p)_{nl} + H_2 \rightarrow [(\pi pp)_{nj\upsilon}p]_{K\nu}ee$ may be formed during the collision of excited pionic hydrogen with H_2 molecules. The binding energy of a few eV and less is absorbed in rotation and vibration degrees of freedom denoted by the quantum numbers njv for the 3–body system πpp [15]. The existence of such complexes is well known in muon–catalyzed fusion [16]. Recently it was found, that a significant fraction of μH atoms in the 2s metastable state decay by that channel [17]. Radiative decays of pionic hydrogen being part of the molecular complex lead to reduced X–ray transition energies, which then falsify the value extracted for the ground–state shift.

- During collisions radiationless so–called Coulomb deexcitation occurs. Here, the deexcitation energy $(\pi p)_{nl} \rightarrow (\pi p)_{n'l'}$ is transformed into kinetic energy of the collision partners, which leads to Doppler broadening of X–ray lines from subsequent transitions. Coulomb deexcitation shows up in the time–of–flight distribution of neutrons from the charge exchange reaction $\pi^- p \rightarrow \pi^0 n$ [18]. Discrete Doppler contributions of several radiationless transitions $n \rightarrow n'$ were identified. Energies up to 200 eV, which corresponds to the 3–2 transition, have been seen both in liquid hydrogen and at a pressure of 40 bar [19].

3. Experimental approach

To provide an intense X–ray source for a reflection–type crystal spectrometer, the cyclotron trap [20] is used to stop pions of the πE5 channel at PSI in a gas cell (Fig. 2). Muons are obtained from the decay of slow pions inside the trap. X–rays emitted from the stop volume are reflected by spherically bent silicon or quartz crystals of up to 10 cm diameter. A large–area X–ray detector built up of 6 Charge–Coupled Devices (CCDs) enables the simultaneous measurement of X–ray transitions close in energy [22].

First goal of the new experiment is to establish a value for ϵ_{1s} independent of pressure. The measurement will prove or disprove an influence of molecular formation on the decay branches involving the πH Lyman transitions. The pressure dependence will be measured by using a cryogenic target in the density range from 3 bar equivalent up to liquid. The decrease of X–ray line yields due to the increasing Stark mixing is at least compensated by the higher stop efficiency of the cyclotron trap for the more dense targets.

The most difficult part is the precise determination of the hadronic broadening. It requires a better knowledge of the Coulomb deexcitation cross section. A detailed investigation of this process will be performed with muonic hydrogen which does not show hadronic effects. The information will be interpreted in terms of a new dynamical cascade picture [21] involving the velocity of the exotic

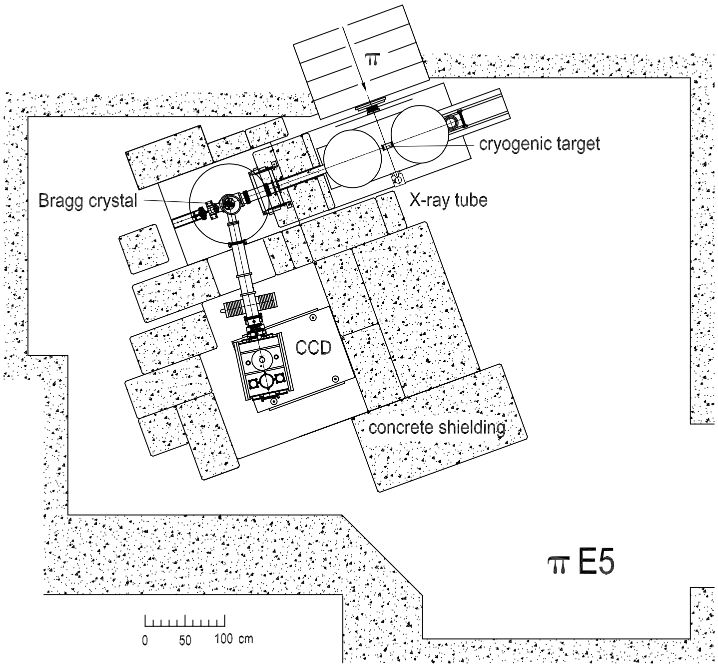

Figure 2. Set–up of the pionic hydrogen experiment at PSI.

atom and the results from recent calculations for the cross section of the various collision processes [23]. Additional constraints for the new cascade picture are provided by the results of the neutron time–of–flight measurements.

The detailed study of the line shapes of pionic and muonic hydrogen requires the knowledge of the crystal spectrometer response at a higher level than available up–to–now. In the few keV range, narrow lines for testing the curved Bragg crystals are not available for practical cases. Fluorescence X–rays have large line widths owing to Auger transitions and, so much the worse, exhibit complicated satellite structures caused by multiple–hole excitation. Therefore, an absolute energy determination is usually limited to a few ppm as, e. g., achieved for the πD pre–experiment with chlorine [8]. The response function, however, had to be obtained from a narrow πNe transition (Fig. 3: top).

Narrow X–ray transitions emerge from exotic atoms formed with noble gases (Fig. 3: middle). Also atoms formed from those systems can be used, where the molecular composition excludes a significant Doppler broadening due to Coulomb explosion [24]. However, the limited rates even at the high–flux pion channels lead to unacceptable long measuring times for detailed crystal studies.

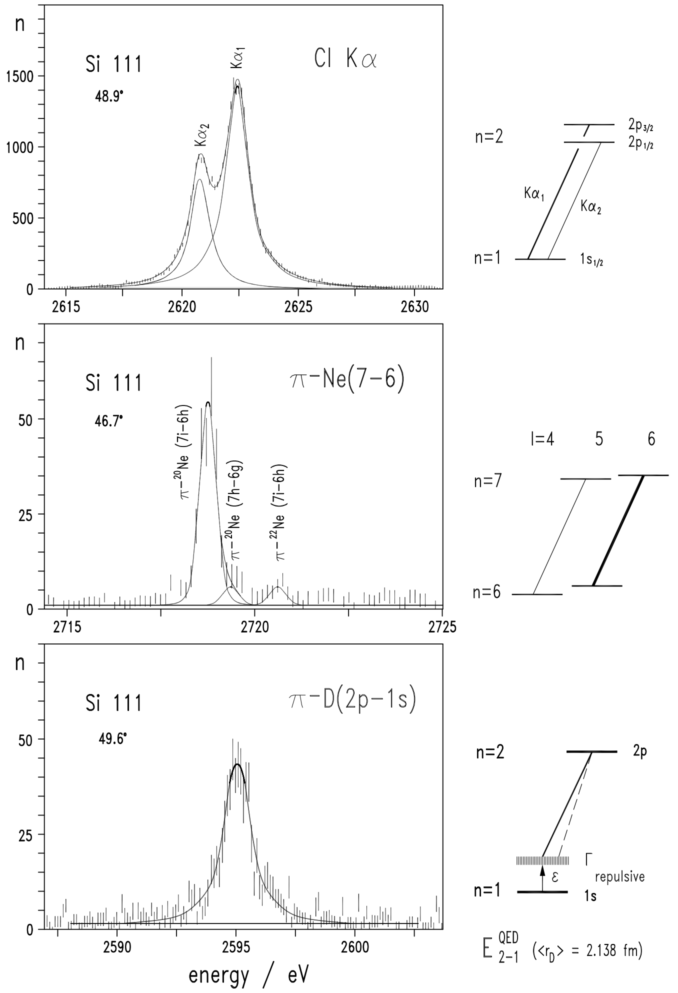

Figure 3. Results from the pre–experiment with pionic deuterium. The Cl Kα_1 fluorescence line was used for energy calibration. The response function of the crystal spectrometer was obtained from the narrow π^{20}Ne(7i–6h) transition.

For that reason, an Electron–Cyclotron–Resonance (ECR) source is being set up. It will be used to produce hydrogen– or helium–like electronic atoms, of which the fluorescence lines are narrow enough for thorough studies of the Bragg crystals without the use of a particle accelerator. The temperature of the plasma is expected not to exceed an equivalent of about 40 meV line width [25]. The magnet of the cyclotron trap itself will be used to provide the mirror field for the plasma [26].

4. First results

Charged pion mass. Up to now, the uncertainty of the charged pion mass contributes with 25% to the systematic error of the level shift ϵ_{1s}. Therefore, as a first step, the pion mass was remeasured with improved precision by comparing the wave length of the πN(5g–4f) transition to the one of the Cu Kα_1 line [27]. The accuracy achieved of about 4ppm is mostly limited by the line shape of the fluorescence line.

As a next step, the πN(5g–4f) transition was measured simultaneously with the μO(5g–4f) line (Fig. 4), which provides a more accurate energy calibration because of the well known mass of the muon ($\Delta m_\mu / m_\mu$ = 0.05ppm [28]). This method is basically free of systematic errors due to long–term instability. The analysis is in progress and an accuracy of about 1ppm for m_π is expected [29].

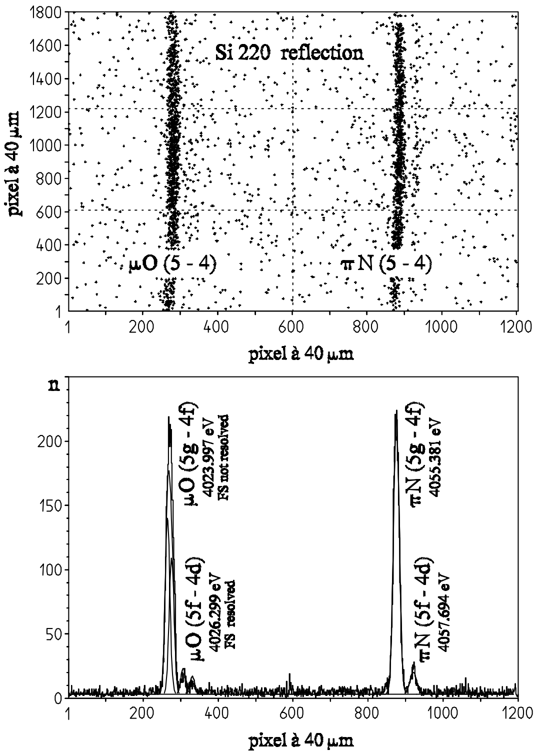

Figure 4. Simultaneously measured reflections of the πN and the μO (5–4) transitions to determine the charged pion mass by using a N_2/O_2 gas mixture of 5%/95% at 1.4 bar. (Top: Horizontal and vertical detector dimensions are not in scale.)

Pionic hydrogen and deuterium. In the πD pre–experiment, a significant improvement for the peak–to–background ratio was achieved with a sophisticated concrete shielding compared to earlier experiments (Fig. 3: bottom). The low background level is essential to be sensitive to the high–energy tails originating from Coulomb deexcitation.

The method of simultaneous measurement of a calibration line can be applied also in the case of pionic hydrogen at not too low temperatures. An initial measurement at the πE5 high–intensity pion channel of the Paul–Scherrer–Institut (PSI) was performed at a density equivalent to 3.5 bar by using a H_2/O_2 gas mixture (98%/2%) in order to achieve similar rates for the πO(6h–5g) calibration line and the πH(3p–1s) transition (Fig. 5). The precision for the shift ϵ_{1s} of a two–day measurement reaches already the one of the previous experiment (Tab. 1).

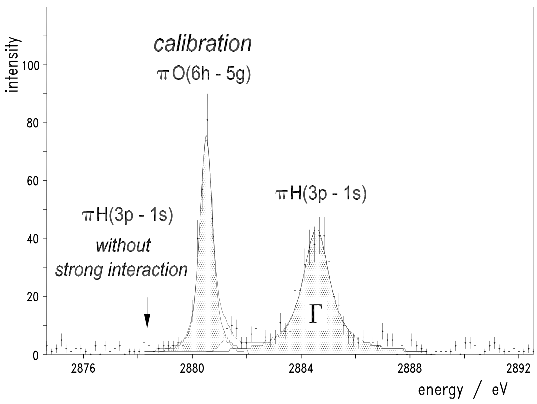

Figure 5. Simultaneously measured reflections of the πH(3p–1s) and the π^{16}O(6–5) transitions.

5. Outlook

The πD pre–experiment and the first results obtained for πH with the new set–up show, that stability for long–term measurements and background conditions are well controlled. Results for the stability of the shift ϵ_{1s} will be available in about one year from now and followed by the investigation of the crystal properties with narrow electronic lines from few electron systems. In about two years from now, the studies of muonic hydrogen and subsequently the high–statistics measurements for the hadronic width Γ_{1s} will be performed.

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