Precision Studies on Strong Interaction in Pionic Hydrogen

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The goal of the research program of the Pionic Hydrogen Collaboration at the Paul Scherrer Institute is a precise determination of the shift and width of the pionic hydrogen ground state induced by strong interaction. A crystal spectrometer is used to measure the X-ray transitions to the ground state in order to extract the strong interaction shift and width with a precision of ∼0.2% and ∼1% respectively. The improvement in the precision of the width will amount to almost an order of magnitude compared to the most precise former experiment. The isospin-dependent pion-nucleon scattering lengths can be determined from the shift and width.

The high intensity pion beam available at PSI and a cyclotron trap provide optimal experimental conditions. For determining the resolution function of the crystal spectrometer the Bragg crystals are characterized using the high intensity X-rays from He-like ions produced in an electron cyclotron resonance ion trap.

Measurements of X-ray transitions in muonic hydrogen - an exotic atom without strong interaction - were performed to study the effect of Doppler broadening due to Coulomb transition within the electromagnetic cascade which is an important systematic effect in pionic hydrogen and has to be understood in detail. This will allow the determination of the strong interaction width with unsurpassed accuracy, thus resulting in a precise value of the isovector pion-nucleon scattering length.

The present status of the experiment and the preliminary results on the strong interaction shift and width are presented.

1. INTRODUCTION

An ambitious experimental program at the Paul Scherrer Institute (PSI) [1] aims at the study of the strong interaction in the pionic hydrogen atom with unprecedented precision. Hadronic atoms like pionic hydrogen are very valuable tools for precision studies of low-energy strong interaction [2]. The strong interaction pion-nucleon manifests in the shift ϵ_{1s} and the width Γ_{1s} of the pionic hydrogen 1s atomic ground state. The principal interaction in the pionic hydrogen atom is electromagnetic resulting in a binding energy E_{1s}=3238 eV and in the transition energies $E^{e.m.}_{np\rightarrow 1s}$=2429, 2878 and 3036 eV for n=1,2 and 3 respectively. The electromagnetic transition energies can be obtained with QED calculations with very high precision at the level of meV [3]. Since the p states are negligibly affected by strong interaction the measurement of the transition energy e.g.

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$E^{e.m.+strong}_{3p\rightarrow 1s}$ is giving consequently ϵ_{1s}=$E^{e.m.+strong}_{3p\rightarrow 1s}$ - $E^{e.m.}_{3p\rightarrow 1s}$. Some complications arise from the fact that the pionic hydrogen atoms are not isolated systems and therefore systematic effects for the shift and the width originating from the surrounding gas have to be studied precisely. Theoretical studies predict the existence of molecular effects which might lead to a modified transition energy. On the other hand Doppler broadening of the X-ray emission line occurs due to the acceleration of πp atoms in Coulomb transitions during the electromagnetic cascade.

$$(\pi p)_n + p \longrightarrow (\pi p)_{n'} + p + E_{kin} \qquad (1)$$

In this process the transition energy is transferred to the kinetic energies of the partners. Furthermore, in the past experiments the limited knowledge of the response function of the detection system and relatively high background hindered the precise determination of Γ_{1s}.

Why is the precise determination of ϵ_{1s} and Γ_{1s} extremely important for strong interaction physics and therefore for low-energy QCD as the theory of strong interaction in these systems? It is well known that by applying Deser-type formulae [4,5] the isospin-dependent pion-nucleon scattering lengths a^+ and a^- can be extracted since ($\epsilon_{1s} \propto$ (a^++a^-) and $\Gamma_{1s} \propto$ (a^-)^2). However, electromagnetic corrections to these formulae have to be taken into account, where the correction for the shift is according to recent theory remarkably large with ∼40% error (δ_ϵ=(-7.2 ± 2.9) 10^{-2} [6]. On the other hand the correction for the width (δ_Γ=(0.6 ± 0.2) 10^{-2} [7] represents only a small contribution. The crucial point of this experiment is the precise determination of Γ_{1s} because from this quantity alone the isovector scattering length can be determined with high precision and using the Goldberger-Miyazawa-Oehme sum rule [8] the pion-nucleon coupling constant $f_{\pi N}$ as well as the Goldberger-Treiman discrepancy - an important information on chiral symmetry breaking - can be determined with unsurpassed accuracy. Another information on chiral symmetry breaking provides the pion-nucleon sigma term which can be derived from the small isoscalar scattering length a^+ where the accuracy is limited by δ_ϵ. The scattering lengths extracted from the pionic hydrogen experiment are also extremely important for the the quantification of changes in the nuclear medium studied in deeply bound pionic systems [9].

From the following it is clear that a measurement at utmost precision with accurately determined systematic effects will result in a major step forward in low-energy strong interaction physics. The PSI experiment on pionic hydrogen fulfills all these requirements.

2. PIONIC HYDROGEN EXPERIMENT AT PSI

The required precision in the measurement of the X-ray transitions is provided by a crystal spectrometer. The system used in the experiment R-98-01 at the πE5 beam line of PSI surpasses all spectroscopy systems used so far for pionic hydrogen measurements.

2.1. Experimental Setup

The crystal spectrometer consists of the following parts:(i) cyclotron trap acting as a concentrator for the the incoming pions to reach high stopping efficiency in the light-weight hydrogen target [10], (ii) spherically bent Bragg crystal and (iii) X-ray detection system in which an array of 6 CCDs (charge coupled devices) is employed [11]. A detailed descriptions of the experimental setup can be found in [1].

2.2. Response Function - Crystal Characterization

In order to obtain the response function of the crystal spectrometer the Bragg crystals were characterized using a dedicated ECRIT X-ray source. The cyclotron trap and a hexapole magnet are confining the plasma which is produced by high-frequency heating [12]. The narrow X-ray lines of M1 transitions in He-like ions of the elements S, Cl and Ar are energetically most suited since their energies are adjacent to the 2p-1s, 3p-1s and 4p-1s transition energies of pionic hydrogen. With a tracking routine the measured X-ray spectra could be reproduced.

3. EXPERIMENTAL PROCEDURE

For a precision determination of ϵ_1 we measured the pionic 3p-1s X-ray transition in a hydrogen-oxygen mixture. Thus an adjacent pionic oxygen X-ray line (6h-5g) can be used as an in-situ calibration line. In our experiment the theoretically predicted molecular effects [13] via formation of a complex [(π pp)ee] and thus influencing the ϵ_1 extraction were investigated by variation of the hydrogen density in a wide range as given in tab.1.

Table 1
Measurements of different pionic hydrogen transitions using different hydrogen densities (given in equivalent pressure) were performed. The 3p-1s transition in μp (not listed here) was measured at 12.5 bar.

Equiv. pressure (bar)	3	10	28	800(*liquid*)
$\pi p(2p-1s)$		x		
$\pi p(3p-1s)$	x	x	x	x
$\pi p(4p-1s)$		x		

The influence of the Doppler broadening on the width Γ_{1s} was studied by measuring the 2p-1s, 3p-1s and 4p-1s transitions at the same gas pressure (10 bar). A high statistic measurement on the 2p-1s transition in pionic hydrogen was performed recently. The Doppler broadening effect is clearly visible in the width increasing 4p-1s to the 2p-1s according to the expectations. In 2004 a measurement of the 3p-1s transition in muonic hydrogen μp was performed. In this system without strong interaction the Doppler broadening can be studied in detail and recent electromagnetic cascade calculations [14] can be tested.

4. PRELIMINARY RESULTS

We succeeded in extracting the attractive strong interaction shift ϵ_{1s}=7.120±0.008±0.007 eV with unprecedented precision. Compared to the former experiment at PSI [15] the accuracy was increased by a factor ∼3. Concerning the question of molecular effects affecting the shift no indications were found in our experiment [16].

From the measurements of the transitions of 4p, 3p 2p to the 1s state we find a very preliminary value for the width Γ_{1s}=0.823±0.019 eV. Here the response function determined on the basis of the ECRIT measurements and the corrections of the Doppler broadening due of Coulomb transitions were taken into account. However, the final precision in the width might be considerably higher using the data of a high statistic measurement of the 2p-1s transition -these data are in analysis now - and with further detailed studies of the Doppler broadening.

5. SUMMARY

The precision experiment on pionic hydrogen at PSI lead already to the most accurate values of the strong interaction shift and width and accordingly to the scattering lengths. The goal in the precision of ϵ_{1s} (0.2%) is already reached. The precision of the preliminary result of Γ_{1s} is $\sim$ 2.3% thus a factor of $\sim$3 better than in the preceding PSI experiment [15]. More detailed studies will lead to a further approach to the precision goal of 1% in the strong interaction width.

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