Precision measurements in pionic hydrogen

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The strong interaction in the pion nucleon system leads to a shift and a broadening of the 1s-ground state in pionic hydrogen. These two quantities are being measured in an experiment at the Paul Scherrer Institute with much improved precision and allow an experimental test of recent calculations in the framework of Chiral Perturbation Theory. The experimental techniques using high resolution crystal spectroscopy are described as well as recent results.

1. MOTIVATION

The main objective of the pionic hydrogen experiment at PSI [1] is the precise determination of the isoscalar and isovector pion nucleon scattering lengths for testing of the quantitative low energy QCD predictions by chiral perturbation theory [2–4]. Consequently the pion nucleon coupling constant using the Goldberger-Miyazawa-Oehme sum rule and a quantification of the Goldberger-Treiman discrepancy can be extracted with unprecedented precision. Last but not least this experiment will measure the size of chiral symmetry breaking (pion-nucleon sigma term).

The experiment aims at a precision of 0.2% in the shift and 1% in the width. Therefore, precise values of the isoscalar and isovector scattering lengths using Deser-type formulae can be extracted from the hydrogen data alone, the hadronic shift being proportional to the sum of isoscalar and isovector scattering lengths, the width being proportional to the square of the isovector scattering length. Contrary to former measurements [5,6] one does not rely on constraints given by shift measurements of pionic deuterium in order to achieve precise values for the isospin scattering lengths.

2. CASCADE PROCESSES

Negatively charged pions stopped in hydrogen form pionic hydrogen atoms in high n states. The subsequent cascade is a complicated interplay of different processes like elastic scattering, external Auger transitions, chemical deexcitation, Stark transitions and X-ray transitions. The measured Lyman transitions are subject to the influence of these processes both in their intensities as well as in their line shapes. The result of the experiment is mostly influenced by the two following processes:
(i) Coulomb deexcitation which can lead to Doppler broadening of the X-ray transitions and thus falsify the extracted hadronic width.

$$(\pi p)_n + H \longrightarrow (\pi p)_{n'} + H + kinetic\ energy \qquad (n' < n) \qquad (1)$$

In this process the transition energy is converted into kinetic energy of the pionic atom and a hydrogen atom. The pionic atom can gain energies up to several hundred eV, which gives rise to a Doppler broadening in a range comparable with the hadronic width. Experimental information about reaction (1) can be disentangled by measuring different p transitions to the ground state and from measurements of the equivalent transitions - but without strong-interaction effect - in muonic hydrogen atoms.

ii) Another reaction possibly influencing the determination of the strong-interaction shift is the formation of molecular complexes according to

$$\pi p + H_2 \longrightarrow [(\pi pp)p]ee \qquad (2)$$

(see ref. [8]). The transition energy starting from a molecular state would be shifted due to the binding energy of the molecular complex. Since the formation rate has a linear density dependence one can study this effect by measurements at different target densities.

3. EXPERIMENTAL TECHNIQUE

For the precision aimed at, the pionic K X-ray energies between 2.5 and 3.0 keV have to be determined to about 10 meV. This requires the use of a reflection crystal spectrometer, which was set up in the Johann geometry. The simplified scheme in Fig. 1 shows the arrangement consisting of a cyclotron trap with the B-field perpendicular to the incoming pions, a spherically bent crystal for the Bragg reflection to the position sensitive CCD X-ray detector (for detailed description see [7]). The energy measurement is thus converted to a position measurement on the CCD-array. The response function of the spectrometer was extracted from measurements of pionic carbon using methane, where no broadening effects due to Coulomb explosion should be present. A more flexible crystal characterization has been started using an ECRIT source of argon X-rays. It uses the modified cyclotron trap plus a hexapole magnet for confining the HF heated plasma. Narrow X-ray lines of helium-like ions have been produced at high intensities.

4. MEASUREMENTS

In a series of experiments in 2001 possible density effects according to reaction (2) were studied using the 3p-1s transition at different densities. The preliminary results show no

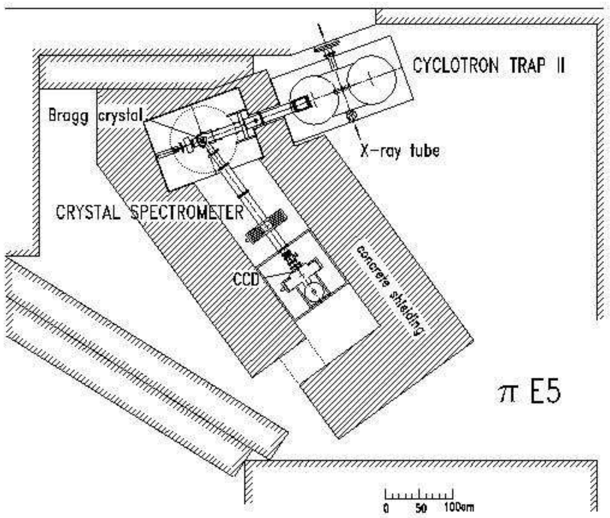

Figure 1. Scheme of the experimental setup

density effect on the shift. Hence, the radiative decay from molecular states is negligible at the present level of accuracy.

In a run period of about 2 months in spring 2002 the X-ray transitions of the states 4p, 3p and 2p to the 1s ground state were measured with high statistics for the first time in the same experimental apparatus. The idea behind this approach is the fact that the strong-interaction width is independent of the transition whereas the broadening caused by the different cascade processes varies. Thus the correctness of corrections applied to the different transitions feeding the ground state can be cross checked by this condition.

As an example, the measured 3p-1s transition of pionic hydrogen is displayed in Fig. 2 exhibiting an excellent signal-to-noise ratio. The energy calibration was done in situ with pionic X-rays from Beryllium foils installed inside the hydrogen target (see insert spectrum in Fig. 2) and Zn fluorescence lines excited by an X-ray tube.

5. SUMMARY AND OUTLOOK

The density dependence studies of the shift show no effect at the present level of accuracy. With the successfully performed measurements of the transitions from 4p, 3p and 2p states to the ground state one has a handle on the influence of the cascade processes, in particular on the Coulomb deexcitation. The data analysis is in progress now. The ECRIT X-ray source was successfully tested this year. The next steps are a comprehensive characterization of the Bragg crystals with the ECRIT source. Direct measurements of the Doppler broadening in muonic hydrogen atoms will be started in about 2005. Together with an advanced cascade model [9] the correction for Coulomb deexcitation should be accurate enough to reach the anticipated accuracy (1%) for the hadronic width in pionic hydrogen.

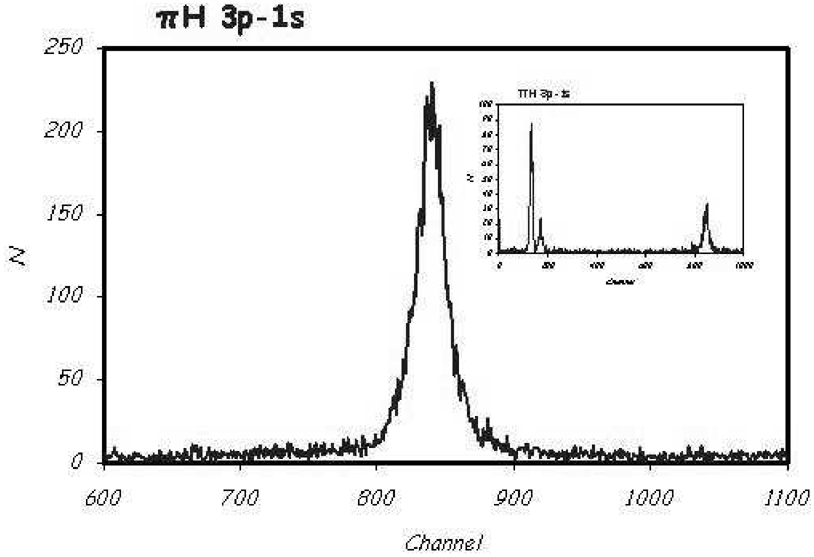

Figure 2. X-ray spectra for the 3p-1s transition in pionic hydrogen. The inserted spectrum shows the in situ calibration using pionic beryllium transitions.

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