The new pionic hydrogen experiment at PSI

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The measurement of the hadronic ground–state shift and broadening in pionic hydrogen is resumed at the Paul–Scherrer–Institut (PSI). The final goal of the experiment is to achieve an accuracy of 0.2% for the shift and of 1% for the width of the ground state, which are improvements by factors of about 3 and 8 compared to the previous high–resolution measurement.

1 Introduction

A high–precision determination of the πN scattering lengths allows conclusive tests of the methods of HBχPT [1]. Experimentally, the scattering lengths may be obtained either by measuring the ground–state shift ϵ_{1s} and broadening Γ_{1s} in pionic hydrogen or by extrapolating πN scattering data to threshold, e.g. by using results from phase–shift analyses [2,3].

The relations between exotic–atom parameters and isoscalar and isovector scattering lengths are given by Deser–type formulas [4–6]. Furthermore, from Γ_{1s}, which is proportional to the isovector scattering length squared, the pion–nucleon coupling constant is obtained by the Goldberger–Miyazaw–Oehme sum rule [7,8]. As seen e.g. from Fig. 2 in [9], Γ_{1s} is the most important quantity to be measured for an improved sensitivity.

The new experiment [10] aims at a significant increase in accuracy compared to the previous precison experiments [9]. An important part will be studies for a better understanding of the atomic cascade.

- First goal of the new experiment is to establish a precise value for the shift, which must be proven to be independent of pressure. Such a dependence on the environment may originate from the formation of complex molecular structures like [(πpp)p]ee when the πp system collides with other molecules in the target [11]. Deexcitation from molecular levels could lead to small energy shifts hidden by the line width of the transition.

- Secondly, a more accurate determination of the ground–state width requires a better knowledge of Coulomb deexcitation, a non–radiative deexcitation channel of the pionic–hydrogen atom, where energy is released by accelerating the collision partners. To obtain the pure hadronic contribution, the measured line width has to be corrected for Doppler broadening.

2 Experimental approach

The measurement is based on techniques developed and applied to the precision spectroscopy of X–rays from antiprotonic and pionic atoms together with substantial improvements in background suppression. The cyclotron trap provides a concentrated X-ray source for a focusing low–energy crystal spectrometer. X–rays emitted from the stop volume are reflected by spherically bent silicon or quartz crystals of up to 10 cm diameter. The X–rays are detected by a large–area detector built up from an array of Charge–Coupled devices (CCDs) [12].

The measurement of ϵ_{1s} in a wide pressure range will prove or disprove the influence of molecular formation on the decay branches involving the πH Lyman transitions. The pressure is varied in the density range from 3 bar equivalent up to liquid by using a cryogenic target, which is operated at about 1.5 bar absolut pressure. The decrease of X–ray line yields due to the increasing Stark mixing is 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. Muons are obtained from the decay of slow pions inside the cyclotron trap close to the cryogenic target. The line width in muonic hydrogen will be interpreted in terms of a new dynamical cascade picture involving the velocity of the exotic atom and the results from recent calculations for the cross section of the various collision processes [13].

To exploit the detailed studies of the line shape requires a better knowledge of the crystal spectrometer response than available up–to–now. In the few keV range, narrow X–ray 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, crystal response functions had been obtained from narrow pionic–atom transitions in the previous experiments [9,14]. However, the limited rates even at high–flux pion channels lead to unacceptable long measuring times for detailed crystal studies.

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 [15]. The magnet of the cyclotron trap itself is used to provide the mirror field for the plasma [16].

3 First results

A first series of measurements took place at the high–intensity pion channel πE5 of PSI. At a target density equivalent to about 4 bar, with a H_2/O_2 gas mixture the πO(6h–5g) calibration line and the πH(3p–1s) transition were measured simultaneously. This method is basically free of systematic errors in the energy calibration due to long–term instability and will be applied in a high-statistics measurement within the next year.

At higher densities hydrogen and oxygen have to be measured alternately to prevent the oxygen from freezing. For the first time, pionic hydrogen was measured in the liquid phase.

4 Conclusions and outlook

No pressure dependence of the ground–state shift was observed for pionic hydrogen due to molecular formation. However, evidence for an increase of the line width was found in the liquid phase. This observation, attributed to Coulomb deexciation, will be studied again in the forthcoming beam time.

Later on in the second part, after detailed studies of the Bragg crystals, the investigation of the line widths in muonic hydrogen, where the hadronic effects are absent, will yield more precise information on Coulomb deexcitation. Based on the advanced cascade code then a further substantial improvement on the accuracy for the hadronic line width will be feasible.

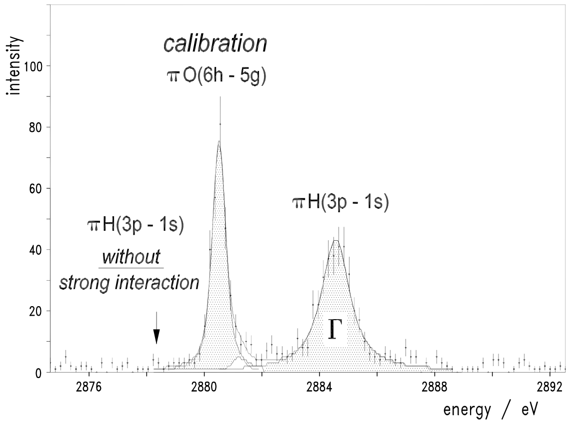

Figure 1: Simultaneously measured reflections of the πH(3p–1s) and the π^{16}O(6–5) transitions.

Table 1: Preliminary results of line shift and broadening for the $\pi H(3p-1s)$ transition obtained at 3 different densities. For the electromagnetic transition energy a value of 2878.808 eV was used as in the analysis of the previous experiment at 15 bar equivalent density [9].

density equivalent	ϵ_{1s} /meV $\pm stat \pm sys$	Γ_{1s} /meV $\pm stat \pm sys$	ref.
3.5 bar	+ 7082 ± 31 ± 15	973 ± 75 ± 10	this exp.
28bar	+ 7137 ± 18 ± 40	969 ± 26 ± 10	this exp.
liquid	+ 7095 ± 25 ± 25	1052 ± 58 ± 10	this exp.
15 bar	+ 7108 ± 13 ± 34	969 ± 45 ± 10	[9]

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