Strong interaction shift and width in pionic hydrogen isotopes

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The measurement of the strong interaction shift and width of the ground state of the pionic hydrogen atom allows to determine the isospin separated s–wave scattering lengths of the pion nucleon system. The development of such measurements lead to the present high precision results obtained at PSI. The need for still further improvement especially in the width determination lead to a new proposal at PSI. The implications of this proposal are discussed in detail.

1 Introduction

The pionic hydrogen atom is dominated by the electromagnetic interaction of its constituents. Their strong interaction is only effective in case the wave functions of pions and the proton significantly overlap. In the ground state it results in a broadening of $\approx$ 1 eV and a shift of $\approx$ 7 eV to be compared to an electromagnetic binding energy of E_{1s} = 3238 eV. The relations of the measured quantities to the hadronic scattering lengths a^h describing the $\pi^- p \to \pi^- p$ and the $\pi^- p \to \pi^0 n$ process, respectively, are given by the Deser–type formulae[1,2]:

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

$$\frac{\Gamma_{1s}}{E_{1s}} = 8\frac{Q_0}{r_B}(1+\frac{1}{P})(a^h_{\pi^- p \to \pi^0 p}(1+\delta_\Gamma))^2 \tag{2}$$

Here r_B is the Bohr radius of the pionic hydrogen atom with r_B = 222.56 fm, $Q_0 = 0.142\ fm^{-1}$ is a kinematical factor and P=1.546±0.009 is the Panofsky ratio[3]. δ_ϵ and δ_Γ are electromagnetic corrections, which have recently been calculated with an accuracy of about $5 \cdot 10^{-3}$.

Some unique features of the exotic atom's method should be recalled:

- The electromagnetic interaction in exotic hydrogen atoms is well understood. Any deviations caused by another interaction can therefore be studied with high precision.
- Conventional scattering experiments are restricted to energies above about 10 MeV and have to rely on an extrapolation to zero energy in order to extract the scattering lengths. The exotic atom's method, however, directly measures linear combinations of the isospin separated scattering lengths with highest intrinsic accuracy.

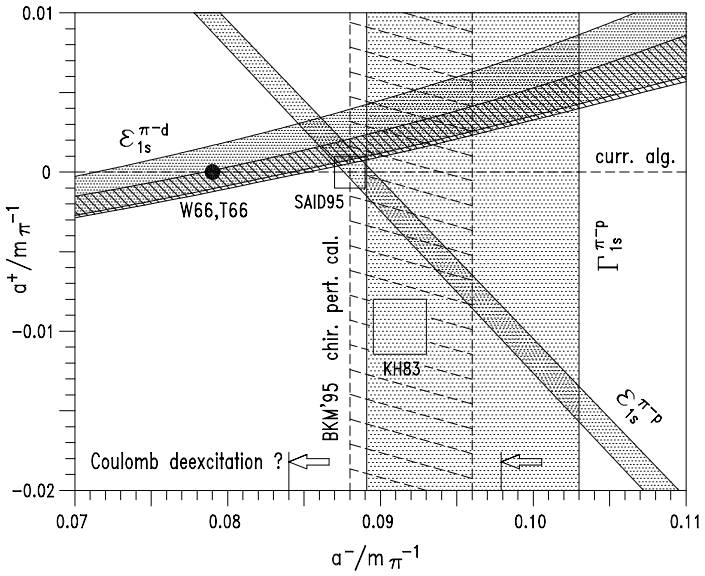

Figure 1: The scattering lengths.

- Pionic hydrogen is one of the simplest hadronic systems bound electromagnetically and is therefore ideally suited for a study of strong interaction. The even simpler $\pi^+\pi^-$ atoms are at the moment subject of a challenging proposal at CERN [5]. They are difficult to produce and will not allow to perform high precision studies comparable to those in pionic hydrogen in next future.

2 Present status

The shift and the width of the ground state in pionic hydrogen and deuterium have been determined in a series of experiments by the ETHZ-Neuchâtel-PSI collaboration by measuring the 3–1 transition at 2886 eV. The relation of the measured quantities with the isospin separated scattering lengths a^+ (isoscalar) and a^- (negative value of the isovector component) is given by:

$$a^h_{\pi^- p \to \pi^- p} = a^+ + a^- \tag{3}$$

and

$$a^h_{\pi^- p \to \pi^0 p} = -\sqrt{2} a^- \tag{4}$$

The results represent an improvement by more than an order of magnitude compared to earlier work for the strong interaction shift. The experiment gave the first result for the width of the ground state [9]. At present the error in the width caused by Doppler broadening is almost an order of magnitude bigger than the one in the shift. This excludes the extraction of the isospin separated scattering lengths with errors on the %–level. The measurement is very useful, however, to put constraints on the different work in phase shift analysis of the scattering experiments in the pion nucleon system. A synopsis of the present knowledge for a^+ and a^- is shown in Fig. 1. The point at $a^- = 0.079$ indicates the current algebra calculations of Weinberg and Tomonaga [10,11]. The rectangles KH83 [12] and SAID95 [13] stand for different phase shift analysis of pion scattering data. The slope with the inscription $\epsilon_{1s}^{\pi^- p}$ shows the constraint from the shift measurement. The vertical band $\Gamma_{1s}^{\pi^- p}$ denotes the constraint from the width data. It can be compared with a recent chiral perturbation calculation BKM '95 [14]. As there may be additional broadening effects by Coulomb deceleration the possible trend in a change of the experimental band is also shown. Additionally the two shift measurements in pionic deuterium lead to constraints in this plot indicated by $\epsilon_{1s}^{\pi^- d}$, where the influence of higher order contributions is taken into account in the interpretation of the data [15,16].

2.1 Proposed measurements of the strong interaction width in pionic hydrogen

First tests with the newly designed cyclotron trap (cyclotron trap II) showed an enhancement in intensity by more than an order of magnitude and a further reduction of background (see Fig. 2) compared to earlier experiments.

As the intensity problem can be considered to be solved, the limitation in the determination of the strong interaction width is given by the Doppler effect caused by the so-called Coulomb deexcitation acceleration. In a recent proposal to PSI it is therefore planned to determine the ground state width (and shift) for the 2–1 (2433 eV) and the 3-1 (2886 eV) transitions at 3 different pressures between 3 and 15bar [17]. In a first step, however, it is planned to establish the independency of the ground state shift from pressure by measuring the energy of pionic 3-1 transition simultaneously to the pionic oxygen 6–5 transition at 2876 eV. The strong width is in a second step extracted from a simultaneous fit of the 6 transitions, which keeps the different Doppler broadenings free, but leaves the resolution for the different transitions fixed at its known value. In addition the strong interaction width is assumed to be the same for all transitions. With this procedure a common value for the strong interaction width can be extracted with an accuracy of about 2.5%.

The still necessary increase in accuracy can be achieved by a simultaneous

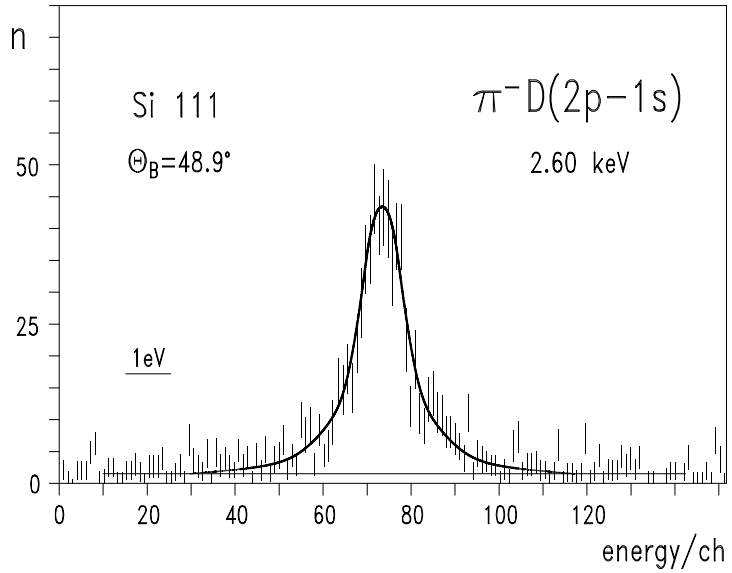

Figure 2: The 2–1 transition of pionic deuterium measured with the Jülich crystal spectrometer and cyclotron trap II.

spectroscopy of pionic and muonic hydrogen atoms in a third step of the experiment. The muonic X–rays do not show any strong interaction broadening, but exhibit a similar Doppler broadening as pionic atoms. In addition recent experiments determined the velocity state of the pionic hydrogen atom at the moment of the charge exchange reaction [18]. These results constrain the input parameters for the cascade calculations as well as the direct X–ray measurements from muonic hydrogen. The results of the cascade calculations can then be used to correct for the influence of the Doppler broadening.

2.2 Combined measurement of muonic and pionic X-raxs

For the newly proposed measurement a method was found to measure pionic and muonic X–rays simultaneously. The reduced masses of pionic and muonic hydrogen exhibit almost the same ratio as two lattice plane differences of quartz. With a two crystal set up the pionic and muonic X–rays can be Bragg reflected to the same CCD detector.

A computer simulation of the muonic 2–1 transition alone is shown in Fig. 3. It comprises 20000 measured muonic X–rays which corresponds to a

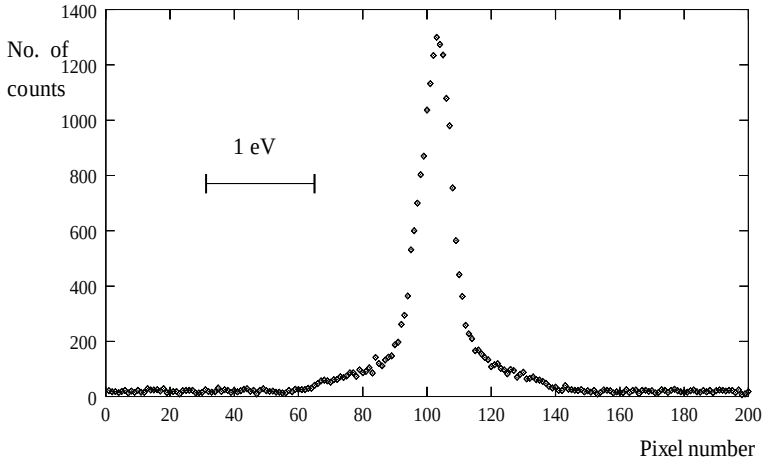

Figure 3: A simulation of the 2–1 transition in muonic hydrogen. The structure of the line reflects the different contributions from Coulomb deexcitation processes.

measuring time of 2 weeks at a pressure of 15 bar. The line is broadened by different contributions from Coulomb deexcitation process as calculated with a modern cascade program. A resolution of 220 meV is assumed for a quartz crystal and a statistically populated hyperfine splitting of 180 meV is taken into account. The peak to background ratio corresponds to recent experience.

2.3 Calibration procedures

A successful X–ray spectroscopy of the quality required for the pionic hydrogen experiment bases on a narrow and well understood response function of the crystals. An energy calibration or an optimization can not be achieved with fluorescence X–rays as produced with X–ray tubes. Their width is an order of magnitude broader than the resolution of the crystals. The line shape is moreover influenced by not well determined satellite lines.

There are about 10 useful pionic X–rays in the energy region between 2 and 3 keV available from pion stops in low Z gases. Their rates, however, are not sufficient to do a time consuming optimization of the crystal resolution. A solution of this problem is the production of X–rays from one- or two–electron atoms. They can be delivered copiously by electron cyclotron resonance (ECR) sources, which have been developed as ion sources for accelerators. The line width of the X–rays is determined almost exclusively by a very much reduced

Doppler effect which leads to broadenings negligible compared to the intrinsic resolution of the crystals. Presently such a source is being set up at PSI. It is planned to test it first with Si crystals of well understood response function. In a second step the response function of quartz crystals will be optimized and fluorescence sources will be calibrated. During the measurement with pions and muons the crystals can then be routinely surveyed with pionic X–rays which in turn can be used to energy calibrate the ECR measurement on the ppm level.

3 Conclusions

Recent experimental developments allow to extend the crystal spectroscopy measurements in pionic hydrogen isotopes to a precision level of % in the detrmination of isospin separated scattering lengths. After a preparation time of about two years first results should become available in the year 2001.

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